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Spatio-temporal variation of PM_{2.5} pollution in Xinjiang and its causes: The growing importance in air pollution situation in China

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Due to the differences in topographic features, water vapor distribution and emission structures between the north and south of Xinjiang Uygur Autonomous Region (hereinafter Xinjiang), the air pollution exhibits remarkable spatial heterogeneity in this region. In this study, Xinjiang is divided into four regions from north to south at the municipality scale based on the data from air quality monitoring sites recorded from 2013–2019, namely, the clean area in the north of northern Xinjiang (region I), the heavily polluted area of the Urumqi-Changji-Shihezi region (region III), the moderately polluted area in the north of southern Xinjiang (region II), and the severely polluted area in the south of southern Xinjiang (region IV). For highly polluted regions in northern and southern Xinjiang, regions III and IV are compared with those typical polluted regions in central and eastern China, and the spatio-temporal variation characteristics and the causes of PM_{2.5} pollution in each sub-region are discussed. The results show that the region III is a typical area with anthropogenic air pollution source, where the occurrence frequency of PM_{2.5} pollution with the intensity of moderate level or above (18%) is higher than the most heavily polluted area in central and eastern China (16%, regions from the south of North China to the west of Huang-Huai). The region IV is a typical area affected by dust weather, where the pollution frequency being about 52% is much higher than that in other typical polluted regions. In addition, under the combined effects of anthropogenic sources and dust aerosols, the pollution duration in region II is prolonged. Therefore, in contrast to the remarkable improvement of air quality in central and eastern China, the air pollution in typical regions of Xinjiang has become relatively more severe in recent years. Moreover, as Xinjiang is in the upstream of the central and eastern China in the mid-latitude westerlies, the heavy pollution due to sand and dust, anthropogenic sources and their mixing effects has a far-reaching impact on the downstream areas,

further highlighting the growing importance of pollution prevention and control in Xinjiang.

KEYWORDS

PM2.5, PM10, Xinjiang, zoning, spatio-temporal variations, comparative analysis

1 Introduction

The Xinjiang Uygur Autonomous Region (hereinafter referred to as Xinjiang) is located in the northwest border of China. It is the provincial-level administrative region with the largest land area and shoulders the dual missions of ensuring the national energy security and the economic and social development of the autonomous region. In recent years, the problem of regional air pollution caused by resource exploitation, urban construction and economic development has become increasingly noticeable (Jiang et al., 2020). Since the Action Plan on Air Pollution Prevention and Control was issued in 2013, the overall concentration level of air pollutants in central and eastern China shows a decreasing trend. In 2017, the NO₂ concentrations in the Beijing-Tianjin-Hebei region, Yangtze River Delta and Sichuan Basin respectively decreased by 74.1%, 45.1%, and 33.2% compared with that in 2012 (Zhang et al., 2012; Ma et al., 2016a; He et al., 2021). However, the contribution of air pollutant emissions in Xinjiang to the whole country has increased year by year¹ (Shen et al., 2016). Since 2016, due to the adjustment of energy structure in some cities of Xinjiang, the air quality has improved somewhat. However, as affected by urban expansion and the increase in motor vehicle ownership, these cities are still at poor levels in the annual ranking of air quality among national key cities (You 2018).

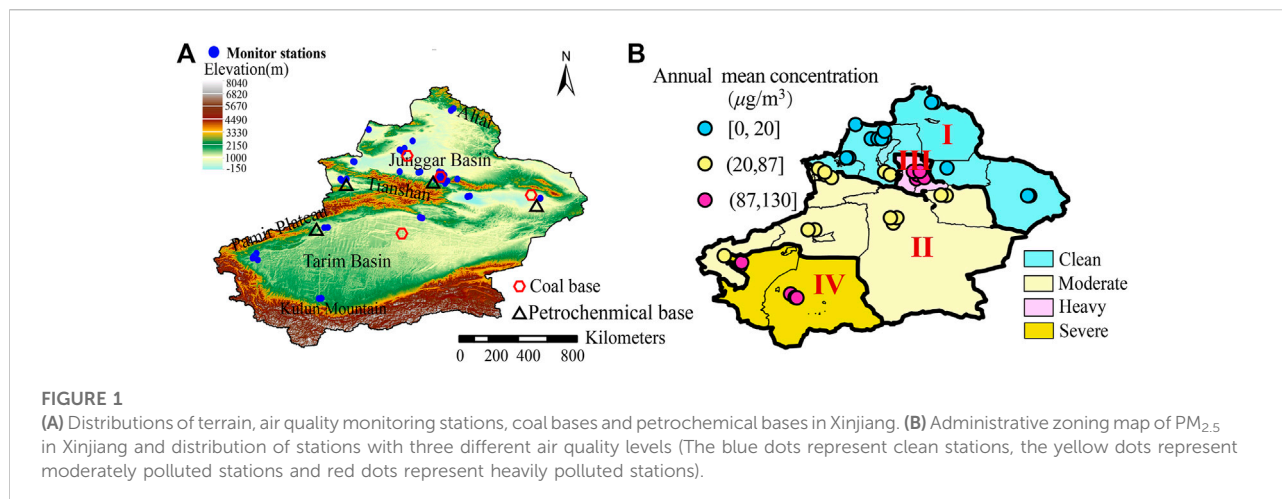
Recently, the research on the spatio-temporal distribution of air pollution and its influencing factors in Xinjiang has gradually attracted attention (Tang et al., 2016; Turap et al., 2019; Wang et al., 2020), which provides scientific evidence for analyzing the types and variation trends of regional air pollutants. However, the current researches on air quality change in Xinjiang mainly focus on local regions or key cities (Gu et al., 2020; Liu et al., 2021), and lack comparative analysis among key urban agglomerations from a national perspective, which are unable to highlight the differences in the spatial distribution pattern and air pollution level between the eastern and western regions of China. Moreover, the study periods in these studies are too short to reveal the variation characteristics of air pollution in recent years (Zhao et al., 2019).

In addition, the desert in Xinjiang is one of the main dust sources in Asia (Guo et al., 2017). On the one hand, the mixing effect of dust with aerosols from anthropogenic sources has a great impact on the pollution level of local particulates (Li 2009). On the other hand, because Xinjiang is located in the upstream of the central and eastern China in the mid-latitude westerlies, the high-concentration particulate matter in Xinjiang will also be transported by the air flow, which has a serious impact on the air quality in central and eastern China and downwind countries, as well as global biogeochemical cycles (Manktelow et al., 2010; Sun et al., 2010; Kim et al., 2012). In future, a shift of precipitation toward more frequent heavy events due to the global climate change contributes to weakened wet removal fluxes, which will increase the concentration of particulate matter (Xu and Lamarque 2018). The meteorological environment in winter in Asia will be conducive to more extreme particulate pollution events as a result of the changing boreal cryosphere (Zou et al., 2017). Therefore, as the air pollution in central and eastern China has been effectively controlled, the proportion of pollution transported from the western regions has become increasingly noticeable for these regions.

At the same time, the complex and diverse geography and climate lead to a larger spatial heterogeneity in the distribution of air pollution in Xinjiang than in other regions (Jiang et al., 2020). Many studies have shown that the southern Xinjiang basin centered on Minfeng and Hotan is the high-frequency center of dusty weather in China (Wang et al., 2003; Qiu et al., 2018), while the air pollution in northern Xinjiang is mainly resulted from the emissions by human activities because of high vegetation coverage and relatively high concentrations of cities, energy exploitation and deep processing industries (Jiang et al., 2020). Therefore, it is necessary to carry out the researches on air pollution in sub-regions of Xinjiang.

Since 2013, Xinjiang has begun to build air quality monitoring stations covering the whole province, providing data support for the assessment of regional air pollution level (Dong et al., 2020). Using the data from national air quality monitoring stations from 2013 to 2019, combined with the differences of geographical characteristics, this study discusses the spatio-temporal distribution characteristics of air pollution in different regions of Xinjiang. Based on the zoning results, the typical polluted regions in Xinjiang are compared with the key polluted regions in the central and eastern China, and the differences and variation trends of air pollution in the eastern and western China are analyzed. The research can

¹ National Bureau of Statistics (2021) <http://www.stats.gov.cn/>.



provide data support for decision-making and cross-regional management in nationwide air pollution prevention and control.

The remainder of this paper is organized as follows. Section 2 introduces the data and research methods. The zoning results and the characteristics of pollution in four sub-regions of Xinjiang with different temporal scales are shown in Section 3, where the causes of pollution are also analyzed. Finally, the conclusions and discussion are given in Section 4.

2 Data and methods

2.1 Research area and data

Xinjiang is located in the heartland of the Eurasian continent with complex terrain, where mountains are intermixed with basins. There are three west-east oriented mountains in Xinjiang, which are the Altai Mountains, Tianshan Mountains and Kunlun Mountains from north to south. Junggar Basin and Tarim Basin are sandwiched between the three mountains. The Qinghai Tibet Plateau is located to the south side of Kunlun Mountains. Xinjiang is divided into northern Xinjiang and southern Xinjiang by the Tianshan Mountains (Figure 1A). Affected by the factors of steep terrain, complex boundary layer processes and water vapor transport, the climate in the northern Xinjiang is much wetter than that in the southern Xinjiang (Yang and Liu 2018). In addition, in terms of the structure of emission sources, coal bases and petrochemical bases are mainly located in the northern Xinjiang (Figure 1A), while deserts are widely distributed in the central and east parts of southern Xinjiang.

This study adopts the hourly air quality data observed at the state-level stations from China National Environmental Monitoring Centre in 2013–2019, including six types of air

pollutants, namely $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , and CO. As shown in Figure 1A, there are a total of 41 stations in Xinjiang. The meteorological data used in this paper comprise the observation data of 10-m wind speed, visibility, weather phenomena, etc., which are derived from the representative meteorological stations in Xinjiang, with their temporal resolutions being 3 h from 2013 to 2019. Particularly, the observed air temperature data covers the period from 1951 to 2019. Besides, the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) data during 2013–2019 is also used, with the spatial resolution being 0.25×0.25 and the temporal resolution being 1 h.

2.2 Materials and Methods

2.2.1 Zoning of $PM_{2.5}$ in Xinjiang

According to the annual mean concentration of $PM_{2.5}$, the air quality observation stations in Xinjiang are ordered and preliminarily classified by using the natural break classification method (Jenks 1967). As a result, the stations with similar concentration values are divided into the same class. The method given by Yao et al. (2020) is further adopted to solve the problem of geographical discontinuity for stations in the same class. Finally, the administrative zoning map of $PM_{2.5}$ in Xinjiang is given after the adjustment of boundaries according to the administrative division.

2.2.2 Comparison between typical polluted areas

The relatively heavily polluted regions in Xinjiang are selected based on the above zoning result, and meanwhile, the typical polluted regions in central and eastern China are also selected based on the administrative zoning of $PM_{2.5}$ in China

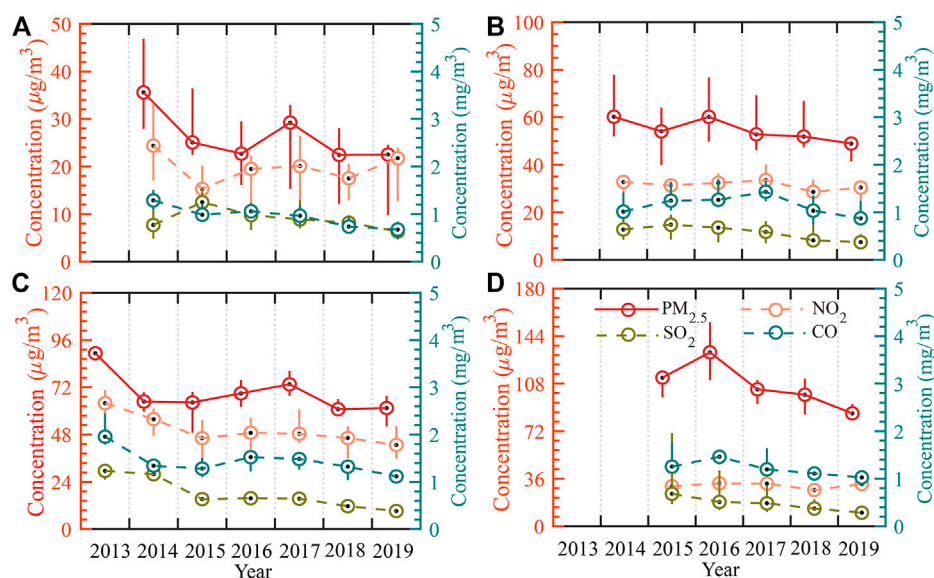


FIGURE 2

Box plots of annual average $PM_{2.5}$, NO_2 , SO_2 , CO concentrations in (A) region I, (B) region II, (C) region III and (D) region IV of Xinjiang from 2013 to 2019.

(Yao et al., 2020). On this basis, the $PM_{2.5}$ pollution level and variation trends in these regions are compared and analyzed.

2.2.3 Analysis method of spatio-temporal variations

The spatio-temporal variations of the hourly, monthly and annual mean concentrations of $PM_{2.5}$ in sub-regions of Xinjiang are analyzed. The daily mean value in this study refers to the arithmetic mean of hourly concentration values at 24 h in a natural day, and the monthly (annual) mean value is defined as the arithmetic mean of the daily mean concentration in a month (year). In addition, the Pearson correlation analysis with two-tail t -test is used to validate the significance of the data, and the least squares method is adopted to estimate the linear trend value of the data.

3 Results

3.1 Administrative zoning map of $PM_{2.5}$ in Xinjiang

Supplementary Figure S1 shows the annual mean $PM_{2.5}$ concentrations at 41 stations in Xinjiang in descending order. By taking the breakpoint value as the boundary, the stations are divided into three classes, which are 12 clean stations with the annual mean concentration less than $37 \mu\text{g}\cdot\text{m}^{-3}$, 12 moderately polluted stations with the concentration being $37\text{--}80 \mu\text{g}\cdot\text{m}^{-3}$, and 17 heavily polluted stations with the concentrations over

$80 \mu\text{g}\cdot\text{m}^{-3}$. As shown in Figure 1B, the heavily polluted stations are located in Urumqi urban agglomeration and southern Xinjiang. Meanwhile, there are isolated stations with geographical discontinuities around the Urumqi urban agglomeration. To obtain zoning results with geographical continuity along the boundaries, the zoning correction algorithm based on geographical distance proposed by Yao et al. (2020) is adopted. As the basic unit for the construction of air quality monitoring stations and the implementation of air pollution control strategies, the prefecture-level city is taken as a zoning unit, and the administrative zoning map of $PM_{2.5}$ pollution in Xinjiang is obtained (Figure 1B), Xinjiang is divided into four sub-regions, namely the clean region located in the north of northern Xinjiang (region I), moderately polluted region in the north of southern Xinjiang (region II), heavily polluted region in Urumqi urban agglomeration including Urumqi, Changji and Shihezi (region III, hereinafter Urumqi-Changji-Shihezi region), and severely polluted region in the south of southern Xinjiang (region IV). It should be noted that although the annual mean concentration of pollutants in region III approximates to that in region IV, they are divided into different classes due to the differences in geographical locations.

3.2 Annual variation and comparative analysis

As shown in Figure 2, from 2013 to 2019, the $PM_{2.5}$ concentration in Xinjiang generally shows a decreasing trend;

with the annual means in regions I–IV in 2019 respectively decrease by 36.75%, 18.74%, 35.4% and 23.98% compared with those in 2013, and the SO₂ concentration is steadily falling, with the regional annual means reduce to about 10 μg m⁻³ by 2019. Besides, the CO concentration showed a downward trend in the regions I and III, but maintained stable levels in the remaining two regions. For NO₂, the concentration remained stable and even increased in some regions. Specifically, the annual mean concentrations of PM_{2.5} in regions I, II and IV display a linear decreasing trend at a decreasing rate greater than 1.91 μg·m⁻³·yr⁻¹. While for region III, the annual variation of PM_{2.5} concentration can be divided into three stages (Figure 2C). First is the remarkable decreasing stage in 2013–2014. Before 2012, dust from coal-burning was the main source of PM_{2.5} during the heating season in region III (Li et al., 2009). After 2012, the local government adjusted the structure of heating energy and carried out the coal-to-gas project, which has reduced the coal-burning pollution (Abudumutailifu et al., 2018). At the same time, the observation data has also witnessed a significant decline in pollutants such as CO and NO₂. Second is the increasing stage in 2014–2017. The increasing trend at this stage is consistent with the results of many studies (You 2018; Dong et al., 2020). As the coal-to-gas project has not achieved full coverage, the decline in SO₂ concentration is limited. At the same time, affected by urban expansion and the increasing population and industrial emissions, NO₂ emissions increase, and heavily polluted weather occurs frequently in winter (Zou et al., 2017). Third is the slowly decreasing stage in 2017–2019. Under the control measures such as the readjustment of regional energy structure, the implementation of denitration devices in power stations, and the upgrading of vehicle fuels (Ma et al., 2016b; Su et al., 2021), the concentrations of various air pollutants show a decreasing trend.

In June of 2018, the State Council issued a notice about the 3-years plan on defending the blue sky², known as the blue sky action plan, which took the Beijing-Tianjin-Hebei and surrounding areas, the Fenhe and Weihe Plain, and the Yangtze River Delta as key areas for joint prevention and control of air pollution. Based on the air quality monitoring data from 2013 to 2018, Yao et al. (2020) divided China into 17 regions by taking prefecture-level city as unit according to the regional collaborative change. Moreover, the key areas involved in the blue sky action plan were divided into four regions, in which the whole of Xinjiang was considered as one region. The annual mean concentrations of PM_{2.5} in the above regions from high to low are 85.47 μg·m⁻³ in the south of North China to the west of Huang-Huai Region, 69.22 μg·m⁻³ in the Fenhe and Weihe Plain, 69.17 μg·m⁻³ in the north of North China, 65.97 μg·m⁻³ in Xinjiang, and

58 μg·m⁻³ in the Yangtze River Delta. Specially, the air pollution level in regions from the south of North China to the west of Huang-Huai Region is the highest in China. However, due to the unique geography and climate in Xinjiang, Wang et al. (2015) pointed out that Xinjiang should be divided into two regions of the northern and southern parts with respect to the spatial distribution characteristics of PM_{2.5} concentration. In this study, regions III and IV refer to the heavily polluted regions in northern and southern Xinjiang respectively. In order to investigate the difference of PM_{2.5} pollution level in representative regions between the eastern and western China, the variations of PM_{2.5} pollution frequency in the above four typical regions in central and eastern China and in regions III and IV in Xinjiang are compared, as shown in Figure 3.

The annual variation shows that compared with the consistent improvement trend in central and eastern China, the reduction of pollution level in typical regions of Xinjiang is limited. (Figures 3A,B). Specifically, the occurrence frequency of PM_{2.5} concentration above the moderately polluted level in the region III exhibits a steady increasing trend since 2016, and even exceeds that in the most heavily polluted regions in central and eastern China, namely, the south of North China to the west of Huang-Huai Region. Meanwhile, the pollution in the region IV remains high level. The frequency of PM_{2.5} concentration above the moderately polluted level decreases by 7.9% from 2013 to 2019, which is much lower than 20.9% in the four regions of central and eastern China. The 7-years average displays that the selected regions of Xinjiang present high pollution frequency (Figure 3C). Specially, the region III shows the characteristics of high excellent rate along with high pollution rate. The excellent rate in this region reaches 46%, which is the highest among the six selected regions. Meanwhile, the frequency of pollution above the moderately polluted level is 18%, higher than that in the four regions of central and eastern China (<16%). In the region IV, the frequency is characterized by low excellent rate and high pollution rate. The excellent rate is only 16%, while the frequency of pollution above the lightly polluted level reaches 52%, which is much higher than that in other representative regions.

3.3 Variation characteristics of PM_{2.5} concentration at different temporal scales in sub-regions of Xinjiang

For a detailed variance analysis of the long-term trend of PM_{2.5}, the daily PM_{2.5} data were binned into a series of datasets, where the time intervals with different lengths (“timescales”) ranging from 1 day to 3 years (Rohrer and Berresheim, 2006). Figure 4 displays the variation of PM_{2.5} concentration variances at different timescales in each region of Xinjiang. It can be seen that the variation of PM_{2.5} concentration in each region is

² The State Council, (2018) http://www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm.

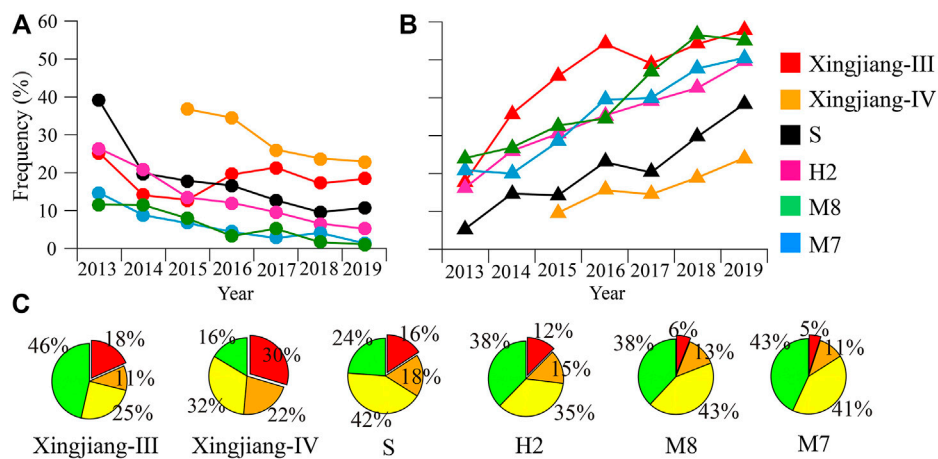


FIGURE 3

Occurrence frequencies of air quality (A) above the moderately polluted level and (B) the excellent rates in the Urumqi-Changji-Shihezi region (Xingjiang-III, red), southern Xingjiang (Xinjiang-IV, orange), the south of North China to the west of Huang-Huai Region (S, black), the Fenhe and Weihe Plain (H2, pink), the north of North China (M8, green) and the Yangtze River Delta (M7, blue) from 2013 to 2019. (C) Average occurrence frequencies of the air quality at the good level (green, daily $PM_{2.5}$ concentration between 0 and $35 \mu g \cdot m^{-3}$), moderate level (yellow, $35-75 \mu g \cdot m^{-3}$), lightly polluted level (orange, $75-115 \mu g \cdot m^{-3}$) and above moderately polluted level (red, greater than $115 \mu g \cdot m^{-3}$) in each region from 2013 to 2019.

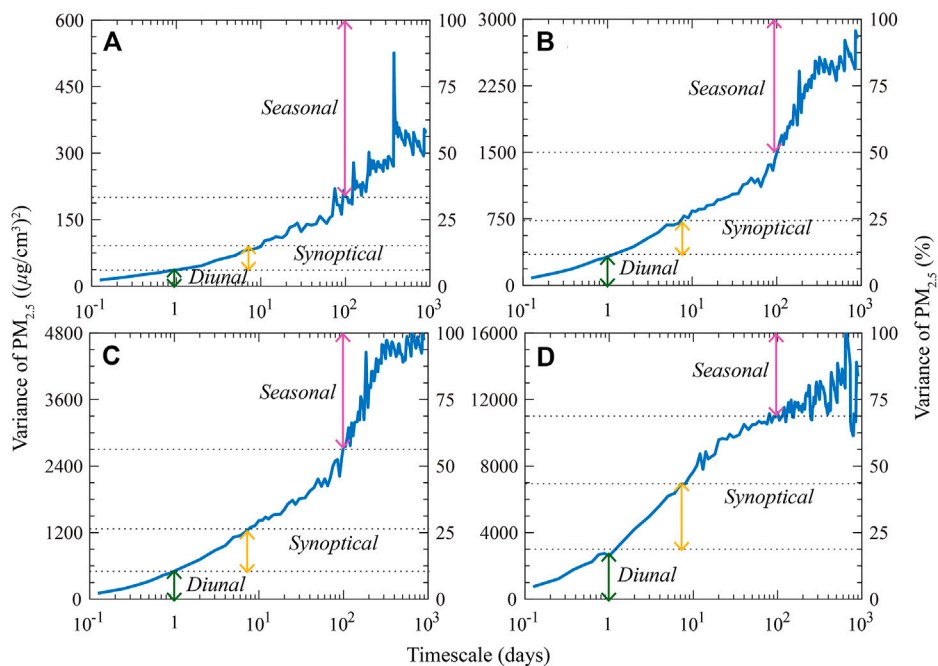


FIGURE 4

Variations ($\mu g \cdot m^{-3}$)² and proportions (%) of $PM_{2.5}$ concentration variance at different timescales in (A) region I, (B) region II, (C) region III and (D) region IV of Xinjiang from 2013 to 2019.

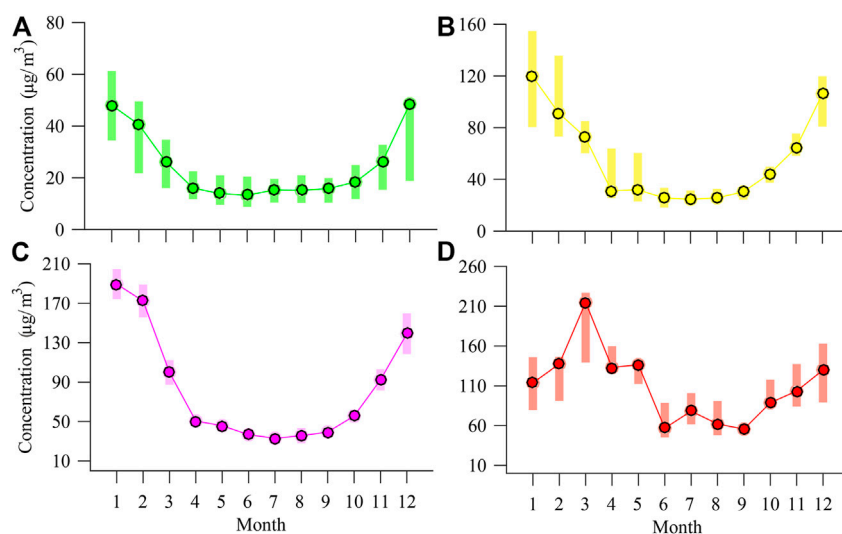


FIGURE 5

Box plots of monthly average $PM_{2.5}$ concentrations in (A) region I, (B) region II, (C) region III and (D) region IV of Xinjiang from 2013 to 2019.

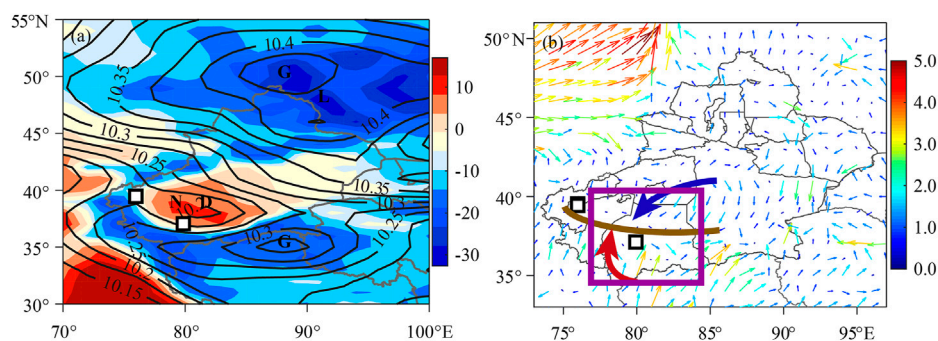


FIGURE 6

(A) Average sea level pressure (black contour, 10^3 Pa) and 2-m temperature (shaded, $^{\circ}C$), and (B) average 10-m wind field (colored vector, $m\cdot s^{-1}$) in March from 2013 to 2019. **G** is the center of high pressure, **D** is the center of low pressure, **L** is the center of cold air and **N** is the center of warm air. Brown thick line, blue and red vector indicate the location of surface convergence line, northerly wind and southerly wind, respectively. White squares indicate the monitoring stations in region IV.

dominated by seasonal variation and synoptic-scale variation (between 1 and 7 days), with the average variance contributions over Xinjiang being about 50% and 15% respectively. With the increase of regional $PM_{2.5}$ concentration, the proportion of diurnal variation and synoptic-scale variation is gradually increasing. Specifically, the seasonal variation in region I plays a dominant role, with its proportion being greater than 65%. In region II and III, the proportion of seasonal variation is about 40%, and the proportion of synoptic-scale variation increases to about 15%. In region IV, the proportion of synoptic-scale variation is about 25% and is close to that of the seasonal variation (about 30%), and the proportion of diurnal variation also increases to about 20%.

The seasonal variation of monthly average $PM_{2.5}$ concentration in each region of Xinjiang is shown in Figure 5. Specifically, the variation characteristics in region I and region III are similar, exhibiting high concentration in winter (October to March of the next year) and low concentration in summer (April to September). The pollution in region III is prominent in autumn and winter, with the average concentration increasing from $28.04 \mu g\cdot m^{-3}$ in summer to $101.96 \mu g\cdot m^{-3}$ in winter. In region IV, the peak of $PM_{2.5}$ concentration appears in March, which may be caused by the dust weather process in spring. Affected by factors of alternative freezing and thawing of soil, scarce precipitation and frequent cold air activities, the number of days of dust

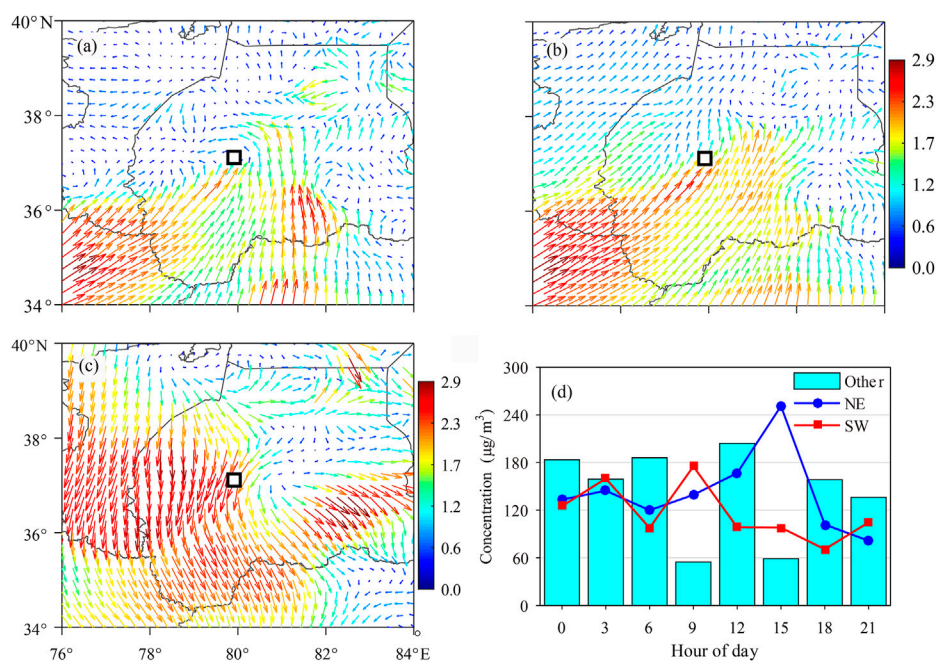


FIGURE 7

Average 10-m wind fields ($\text{m}\cdot\text{s}^{-1}$) at (A) 0200 BJT (Beijing Time), (B) 0800 BJT and (C) 1400 BJT in Hotan area in January of 2013–2019. (D) Diurnal variations of average $\text{PM}_{2.5}$ concentration in southwesterly wind direction (red line), northeasterly wind direction (blue line) and other wind directions (cyan histogram).

weather in March is the highest in the whole year (Wang et al., 2019). In addition, the secondary peak of $\text{PM}_{2.5}$ concentration is found in July, which may be related to the development of thermal low and the stable maintenance of high pressure gradient in the southern Xinjiang basin in summer. Cyclonic circulation and southwesterly transport the dust aerosol from the hinterland of the upstream desert to region IV (Figure 6). Qiu et al. (2018) pointed out that the increase in southwesterly wind speed is well related to the summer dust pollution in the south of southern Xinjiang. In region II, although overall characteristics are similar to the region III, the boxplot represents a high concentration bias in May and April, and meteorological observations show that this is related to several dust processes in spring, indicating that the anthropogenic sources and sand-dust both have a certain impact on the $\text{PM}_{2.5}$ concentration in this region.

As shown in Supplementary Figure S2, the diurnal variation of $\text{PM}_{2.5}$ concentration in Xinjiang presents a bimodal structure. The diurnal variation amplitude of $\text{PM}_{2.5}$ concentration tends to weaken from 2013 to 2019, which may be related to the overall decreasing trend of the annual mean pollutant concentration in all four regions. From the perspective of regional differences, the variation amplitude in region I is the smallest, which is consistent with the result of variance analysis, while region II (I) and region IV (III) show similar variation characteristics. Therefore, the

following analysis focuses on the diurnal variation characteristics in region III and region IV.

The peak (valley) values of $\text{PM}_{2.5}$ concentration in region III appear around 1600 BJT (0900 BJT, Beijing Time) and 0100 BJT (2100 BJT), which may be related to the distribution of industrial emission sources, human activities and diurnal variation of wind direction (Li 2013). The meteorological data shows that in region III, the northerly wind is dominant during the daytime, and the wind speed reaches the maximum around 1500 BJT. In this case, the prevailing wind direction is conducive to the southward transportation of pollutants from the northern industrial area. In the evening, the pollutant transport is decreased due to the change of wind direction to southerly and the reduction of industrial emissions, and thus the $\text{PM}_{2.5}$ concentration falls to a valley value. Due to the decrease in the boundary layer thickness and the increase in pollutants from coal burning in the winter evening, the $\text{PM}_{2.5}$ concentration increases to a maximum in the early morning.

The maximum (minimum) values in region IV appear at 1400 BJT (0900 BJT) and around 0200 BJT (2000 BJT), which may be related to the distribution of dust sources and the diurnal variation of local wind field. According to the statistics of the frequency of surface wind direction from 2013 to 2019 in Hotan, a representative station in southern Xinjiang, the northeasterly wind prevails in the daytime and the southwesterly wind is dominant in the nighttime. Based on

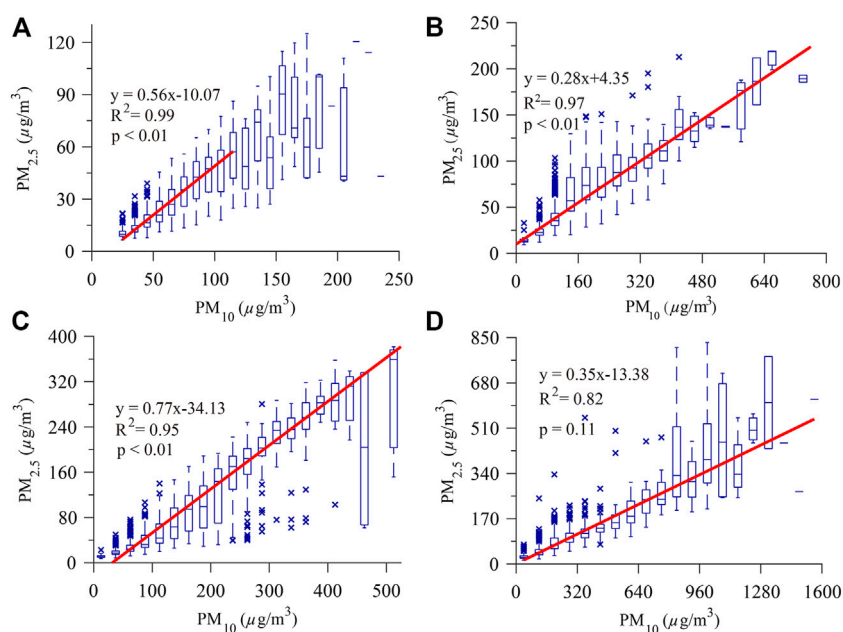


FIGURE 8

Box plots of daily average $PM_{2.5}$ concentration based on PM_{10} concentration in (A) region I, (B) region II, (C) region III and (D) region IV of Xinjiang from 2013 to 2019. Red line shows the variation trend of median value.

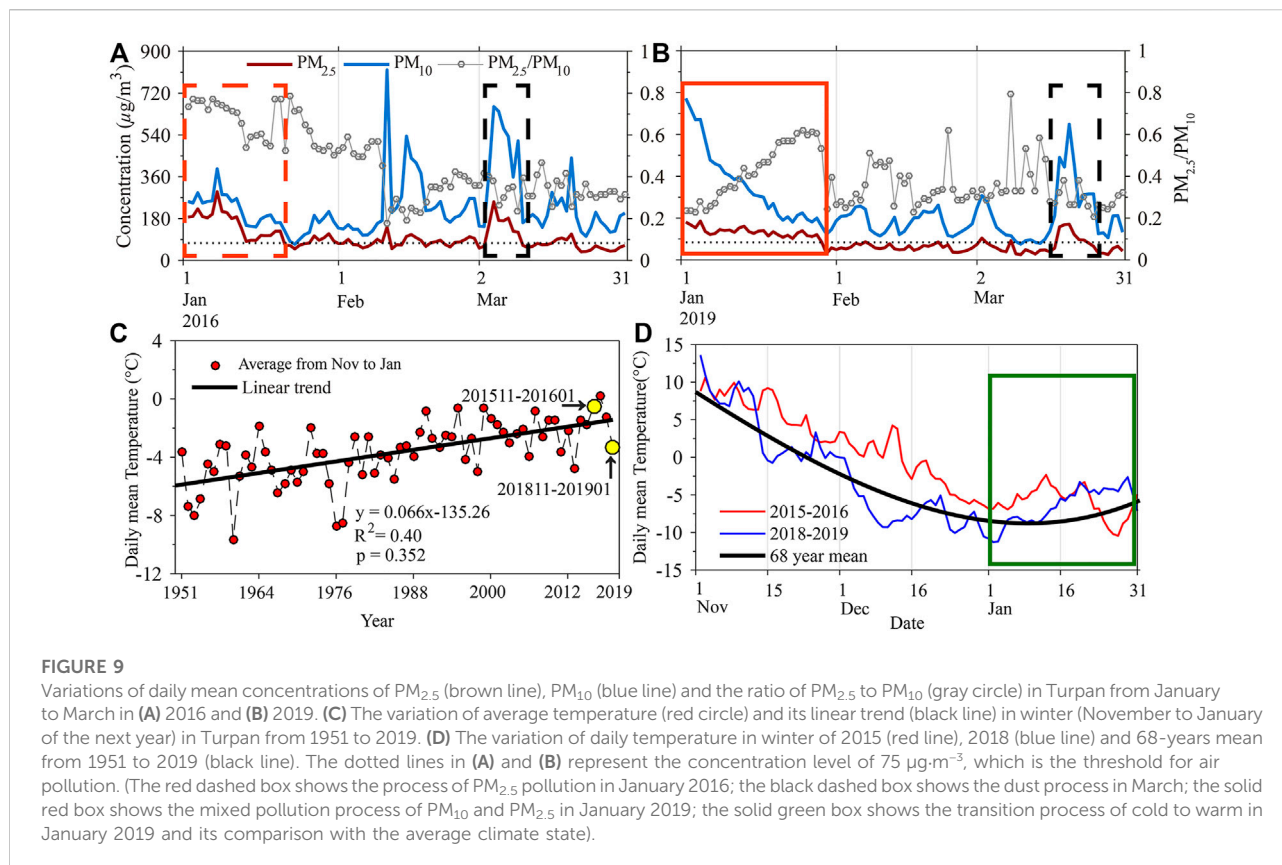
the meteorological data with a 3-h interval, the $PM_{2.5}$ concentrations in different wind directions are calculated, as shown in Figure 7D. After nightfall, the $PM_{2.5}$ concentration in southwesterly wind direction increases, reaching the maximum at 0600–0900 BJT, while the concentrations in northeasterly wind direction peak at 1200–1500 BJT in the daytime. In order to eliminate the influences of inter-annual, seasonal and synoptic-scale variations, January and July are selected as the representative months of winter half year and summer half year respectively, and the average surface wind field at typical time in Hotan is calculated (Figures 7A–C; the calculation process of wind field in summer half year is similar to that in winter half year, and the figures are omitted). In combination with the terrain and surface meteorological field, the diurnal variation of dust transport is comprehensively analyzed. Hotan is adjacent to the Kunlun Mountains in the south, and to the Taklamakan desert in the northeast (Figure 1A). During the daytime, the thermal low in the basin develops, extends southward and reaches to the strongest in the afternoon. Affected by the valley breeze which manifests as northeasterly that blows from the basin to the mountains, the northeasterly wind speed reaches maximum in the afternoon, corresponding to the peak of $PM_{2.5}$ concentration related to the daytime dust transport (Figures 6,7C). After nightfall, the thermal low shrinks northward, and the valley breeze changes to

mountain breeze featured by southwesterly wind blowing from the mountains to the basin. The transition of valley breeze to mountain breeze and the movement of the convergence zone from south to north result in the peak of $PM_{2.5}$ concentration before dawn (Figure 7A). However, as the upstream of the southwesterly wind is the relatively clean area (the Kunlun Mountains), when southwesterly wind prevails and the convergence zone moves out, the concentration of pollutants in this region decreases after midnight (Figure 7B).

3.4 Causes of pollution

3.4.1 Characteristics of $PM_{2.5}$ and PM_{10}

Statistics on the proportion of $PM_{2.5}$ in regional particulate pollution is an important method to analyze the causes of regional pollution. Based on the daily mean concentration of $PM_{2.5}$ and PM_{10} , box plots of $PM_{2.5}$ are drawn within a certain range of PM_{10} concentrations, which are 10, 40, 25, and $80 \mu\text{g}\cdot\text{m}^{-3}$ in regions I–IV respectively (Figure 8). It can be seen that there is a significant positive linear correlation relationship between $PM_{2.5}$ and PM_{10} in terms of their concentrations in each region. However, this linear relationship is non-significant in high concentration sections of each region, which may be related to the small sample sizes within these sections. Especially for high concentration section in



region I, the relationship fluctuates remarkably with the increase in concentration.

The linear fitting coefficient of the median value can be regarded as the average condition of $PM_{2.5}$ and PM_{10} in a certain region. It is found that $PM_{2.5}$ contributes more to particulate pollution in northern Xinjiang (regions I and III) with the slope being greater than 0.56. Especially in region III, the slope is greater than 0.75, which is close to the average value in winter of China and the annual average value in Beijing from 2015 to 2019 (Dong et al., 2020). Moreover, there are outliers with high $PM_{2.5}$ concentration and low PM_{10} concentration in region III, and the proportion of $PM_{2.5}/PM_{10}$ greater than 0.75 gradually increases with the $PM_{2.5}$ concentration. Southern Xinjiang (regions II and IV) shows more obvious characteristics of dust impact, with the linear fitting slope of median values being less than or equal to 0.35. Moreover, the particle concentration in region IV is much higher than that in region II. The upstream of region IV is the Taklimakan desert, where the combined effect of average wind and terrain transports dust aerosol southwestward to region IV and forms a convergence (Figure 6). Using the Goddard Chemistry Aerosol Radiation and Transport model with satellite data in 2000–2007, Guo et al. (2017) revealed that the aerosol divergence in southern Xinjiang is mainly affected by aerosol advection, while there is a strong convergence center

of dust aerosols in the west of Tarim Basin and the north of Tibet Plateau, whose location basically coincides with region IV in this study. The monitoring stations in region II are mainly located in the upwind direction of the sand source and the strong divergence area, so the influence of sand and dust is lower than that in region IV.

3.4.2 Contributions of anthropogenic source and dust sources

Xinjiang has a vast territory. Affected by geography, climate, energy exploitation, urban development, and wide distribution of sand sources, the contributions of anthropogenic sources and sand-dust sources to $PM_{2.5}$ pollution in different regions have remarkable differences.

In region I, the station-averaged occurrence frequency of days with the good level (daily $PM_{2.5}$ concentration less than $75 \mu\text{g}\cdot\text{m}^{-3}$) exceeds 96%. The pollution mainly appears in winter with the major pollutant of $PM_{2.5}$, while the proportion of days with the ratio of $PM_{2.5}$ to PM_{10} less than 0.4 is only 8.7%. As the industrial emission sources are mainly located in the south of region I (Figure 1A), attention should be paid to the pollution caused by local emissions and pollutants transported from the east and south of northern Xinjiang in winter.

In region III, which is also the core area of urban and industrial development in Xinjiang, where there are great

differences in the pollution levels between winter and summer. The proportion of days with the ratio of $PM_{2.5}$ to PM_{10} less than 0.4 is 4.54%, that is, the major pollutant in this region is $PM_{2.5}$, and the pollution source has been changed from coal-burning to complex sources (Ma et al., 2016a). Therefore, it is necessary to strengthen the control of fine particulate pollutant emissions in winter. In the daily refined prevention and control stage, we should consider the impact of northern industrial emissions on downstream area under the influence of canyon topography and diurnal variation of wind.

In region II, there are coal and petrochemical bases in the north and middle of the region, and deserts in its east and south (Figure 1A). Affected by both anthropogenic sources and sand-dust sources, the pollution level is high in winter and spring, and the proportion of days with the ratio of $PM_{2.5}$ to PM_{10} less than 0.4 is 34.28%. Figures 9A,B show the daily variations of air pollution in Turpan from January to March in 2016 and 2019, respectively. The variation of particulate pollution in 2016 shows remarkable stage characteristics (Figure 9A). $PM_{2.5}$ is the major pollutant in January with the ratio of $PM_{2.5}$ to PM_{10} being greater than 0.6. Dust concentration increases after the middle of February and the ratio of $PM_{2.5}$ to PM_{10} drops below 0.4. In March, both the duration and intensity of $PM_{2.5}$ pollution related to dust increase (marked by the black dotted rectangle). Compared with January 2016 (red dashed box in Figure 9A), although the overall pollution level was lower in January 2019 (red solid box in Figure 9B), the duration of pollution was significantly increased (29 days). Observations clearly reveal that, a dust weather around the turn of 2018–2019 led to a sharper rise in the concentration of PM_{10} . The pollution level of PM_{10} decreased after the dust weather, but $PM_{2.5}$ pollution continued to the end of January. The ratio of $PM_{2.5}$ to PM_{10} also clearly reveals the transition of this pollution process (Figure 9B). This indicates that the mixing effect of dust weather and $PM_{2.5}$ pollution in winter may be one of the important reasons for the increase of $PM_{2.5}$ pollution duration in region II. Zhou et al. (2021) showed that the dust pollution in the hinterland of the desert area in Xinjiang and its surrounding areas is not rare in winter, where Turpan Basin and the Kumta desert in its southeast are one of the main source areas (Peng 2020). Cold air and the accompanying gale are the direct inducements of sand and dust. It is considered that the diurnal variation of air temperature can reflect the cold air activities on the synoptic-scale, and the temperature anomaly in a long period can reflect short-term climate anomalies. Thus, the winter average temperature of Turpan from 1951 to 2019 is analyzed, where the winter of a certain year refers to the period from November to the next January. It can be seen from Figure 9C that the winter temperature in this area shows a linear upward trend with the increase rate being 6.6°C per 100 a specially, the winter of 2015 is much warmer, while the winter of 2018 is colder. The daily temperature variations in the winter of 2015 and 2018 are further compared with the 68-years mean temperature in winter from 1951 to 2019. Focusing on the temperature variation in January (marked by green solid rectangle) shown in Figure 9D, it is found that there is an extreme high temperature value in the early and middle

10 days of January in 2016, which is 3.62°C higher than the same period in history, corresponding to the continuous $PM_{2.5}$ pollution in the same period. In 2019, the temperature exhibits an obvious rising trend after a cold air process at the beginning of January, corresponding to the pollution process dominated by PM_{10} and $PM_{2.5}$ alternately in the same period. Supplementary Figure S3 shows the annual variations of winter mean temperature and the duration of the longest pollution process in region II. It can be seen that the winter of 2018 is relatively cold, and the longest pollution duration interrupts the downward trend since 2016, with an average extension of 11.5 days compared with 2017. Besides, in January 2019, the mixed pollution of PM_{10} and $PM_{2.5}$ appear in more than 90% of the stations (10/11) in region II, and are accompanied by a temperature conversion from cold to warm. This indicates that under the background of climate change, the temperature variation in winter of warm years is relatively gentle, and the stable weather leads to continuous $PM_{2.5}$ pollution. However, in cold years, the temperature variation is intense, the mixing efficiency of sand-dust and anthropogenic pollutants increases, and the duration of pollution processes is prolonged under the alternative effects of dust and $PM_{2.5}$ during the cold-warm transition period.

In region IV, where the regional annual mean concentration reaches as high as $105.74\ \mu\text{g}\cdot\text{m}^{-3}$, dust pollution is dominant and the proportion of days with the ratio of $PM_{2.5}$ to PM_{10} less than 0.4 is 57.84%. Dust weather may occur in all four seasons in this region, especially in spring. On the one hand, the wide-range dust weather under the influence of cold air activities in spring has an important impact on the transportation in northern Xinjiang and central and eastern China in the downstream (Wang et al., 2003; Li et al., 2009). On the other hand, due to the influence of large terrain and surface thermal properties, the $PM_{2.5}$ concentration exhibits an obvious diurnal variation in this region. It is necessary to notice the impacts of advection and the location variation of convergence area on regional pollution.

In a word, considering different emission structures in the north and the south of Xinjiang, it is necessary to further control the growth of pollution in autumn and winter in the core polluted area generated by anthropogenic sources. In the transition area with pollution caused by anthropogenic sources and dust sources, it is also needed to pay attention to the impact of dust weather processes besides reducing relevant pollution emissions, and carry out the early warning and prevention in advance, thus reducing the impact of anthropogenic sources mixing with dust aerosol on the local pollution and the long-range transport to the downstream area.

4 Conclusion and discussion

Based on the hourly observation data at air quality monitoring stations from 2013 to 2019, Xinjiang is divided into four regions under the comprehensive consideration of $PM_{2.5}$ concentration, geography, climate and administrative

divisions by taking prefecture-level city as a unit. The typical pollution regions in Xinjiang are selected and compared with the typical regions in the central and eastern of China. Combined with the analysis of variance, the seasonal and diurnal variation characteristics of $PM_{2.5}$ concentration in the four regions are discussed. Finally, the causes of pollution in each region are analyzed, and corresponding prevention and control suggestions are also given. The main conclusions are as follows.

The $PM_{2.5}$ pollution regions in Xinjiang from north to south are clean area in the north of northern Xinjiang (region I), heavily polluted area of the Urumqi-Changji-Shihezi region (region III), moderately polluted region in the north of southern Xinjiang (region II), and severely polluted region in the south of southern Xinjiang (region IV). The regional-averaged $PM_{2.5}$ concentration increases from region I to region IV. Except region III, the concentrations of $PM_{2.5}$ in other regions show a decreasing trend year by year.

As highly polluted regions in northern and southern Xinjiang, the pollution situation in regions IV and III deserves more attention. Compared with the typical polluted regions in the central and eastern China, the occurrence frequency of $PM_{2.5}$ pollution above the moderately polluted level in autumn and winter in region III increases since 2015 and is higher than those in the regions of eastern China. As a region with the lowest excellent rate and highest pollution rate, region IV becomes the region with most severe $PM_{2.5}$ pollution among the typical regions in eastern and western China.

Combined with the variance analysis of $PM_{2.5}$ concentration variations at different timescales and the ratio of $PM_{2.5}$ to PM_{10} , the spatio-temporal variation characteristics of $PM_{2.5}$ pollution and the causes in each region of Xinjiang are explored. Region III is a typical area affected by anthropogenic sources, where the seasonal variation plays a dominant role, and the $PM_{2.5}$ concentration shows the characteristics of higher in autumn and winter and lower in spring and summer. Seasonal heating, industrial distribution and urban domestic emissions play a vital role in $PM_{2.5}$ pollution. Region IV is a typical area affected by sand and dust. The weather process, seasonal and diurnal variations all play an important part in regional pollution processes. The large-scale topography, the distribution of sand sources and the surface thermal properties exert great impacts on the advection of particulate matter. Regions I and II exhibit the transitional characteristics. Specifically, region II is affected by the mixing effect of anthropogenic sources and dust sources, resulting the continuous pollution process dominated by PM_{10} and $PM_{2.5}$ alternately in winter.

Although the overall pollution level in Xinjiang is lower than that in the traditional polluted regions in central and eastern China, the pollution level of $PM_{2.5}$ in region IV and in autumn and winter of region III are higher than that in the most severely polluted regions in eastern China. In addition, affected

by the mixing effect of anthropogenic sources and dust sources, the pollution duration is prolonged remarkably in the north of southern Xinjiang in some periods. In the mid-latitude westerlies, Xinjiang is in the upstream of the central and eastern China, and the change of pollution situation in this region will have a far-reaching impact on the prevention and control of $PM_{2.5}$ in central and eastern China and even further downstream areas. Therefore, the pollution prevention and control work should be attached greater importance, and differentiated measures in the prevention and control of $PM_{2.5}$ pollution should be taken in different regions and periods.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

XY: Data curation and visualization; methodology; writing original draft. BG: Conceptualization; design of methodology; ensuring that the descriptions are accurate and agreed by all authors. AL: Evolution of overarching research goals; investigation. GC: Data collation and analysis. FF: Data analysis and visualization. DX: Visualization; writing reviewing and editing. YW: Visualization; Writing editing. XT: Data analysis and validation. LK: Writing reviewing and editing. ZW: Supervision.

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Conflict of interest

Author FF was employed by the company 3Clear Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.1051610/full#supplementary-material>

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