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Effect Simulation of Responding Measures During a Heavy Pollution Red Alert in Tianjin City

Minjiao Li ^{1,2}, Ting Li ³, Huaiming Li ^{1,2,*}, Xing Wang ^{1,2}, Zilin Wang ^{1,2},
Lifeng Yin ¹ and Yuhong Yang ^{1,2}

¹ Tianjin Academy of Environmental Sciences, Tianjin, China

² Tianjin Environmental Sciences and planning technology development Co., Ltd.,
Tianjin, China

³ Ningxia Meteorological Observatory, Yinchuan, China

*Corresponding author e-mail: 695149805@qq.com

Abstract. The WRF/SMOKE/CMAQ model is used to simulate a heavy pollution process in the winter of 2016 in Tianjin. Three types of simulation scenarios are set up for the activation of red alert due to the "Tianjin Heavy Pollution Weather Emergency Plan". The extinction effect of emergency measures on PM_{2.5} concentration is assessed quantitatively. Simulation results show that during this red alert period, a 30% reduction of industrial production can be implemented to reduce the average PM_{2.5} concentration by 3% to 10%, while odd-and-even license plate rule of motor vehicle can be implemented to reduce the average PM_{2.5} concentration in the city by 3% to 5.5%. The simultaneous implementation of two measures can reduce the average PM_{2.5} concentration by 5% to 12%. From the perspective of PM_{2.5} peak and mean drop under the three control scenarios, the control effect of industrial limited production measures on the peak value is more obvious than the mean value. The control effect of the vehicle's line-limit measures on the mean is more obvious than the peak value. The control effect of the peak value and mean value control of PM_{2.5} under industrial and motor vehicle simultaneous measure scenarios is similar to that of industrial limited production measures. It shows that industrial emissions are still the main source of contribution during heavy pollution, and that vehicle control has played a certain role.

1. Introduction

In recent years, with the rapid development of social economy and the increase of energy consumption, atmospheric pollution problem in China has become increasingly significant [1-5]. In the Beijing-Tianjin-Hebei region, which is in the period of superposition of industrialization and post-industrialization, heavy air pollution process frequently occurs, because of pollution emission from fire coal, industry, motor vehicles, and residents, particularly during the winter heating period with intensive pollutant emission and unfavorable meteorological conditions [6-10]. To effectively cope with heavy atmospheric pollution, *Tianjin Heavy Pollution Weather Emergency Plan* is released annually from 2013 to 2016 in Tianjin City, in which early warning levels are determined, and responding measures to various warning levels are elaborated correspondingly in accordance with the daily mean value of *air quality index* (AQI). This paper intends to analyze the weather process during a heavy pollution red alert



in winter of 2016 in Tianjin, and makes preliminary assessment of the impact of the implementation of Class I responding measures to “the heavy pollution weather in Tianjin” in 2016 on the concentration of pollutants such as PM_{2.5} in Tianjin, so as to provide a certain reference for the scientific formulation of emergency plans.

2. Research methods

2.1. Data sources

The monitoring hourly concentration of PM_{2.5}, PM₁₀, NO₂, SO₂ and CO in the study are released by China National Environmental Monitoring Center (<http://106.37.208.233:20035/>). The major atmospheric pollutant emission data come from the environmental statistical data of Tianjin and the statistical yearbook data of Tianjin in 2015 [11]. Pollutant calculation methods and emission factors refer to nine technical guidelines issued by Ministry of Environmental Protection [12, 13], such as *Technical Guidelines for the Preparation of Atmospheric Inhalable Particulate Matter Source Discharge Inventory (Trial)*. The emissions of pollutants in the surrounding provinces and cities around Tianjin are provided by Tsinghua University MEIC emission inventory data [14]. The emergency response measures come from *Tianjin Heavy Pollution Weather Emergency Plan* (No. 89 [2016] of the General Office of the People's Government of Tianjin Municipality). Pollutant emission reductions are estimated according to the requirements of Grade I responding measures of *Tianjin Heavy Pollution Weather Emergency Plan* in 2016.

2.2. Model settings

This study uses the WRF/SMOKE/CMAQ model to simulate the changes in air quality during the red alert period from December 16 to December 21, 2016 in Tianjin. A triple nested analog domain is adopted by the model in the horizontal direction. The grid resolutions are 27km, 9km, and 3km, respectively. The outermost and sub-surface simulation regions cover most of China's regions and North China respectively. The innermost simulation area covers Tianjin, the surrounding areas of Beijing, Hebei, Inner Mongolia, and parts of the Bohai Sea, which is concerned by this study. A total of 28 pressure layers are set in the vertical direction, and the layer spacing gradually increases from bottom to top. The initial input data of WRF[15] model adopts global analysis data[16] which is 6h per time and 1°×1° resolution, and provided by National Center for Environmental Prediction (NCEP). In the SMOKE model, the MEIC emission data is used for the D01 and D02 region, the emission data of down-top and top-down establishments based on the city's environment and statistical is used for data the D03 floor in Tianjin, and the MEIC emission data is used by the other areas. CB05 gas-phase chemical reaction mechanism and AE6 aerosol mechanism are used by the CMAQ model. The process analysis period is from December 20, 2016, 20:00 to December 24, 2016 24:00. The simulation period is from 20:00 to 22:00 on December 20, 2016. Four scenarios are set for this simulation: the basic scenario without emergency measures, the implementation scenario of industrial emergency measures, the implementation scenario of emergency measures for motor vehicles, and the implementation scenario of simultaneous emergency measures for industrial and motor vehicles. Since red alert contingency plans have been also issued by various provinces and cities in the Beijing-Tianjin-Hebei region, so the pollutant emission reductions in the surrounding areas are reduced in proportion to the Tianjin estimates.

3. Results and discussion

3.1. Heavy pollution process analysis

3.1.1. Heavy pollution process evolution. From December 16 to December 21, 2016, there is a continuous regional heavy pollution process under high-humidity, stable weather and poor spread conditions in the Beijing-Tianjin-Hebei region. Tianjin City launches the heavily polluted weather red alert at 20 o'clock on December 16, and launches a Class I emergency response. Recalling the entire

pollution process, Tianjin's air quality quickly deteriorates on December 16 and the AQI value rise from 77 at 01 o'clock to 189 at 20 o'clock. After starting red alert, the AQI value reaches 206 at 22 o'clock and the air pollution level changes from moderately polluted to heavily polluted. On 17 December, the AQI is stable between 200 to 270, and the daily $PM_{2.5}$ concentration reaches $188 \mu g/m^3$. $PM_{2.5}$ concentration continues to rise on 18 December. The maximum concentration, which is $381 \mu g/m^3$, appears at 12 o'clock, and the AQI value reaches 300 at 06 o'clock. The level of pollution rise from heavily polluted to severely polluted, and the AQI value reaches 422 at the peak. The pollution level on December 19 is lower than that on December 18, but the average daily $PM_{2.5}$ concentration is as high as $243 \mu g/m^3$. There is a high value of $365 \mu g/m^3$, whose corresponding AQI value is 411, at 17 o'clock. The pollution remains at a high level from December 20 to December 21, and the daily average AQI is 290 and 309, respectively. The red alert is adjusted to orange warning at 24 o'clock on December 21. On December 22, affected by the cold air, the pollution, the diffusion conditions and the air quality are improved significantly. The heavy pollution process basically ends.

During the red alert period, Tianjin City experiences a total of 125 hours of air pollution, where moderate pollution is 2 hours, heavy pollution is 69 hours, and severe pollution is 54 hours. The average AQI is 291. The primary pollutant is $PM_{2.5}$, and the mean concentration is $240 \mu g/m^3$.

3.1.2. Spatial characteristics of pollutant concentration. Table 1 shows the mean concentration ratios of five pollutants such as $PM_{2.5}$, PM_{10} , SO_2 , NO_2 and CO at 14 national control points in Tianjin during the red alert period. The concentrations of $PM_{2.5}$ are prominent in Beichen Science Park, Zhongshan North Road, and Qinjian Road. The concentration of $PM_{2.5}$ in Beichen Science Park is 26.1% higher than the city average concentration. PM_{10} presents similar distribution compared to $PM_{2.5}$, and the pollution level at the stations of Zhongshan North Road and Beichen Science Park are relatively heavy. SO_2 has the highest concentration around Qinjian Road, which is 63.1% higher than the city average value, followed by Hexi Yijing Road and Beichen Science Park site, which are 44.5% and 32.4% higher than the city average respectively; the average concentration of NO_2 is higher than the highest value at Beichen Science Park site, reaching 20.6%; the average concentration of CO is higher than that of the Hexi Yijing Road, followed by Beichen Science Park. It can be found that the pollutant concentration indicators of Beichen Science Park, Qinjian Road and Zhongshan North Road are all higher than the city average. At the same time, the mean concentration ratio of SO_2 and CO in the Hexi Road Station is also more than 20%; the pollution responding to two sites of the Binshui West Road and Yongming Road is relatively light, and its various pollutant concentration indicators are lower than the city average. Therefore, during the red alert period, the northern part of Beichen District, Hongqiao District, Hebei District and Binhai New Area are heavily polluted, while Nankai District and the southern part of Binhai New Area are lightly polluted.

Table 1. The mean ratio of pollutants concentrations in state controlling in Tianjin during the red alert

Monitoring sites	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Beichen Science Park	26.1%	14.0%	32.4%	20.6%	17.4%
Binshui West Road	-6.8%	-10.3%	-58.3%	-17.3%	-8.7%
Dali Road	5.0%	-2.3%	-6.9%	0.2%	-7.4%
Dazhigu Bahao Road	8.3%	4.6%	-15.4%	-0.3%	-13.2%
Fourth Avenue	-19.9%	-8.5%	-21.9%	4.7%	-4.7%
Hanbei Road	-12.4%	-5.2%	-10.5%	-13.5%	-4.4%
Hangtian Road	-5.1%	1.5%	9.0%	3.8%	8.5%
Hexi Yijing Road	-4.4%	11.0%	44.5%	3.5%	20.7%
Jingu Road	-23.4%	-16.2%	7.9%	-3.6%	-15.3%
Qianjin Road	8.9%	6.2%	-17.7%	5.8%	4.6%
Qinjian Road	16.4%	6.1%	63.1%	3.2%	7.7%
Yongming Road	-15.7%	-14.2%	-15.4%	-15.2%	-23.3%
Yuejin Road	-1.6%	1.5%	-23.2%	0.0%	3.6%
Zhongshan North Road	23.2%	22.5%	13.1%	6.6%	15.0%

In addition, the HYSPLIT model [17] developed by the United States National Oceanic and Atmospheric Administration (NOAA) is used to simulate the air mass trajectory of the heavy pollution process. From the air mass trajectory of 24 h after the peak of mass concentration of $PM_{2.5}$ (Fig. 1), near-surface pollutants mainly come from local pollutant accumulation. In particular, the discharge of pollutants in northwestern Tianjin is the most obvious, which is consistent with the observations of abovementioned national control points.

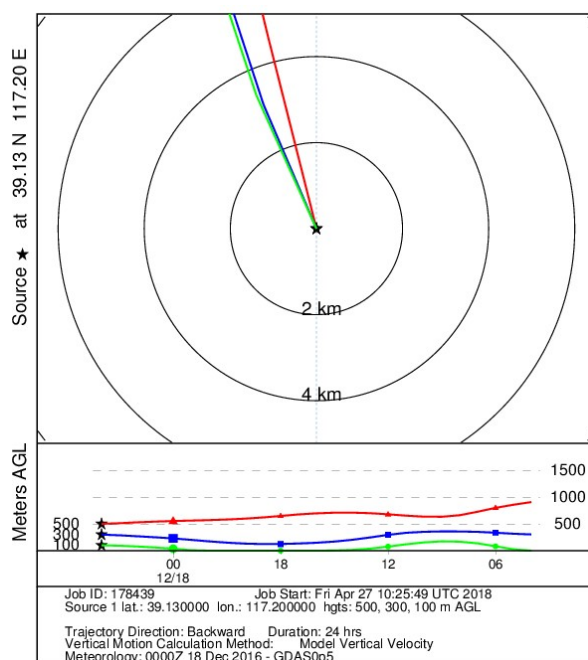


Figure 1. NOAA HYSPLIT MODEL Backward trajectories ending at 12 am on Dec.18

3.2. Effect evaluation of emergency measures

3.2.1. Verification of simulation results. To further verify the simulation results by CMAQ model, this paper applies *standardized average deviation* (NMB), *normalized mean error* (NME), and *correlation coefficient* (R) between the hourly monitoring and simulated concentrations of $PM_{2.5}$ and PM_{10} at 14 national control points in Tianjin from December 16 to December 21, 2016. Calculation method has been introduced in previous literature [18]. As shown in Table 2, for $PM_{2.5}$ the correlation coefficient between simulated and monitoring concentration is 0.724, meanwhile NMB and NME are 3.18% and 13.95%, respectively. For PM_{10} , the correlation coefficient between simulated and monitoring concentration is 0.793, and NMB and NME are 12.96% and 18.52%, respectively. The indicators show similar or better simulation results reported in previous literatures [19-23], indicating that CMAQ model can be used to simulate various emission reduction scenarios during heavy pollution.

Table 2. Performance statistical parameters for $PM_{2.5}$ and PM_{10}

Pollutants	Evaluation Index		
	R	NMB/%	NME/%
$PM_{2.5}$	0.724	3.18%	13.95%
PM_{10}	0.793	12.96%	18.52%

3.2.2. Simulation scenario design. According to *Tianjin Heavy Pollution Weather Emergency Plan* in 2016, I-Grade responding measures include: restricting industrial production, limiting motor vehicle by odd-and-even license plate rule, increasing the frequency of machine sweeping and cleaning on roads, stopping all large-scale activities outdoor and implementing flexible working hours for enterprises and public institutions. To quantitatively evaluate the effect of emergency measures on $PM_{2.5}$ concentration decrease, four simulation scenarios are proposed: (1) Baseline scenario without emergency measures; (2) Emission reduction scenarios by solely restricting industrial production while other types of emission sources remain unchanged; (3) Emission reduction scenarios by solely odd-and-even license plate rule while other types of emission sources remain unchanged, and only the vehicle source in the model will be reduced to 50% of the baseline scenario; (4) Both restricting industrial production and limiting motor vehicle by odd-and-even license plate rule are implemented, with pollutants emitted by industrial sources being reduced to 70% of the baseline scenario and motor vehicles being reduced to 50%.

3.2.3. Result analysis under simulation scenarios. In this paper, the $PM_{2.5}$ concentrations under four scenarios during heavy pollution red alert are simulated. The hourly simulated concentration of $PM_{2.5}$ of 14 national control stations in Tianjin are compared with the hourly simulated concentration of the CMAQ model with different measures. The timing distribution of concentration contrast is shown in Fig. 2. Simulation results can reflect the atmospheric environmental quality during heavy pollution very well: the hourly simulated average concentration of $PM_{2.5}$ has the same trend as the site monitoring value in time. The average $PM_{2.5}$ concentrations for each scenario during the red alert period (from 20:00 to 21:00 on December 16, 2016) are: $279.2 \mu\text{g}/\text{m}^3$ under the baseline scenario, $258.5 \mu\text{g}/\text{m}^3$ under the industrial control measure scenario, $265.0 \mu\text{g}/\text{m}^3$ under the vehicle control measure scenario, and $247.8 \mu\text{g}/\text{m}^3$ under the industrial and motor vehicle simultaneous control scenario, respectively. The industrial and motor vehicle control scenarios are the closest to the average monitoring concentration ($240 \mu\text{g}/\text{m}^3$). This shows that the implementation of various emergency measures after the occurrence of red alert has played a positive role in reducing $PM_{2.5}$ concentration.

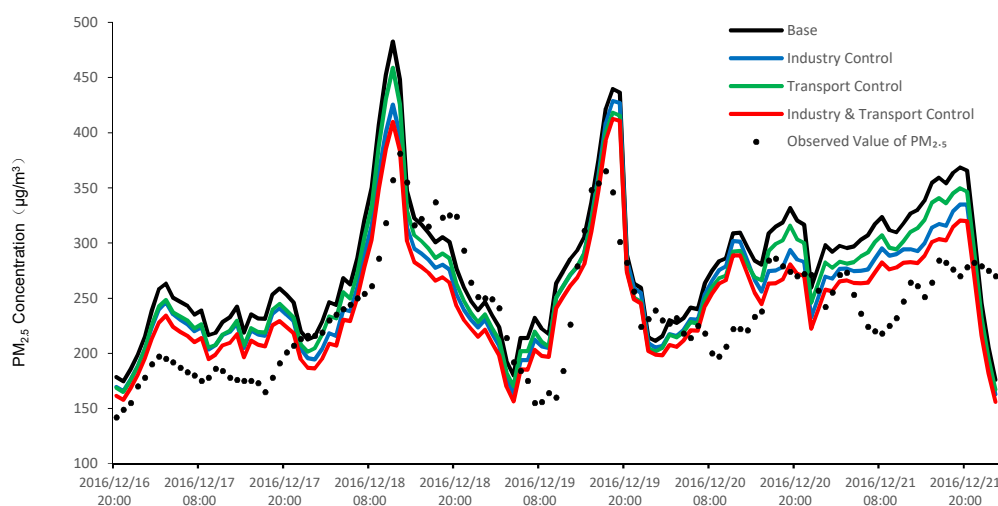


Figure 2. The comparison of the measured value of $PM_{2.5}$ concentration in state controlling in Tianjin and the simulated value in four scenarios during the red alert

The PM_{2.5} peak and mean value drop of 14 national control stations under three control scenarios are compared and analyzed (Table 3). Under the industrial limited production scenario, the peak values of the stations such as Jinji Road, Beichen Science and Technology Park, Hanbei Road, and Zhongshan North Road are greatly reduced by at least 12.4%. The peaks of Aerospace Road, Yuejin Road and Binshuixi Road have decreased by a small margin, which is below 7.62%. In terms of the average value, the sites of the Fourth Avenue, Hanbei Road and Yongming Road in Binhai New Area have the largest declines. The reduction in the six inner districts of the city is not much different, which is between 6% and 8%. Interestingly, the peak value of Beichen Science Park's site is the second larger, while the average decline is the smallest, only 5.22%. In general, the effect of industrial production restriction production measures on peak control is more significant than the average value. However, there is no correlation between the peak value and the degree of mean drop ($R=0.013$). The peak drop shows randomness. The decrease in the average value can more objectively reflect the actual situation of industrial pollution sources and emission reductions.

Under the traffic restriction of motor vehicle scenario, the peak drop at Binshui West Road, Dali Road, Qianjin Road, Qinhuangdao Road and other urban stations will be larger, which are more than 5%, while the peak drop of Fourth Avenue, Yongming Road, and Hexi Road are smaller, which are below 4.36%. The drop ordering of mean site is similar to that of peak case, and both show a strong correlation ($R=0.818$). However, the magnitude of the mean decline is greater than the peak drop, indicating that the restriction effect of the vehicle's line restriction measures on the overall pollution control process during the heavy pollution process is more significant than the control effect on the extremely high value. From the perspective of the city's region, motor vehicle control measures have a more significant effect on the emission reduction in the more densely populated areas. However, the overall decline in the number of sites is very small, demonstrating the importance of the implementation of motor vehicle control measures in the entire region.

Under the scenario of simultaneous control of industrial and motor vehicle measures, the peak drop of the peaks of Jinji Road, Beichen Science and Technology Park, Hanbei Road, and Qinhuang Road is larger, which is more than 16.1%. The peak drop of Aerospace Road, Yuejin Road and Binshuixi Road is less, which is lower than 11.7%. In terms of the average value, the drops of the sites of Fourth Avenue, Yongming Road and Hanbei Road are still larger, which are more than 14%. The drops of several sites in the six districts in the city fell are smaller, which is between 9% and 11%. There is no correlation between the peak value and the mean ($R=-0.007$), and the respective reduction order is similar to the industrial measure scenario. However, there has been a noticeable increase in the amplitude, which indicates that industrial emissions are still a major source of contribution during heavy pollution. The control of the motor vehicle has a certain effect at the same time.

Table 3. The comparison of the reductions of PM_{2.5} peak and average in Tianjin under different control scenarios

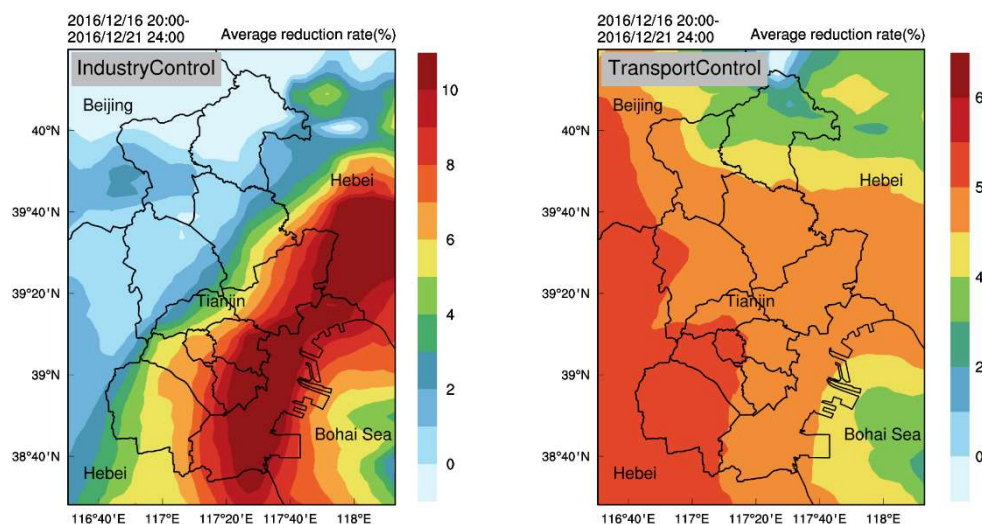
Monitoring sites	Industry control		Transport control		Industry & Transport control	
	Peak	Mean	Peak	Mean	Peak	Mean
Beichen Science Park	12.83%	5.22%	4.96%	5.13%	16.33%	9.15%
Binshui West Road	7.62%	6.56%	5.06%	5.35%	11.63%	10.77%
Dali Road	11.98%	6.90%	5.02%	5.27%	14.96%	10.94%
Dazhigu Bahao Road	12.19%	7.07%	4.96%	5.05%	15.66%	10.86%
Fourth Avenue	10.02%	12.47%	4.19%	4.79%	12.87%	15.77%
Hanbei Road	12.77%	10.66%	4.58%	4.82%	16.14%	14.08%
Hangtian Road	3.43%	7.81%	4.96%	4.93%	7.27%	11.51%
Hexi Yijing Road	10.56%	9.48%	4.36%	4.76%	14.76%	11.82%
Jingu Road	13.21%	9.89%	4.84%	4.95%	16.74%	13.44%
Qianjin Road	11.98%	6.90%	5.02%	5.27%	14.96%	10.94%
Qinjian Road	12.09%	6.06%	5.01%	5.26%	15.72%	10.14%
Yongming Road	11.87%	10.61%	4.23%	4.86%	15.59%	14.09%
Yuejin Road	6.43%	7.81%	4.97%	5.02%	9.74%	11.57%
Zhongshan North Road	12.48%	6.44%	4.96%	5.15%	15.43%	10.36%

Fig.3 shows the distribution of three control scenarios for the average $PM_{2.5}$ reduction rate during red alert. Under the industrial measures scenario, the $PM_{2.5}$ hourly average concentration reduction rate is between 3% and 10% from the total spatial situation of the whole city. Among them, the cut rates have changed the most in Binhai New Area, Dongli District, Jinnan District and Ninghe District. It is followed by six inner districts, Jinghai District, Xiqing District, Beichen District, Yinzhou District, Baodi District, Wuqing District, and other northwest region, whose reduction rate are basically below 6%. In terms of time, the city's extinction effect is the most significant at around 11 o'clock on December 18, with a maximum of 12%.

Under the vehicle measures scenario, the reduction rate of $PM_{2.5}$ hourly average concentration is between 3% and 5.5% according to the overall spatial situation of the city. Among them, the cut rate changes the most in six inner districts, Jinghai district and Xiqing district, with an amplitude of more than 5%. The rate of reduction is around 4.5%-5% in other areas except Jizhou District. In term of time, the city's reduction effect is most significant around 18 o'clock on December 18, which is up to 6%.

Under the simultaneous control of industry and motor vehicle measures, the reduction rate of $PM_{2.5}$ hour average concentration is between 5% and 12% in terms of the total space of the city. Among them, the cut rates have changed the most in Binhai New Area, Dongli District, Jinnan District and Ninghe District. It is followed by six inner districts, Jinghai District, Xiqing District, Beichen District, Jizhou District, Baodi District, Wuqing District and other northwest region, whose reduction rate is basically below 6%. In term of time, the city's extinction effect is the most significant at around 17 o'clock on December 20, with a maximum of 16.4%.

The results of the study show that, in the face of heavy pollution weather in Tianjin, a reduction of 30% in emissions from industrial enterprises can reduce the average $PM_{2.5}$ concentration in the city by 3% to 10%. The odd-and-even license plate rule for motor vehicles can reduce the average $PM_{2.5}$ concentration in the city by 3% to 5.5%. The simultaneous implementation of the two measures can reduce the average $PM_{2.5}$ concentration in the city of Tianjin by 5% to 12%. The results shows that the implementation of responding measures in the emergency plan during heavy pollution can control the increase of $PM_{2.5}$ concentration to a certain extent, and plays a positive role in reducing pollution levels. In addition, the extinction effect of control measures at the peak of pollution is even more significant.



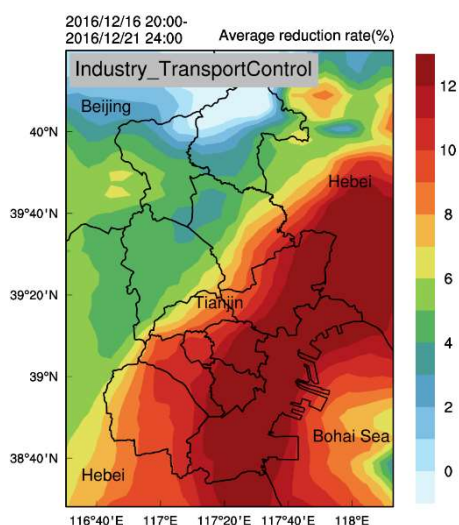


Figure 3. Spatial distributions of reduced ratio of PM_{2.5} concentrations in three control scenarios during the red alert

4. Conclusion

During the red alert period, air pollution process lasts 125 hours in Tianjin City, where the primary pollutant is PM_{2.5}. Pollution is relatively heavy in Beichen District, Hongqiao District, Hebei District and the northern part of Binhai New Area, but relatively light in Nankai District and the southern part of Binhai New Area.

The change of pollutant concentration during heavy pollution is simulated well by WRF/SMOKE/CMAQ model, which reasonably reflects the hourly concentration change and spatial distribution characteristics of PM_{2.5} and its precursors.

Simulation results show that, during this red alert, a 30% reduction in emissions from industrial enterprises in Tianjin can be implemented to reduce the average PM_{2.5} concentration by 3% to 10%. The odd-and-even license plate rule of motor vehicle can be implemented to reduce the city's average PM_{2.5} concentration by 3% to 5.5%. Two measures can be implemented simultaneously reduce the average PM_{2.5} concentration by 5% to 12%.

The maximum and average PM_{2.5} concentrations under the three control scenarios show that the effect of industrial production limitation on the maximum concentration of PM_{2.5} is more significant, whereas vehicle traffic restriction presents better performance on the control of the average PM_{2.5} concentration. Simultaneous implementation of industrial production limitation and vehicle traffic restriction shows similar effect with sole industrial production limitation measure, indicating that industrial emissions are still a major source of air pollution while vehicle traffic control is also necessary.

Acknowledgments

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