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Research Article

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Monitoring of Compound Air Pollution by Remote Sensing in Lanzhou City in the Past 10 Years

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Abstract: Based on satellite remote sensing data acquired by the Ozone Monitoring Instrument (OMI), this study used pixel space analysis, a coefficient of variation, stability analysis, and an atmospheric transmission model to determine the concentration of tropospheric ozone (O_3), NO_2, HCHO, and SO_2 columns in Lanzhou from 2010 to 2019. A series of analyses were carried out on the temporal and spatial distribution of concentration, influencing factors and atmospheric transmission path. The results show that the air pollutants in this area present multi-dimensional characteristics and have a complex spatial distribution. In terms of inter-annual changes, in addition to the increase in the concentration of the HCHO column, the ozone, NO_2, and SO_2 column concentrations have all decreased over time. In terms of monthly average changes, these four pollutants reached their maximum values in April, December, June, and January, respectively. These four types of pollution had a strong spatial correlation, among which HCHO and SO_2 had a significant positive correlation, with a correlation coefficient of 0.76. Many factors affect the Atmospheric Compound Pollution in Lanzhou. Among them, pollutants are closely related to urbanization and to the activities of coal-burning industries. Moreover, temperature, precipitation, and sunshine also have certain effects on air quality. The proliferation of pollutants in Gansu Province was one of the sources of pollutants in Lanzhou, while long-distance transportation in the atmosphere from outside the province (Qinghai, Sichuan, and Shaanxi) also exacerbated the pollution in Lanzhou.

Keywords: OMI; Atmospheric Compound Pollution; coefficient of variation; backward trajectory; Lanzhou area

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Introduction

The rapid development of China's economy has come at the expense of environmental problems involving a complex pollution situation dominated by ecological damage and air pollution (Xue et al., 2016; Ji et al., 2012). At present, common air pollutants include nitrogen oxides (NH_3, NO, NO_2), carbon oxides (VOC_S, CO, CO_2), sulfides (SO_2, H_2S), particulate matter (PM10, PM2.5), photochemical oxides (ozone (O_3), H_2O_2), and other closely related compounds. When the content of these pollutants in the atmosphere accumulates to a certain level, local air quality will be greatly reduced at time by high concentrations of these pollutants. The sources can be divided into natural and man-made sources. Most areas of eastern China have experienced major environmental problems caused by human activities (Chen et al., 2018; Qiao et al., 2012; Guo et al., 2011; Sudo and Akimoto, 2007). When the concentrations of these pollutants in the atmosphere exceed the capacity of the environment to purify the air, this will cause certain types of damage to buildings and scenic spots, resulting in losses to the national economy, as well as hindering the photosynthesis of vegetation and negatively affecting the organizational structure of vegetation. These changes affect the normal operation of the entire ecosystem (Wang et al., 2018; Wittig et al., 2007; Rap et al., 2015; Chen et al., 2009; Shang et al., 2017; Doughty et al., 2010; Badarinath et al., 2007; Tie et al., 2005; Liu et al., 2019; Roderick et al., 2001). In addition, various pollutants can be transformed in the atmosphere and these transformed products influence each other to form secondary pollutants; these pollutants often induce various diseases in the human body, thereby endangering the survival and development of humans (Michal, 2008; David et al., 1996; Brumberg et al., 2021; Kan et al., 2012; Yuh-Chin, 2006; Araujo et al., 2009).

One type of photochemical pollution was found to occur in Lanzhou in the 1970s; the topic attracted a significant amount of attention from the government and scholars from various disciplines, so that research on air pollution in Lanzhou was encouraged (Tang et al., 1989; Dong et al., 2021; Lu et al., 2020; Cheng et al., 2019). Concentrations of near-surface ozone in Lanzhou have been on the rise in recent years. During a typical year, ozone levels are significantly higher in spring than in other seasons (Jia et al., 2020). NO_2 concentrations are significantly positively correlated with the number of hospital visits by humans (Wang et al., 2012). The SO_2 concentration in the Lanzhou area can reach the medium level of SO_2 pollution in winter, which is closely related to seasonal meteorological conditions (Peter et al., 2008). The Lanzhou area is one of the heavy industrial bases and transportation hubs of western China; when coupled with the impact of special topography, these conditions make this area one of the most severely polluted areas in the world (Guo Y. T. et al., 2011). After years of strenuous effort, major breakthroughs have been made in controlling air pollution in Lanzhou, achieving a transformation from a “famous polluted city” to an ecologically civilized city that has successfully employed a model of air pollution control known as the Lanzhou model. This paper systematically analyzes the temporal and spatial distribution of four pollutants and factors that influence their concentrations—ozone, NO_2, SO_2, and HCHO—and discusses the problems related to compound air pollution that have not been analyzed previously.

1. Overview of the study area

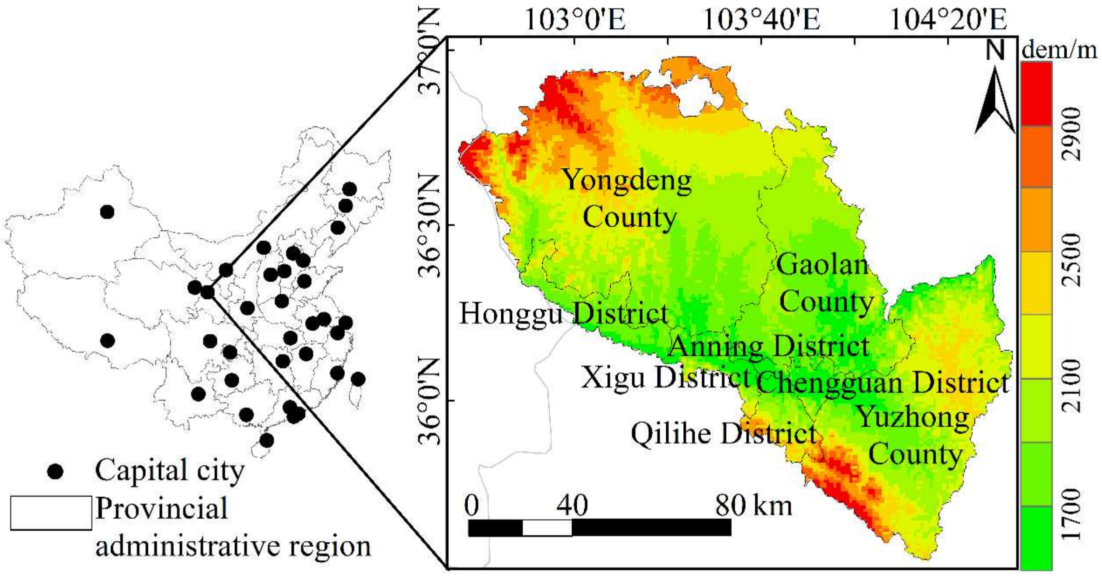

Figure 1 Overview of the study area showing eight counties and districts areas within Lanzhou City with a digital elevation model overlay. An inset map shows the provinces and other administrative area of mainland China and locations of their capital cities.-

The Lanzhou area, located in northwestern China and at the geometric center of Chinese territory, lies roughly between 35–37°N and 102–105°E. As the provincial capital of Gansu Province, Lanzhou serves as the center of provincial politics, economy, and culture. It is also the center of silk production. An important node city in the economic belt and road, Lanzhou also serves as an important industrial base and transportation hub in northwestern China, and as one of the important central cities in the western region. Covering an area of about 13,100 km^2, Lanzhou has about 210,000 hectares of arable land, about 76,000 hectares of forests, and about 765,000 hectares of pasture land. The temperate continental climate features an average annual temperature of 10.3°C with precipitation mainly concentrated in summer and autumn, and an average annual rainfall of about 327 mm (Wu et al., 2019). The terrain of this area is higher in the west and south, and lower in the northeast (Figure 1), with the topography mainly composed of mountains and basins.

As one of China's important industrial bases, the Lanzhou area is also an important base for petrochemical, biopharmaceutical, and equipment manufacturing industries in China. It is a frontier and an important gateway for the country to implement the policy of opening to the west (Zhang et al., 2014). As of the end of 2014, 156 proven mineral deposits and ore sites had been identified in the area, which were mainly divided into nine categories including non-ferrous metals, rare earths, energy minerals, and precious metals. Among them, the reserves of quartzite as the raw material needed for the ferrosilicon industry were as high as 300 million tons. The development of the mining industry has provided sufficient reserve resources for China, while the coal storage reserves total an estimated 905 million tons, which has greatly promoted the development of the region's mining industry. As of the end of 2019, the permanent population of the region was 3,790,900, an increase of 37,300 over the previous year. The regional gross domestic product was 283.736 billion yuan, an increase of 6% over the previous year; the ratio of the output structure of the above three industries was 1.82 : 33.32 : 64.86.

2. Data sources and data processing

2.1 Data sources

In this paper, four pollutants such as SO_2, O_3, NO_2, , and HCHO are studied. The four pollutant gas data were acquired from the ozone monitor on the AURE satellite launched by NASA in 2004. The main task of this satellite is to observe and study the earth's ozone layer, air quality, and its changing climate. In addition to socio-economic factors, the factors affecting the aforementioned gaseous pollutants are also related to the natural factors in the area. Therefore, the data on the socio-economic factors selected in this article (regional production value, secondary production value, raw coal consumption, urbanized area, urban construction land, and so on) are from the Gansu Provincial Bureau of Statistics and the *Lanzhou Regional Statistical Yearbook*. Data related to natural factors (e.g., precipitation, temperature, air pressure, relative humidity, and sunshine duration) come from the *Gansu and Lanzhou Regional Statistical Yearbooks*; in addition, some natural factor data come from ground-based weather monitoring stations in the Lanzhou area.

2.2 Data processing

The remote sensing data from the Ozone Monitoring Instrument (OMI) were verified by a large number of aviation and ground experiments; the results show that the correlation between the tropospheric and the near-ground pollutant concentrations can reach more than 0.8, which is a significant positive correlation. However, because cloud coverage will have a certain effect on the concentration of pollutants, this study uses daily concentration data over a ten-year period; the amount of available data is relatively large. Therefore, data with a cloud cover greater than 0.2 were removed during data processing and did not affect the final results. To improve the credibility of the pollutant concentration data, the latitude range covered by each data point was expanded by 0.5° when processing the data. The daily ozone, NO_2, SO_2, and HCHO column concentration data downloaded from the NASA official website were processed in batches by Python software; next, data were processed by ArcGIS software (ESRI, Redlands, CA, USA) for raster calculation, interpolation, extraction, and analysis. Finally, the temporal and spatial distribution maps of the aforementioned pollutants were obtained.

When analyzing the correlation between these four types of pollution, the year is the unit with spatial correlation method used for analysis. The calculation process is shown in Eq. (1):

$$r_{xy} = \frac{\sum_{i=1}^{n}[(\mathrm{x_i} - \bar{\mathrm{x}})(\mathrm{y_i} - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}, \quad (1)$$

where r_{xy} represents the correlation between the two gaseous pollutants, and its value is between −1 and 1. The closer r_{xy} is to 1, the more significant a positive correlation between the two pollutants will be; the closer r_{xy} is to −1, the more significant a negative correlation between the two pollutants will be. In the equation, x_i refers to the concentration of the gaseous pollutant (x) in the i^{th} year; $\bar{x}$ refers to the annual average concentration of the gaseous pollutant (x); y_i refers to the concentration of the gaseous pollutant (y) in the i^{th} year; $\bar{y}$ refers to the annual average concentration of the gaseous pollutant (y); i refers to the year (2010, 2011,…2019); and n is the sample size (1, 2, 3,…10) (Li et al., 2019).

The coefficient of variation was used to analyze and study the spatial stability of these four pollutants using Eqs. (2) and (3) as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}}, \quad (2)$$

$$c_v = \frac{\sigma}{\overline{x}}\,, \qquad (3)$$

where σ refers to the standard deviation, which is the average distance between the concentrations of each pollutant and the average concentration; c_v is the coefficient of variation of each pollutant, where a smaller value indicates a more concentrated pollutant and a smaller range of fluctuation. In addition, x_i refers to the pollutant concentration in the i^{th} year, and $\overline{x}$ refers to the average pollutant concentration during the study period (Zhang et al., 2020).

The univariate linear analysis method was used to study the change trend of these four pollutants in Lanzhou during the past 10 years; it was calculated using Eq. (4) as follows:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n}(i \times X_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} X_i}{n \times \sum_{i=1}^{n} i^2 \times \left(\sum_{i=1}^{n} i\right)^2}, \qquad (4)$$

where θ_{slope} represents the trend slope of the gaseous pollutant in each pixel, n is the number of samples, i is the year number, X_i is the concentration of the pollutant (X) in the i^{th} year; if the value of θ_{slope} is positive, the concentration of the pollutant increased over time; in contrast, a negative value of θ_{slope} indicates the concentration of the pollutant decreased over time; the larger the $|\theta_{slope}|$, the more obvious the change trend of the pollutant concentration (Xian L. et al., 2019).

Finally, the atmospheric transmission model was used to simulate the transmission path of pollutants in the four seasons in Lanzhou in the past 10 years. The specific process was as follows:

$$\mathrm{P}(\mathrm{t} + \Delta\mathrm{t}) = \mathrm{P}(\mathrm{t}) + 0.5[\mathrm{v}(\mathrm{P}, \mathrm{t}) + \mathrm{v}(\mathrm{P}', \mathrm{t} + \Delta\mathrm{t})]\Delta\mathrm{t}\,, \qquad (5)$$

$$\mathrm{P}'(\mathrm{t} + \Delta\mathrm{t}) = \mathrm{p}(\mathrm{t}) + \mathrm{v}(\mathrm{p}, \mathrm{t})\Delta\mathrm{t}. \qquad (6)$$

The position of the next point was obtained by the product of the average velocity of the previous time, the average velocity of the point where the first guess is located, and the time step (Li et al., 2020). The integral time varied between (1 min and 1 H), as shown in Eq. (7):

$$U_{max}(grid - units_{min} - 1)\Delta\mathrm{t}(\mathrm{min}) < 0.75(\mathrm{grid} - \mathrm{units}). \qquad (7)$$

3. Results and analysis

3.1 Spatial distribution of pollutants in Lanzhou

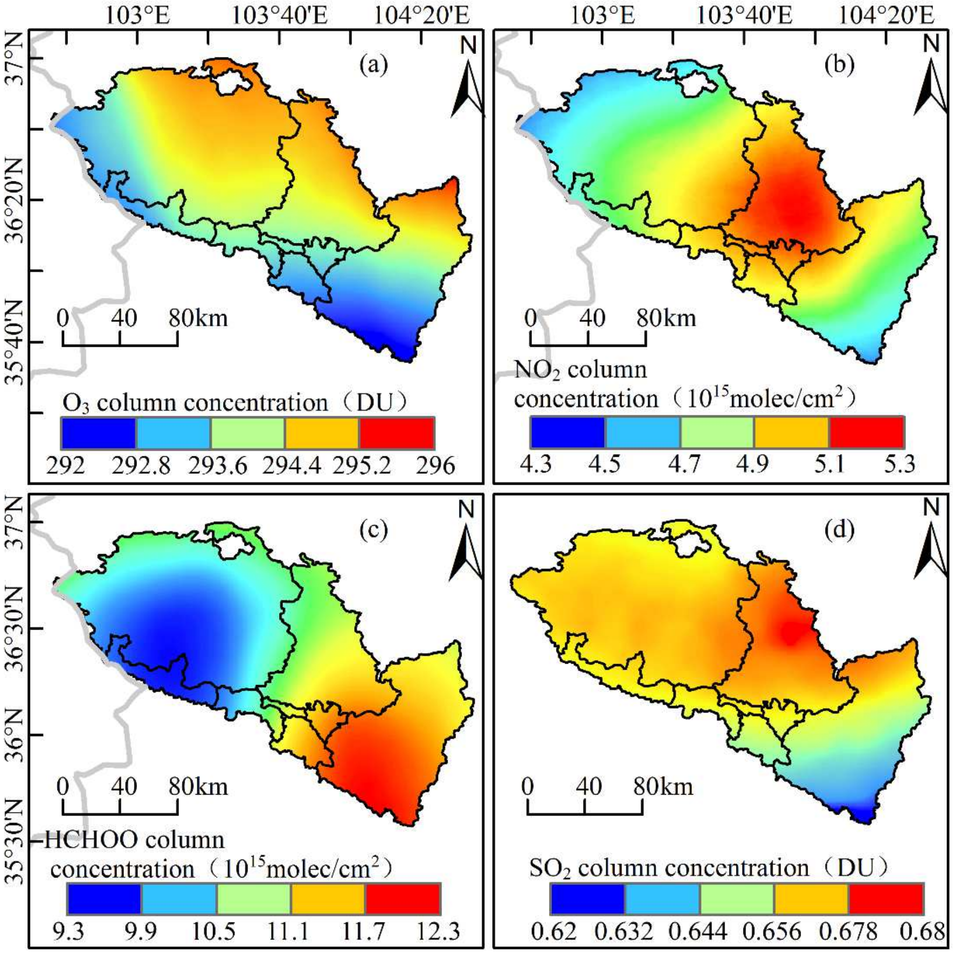

Figure 2 The overall spatial distribution of (a) O_3, (b) NO_2, (c) HCHO, and (d) SO_2 concentrations in Lanzhou from 2010 to 2019

By processing the data on the concentrations of tropospheric ozone, NO_2, HCHO, and SO_2 in the air column in Lanzhou from 2010 to 2019, the overall spatial distribution of these four pollutants was obtained (Figure 2). Figure 2 shows that the ozone concentration in the column presented a distribution pattern of high in the north and east while it was low in the south and west. The overall trend was for increasing concentrations from the southwest to the northeast. The high value areas were mainly distributed in the northeast of the Lanzhou area, namely, in Yongdeng County, the northeastern part of Deng County, Gaolan County, and the northern part of Yuzhong County. The distribution pattern of NO_2 presented a medium-high and low distribution pattern on both sides; that is, high-value areas were mainly distributed in economically developed areas (the districts of Chengguan, Xigu, and Qilihe, along with Gaolan County), while low-value areas were mainly distributed in western Yongdeng County and southeastern Yuzhong County. The overall spatial distribution of HCHO presented two obvious concentration centers, namely, Yongdeng as the main low-value center, while high-value centers were located in the southern part of Yuzhong County, Qilihe District, and the eastern part of Chengguan District. The spatial distribution pattern of SO_2 was mainly high in the north and west while it was low in the south and east. The high-value areas were mainly distributed in the northern part of Gaolan County, while the low-value areas were mainly distributed in the southern part of Yuzhong County. In addition, Lanzhou New District, composed of Yongdeng and Gaolan counties, are China's fifth and first national-level new districts in Northwest China. This region serves as an important economic growth center in Northwest China, an important national industrial base, and an important strategic platform for opening to the west. To create an industrial transfer demonstration zone, together with the Lanzhou area, a major move was made to transfer industries to the Lanzhou New District, including many heavy industry, materials, heating, and power supply companies, thus making the ozone and SO_2 column concentrations higher than in other regions. Figure 1 shows that Yuzhong County has relatively high elevation terrain with many mountains and hills, relatively lush vegetation, and a relatively sparse distribution of industries and enterprises in the area. As a result, the ozone, NO_2, and SO_2 column concentrations in this area were relatively low when compared with other areas. Studies have found that isoprene emitted by plants is the main component of VOCs and contributes particularly prominently to the concentration of HCHO, so that the HCHO concentration has a significant positive correlation with the amount of vegetation cover. Therefore, the concentration of the HCHO column in Yuzhong County was significantly higher than that in other areas (Fan et al., 2020). In recent years, China has increased its efforts to control air pollution and has implemented industrial transfer measures in the Lanzhou area; as a result, the ozone and HCHO column concentrations in the municipal districts (Anning, Chengguan, Qilihe, and Xigu districts) in the Lanzhou area have been lower than in the past.

3.2 Inter-annual variation of pollutants in Lanzhou

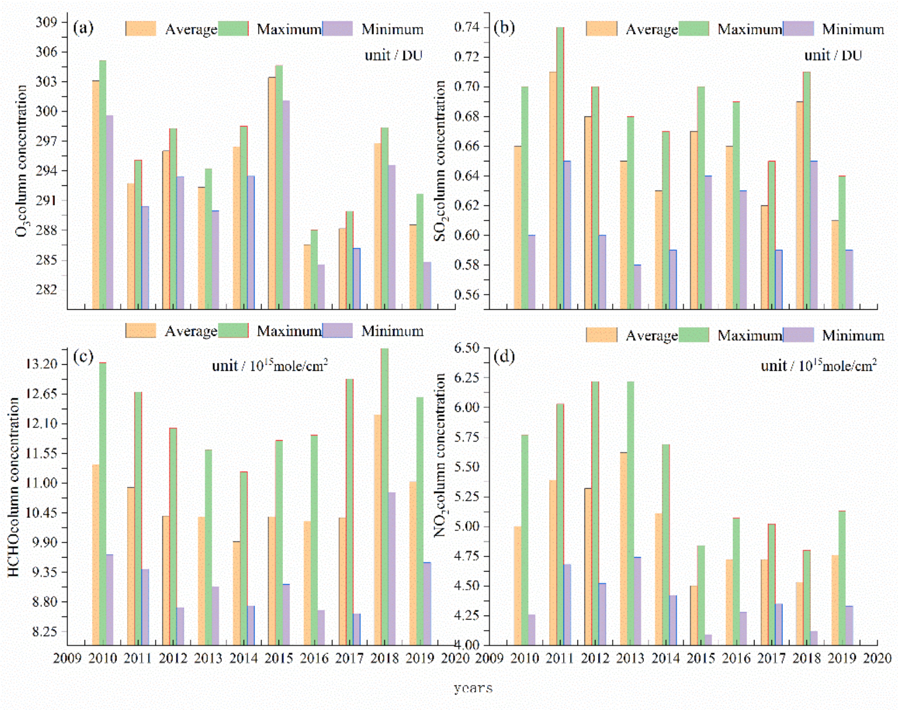

Figure 3 Inter-annual changes of (a) O_3, (b) SO_2, (c) HCHO, and (d) NO_2 concentrations in Lanzhou from 2010 to 2019

The inter-annual variation trends of four pollutants in Lanzhou from 2010 to 2019 were obtained by processing the concentration data in the region (Figure 3). In the past 10 years, the ozone column concentration has shown a wave-like change trend; that is, the ozone column concentration rebounded in 2012, 2015, and 2018. The change of the ozone column concentration before 2015 had a “V-shaped” trend. From 2010 to 2012, the ozone column concentration generally had a downward trend, while the ozone column concentration rose from 2013–2015. After 2015, the ozone column concentration was significantly lower than before 2015. The maximum value in 10 years appeared in 2010, which was 305.14 DU; the minimum value appeared at 284.57 DU in 2016. The SO_2 has shown an overall downward trend since 2011, after peaking in 2011 at 0.74 DU; the minimum value appeared in 2013 at 0.58 DU. The inter-annual changes were not obvious, and the SO_2 column concentrations in 2015 and 2018 had rebounded compared with previous years. The SO_2 peaked 0.74 DU in 2011, while the minimum value was 0.58 DU in 2013. The concentration of the HCHO column had obvious regularity during the study period, with an overall trend “V-shaped” trend. That is, HCHO had a decreasing trend in 2010–2014, and an increasing trend in 2015–2018. It peaked in 2018 at 13.75$10^{15}$ molec/cm^2, and a minimum value appeared in 2017 at 8.59 10^{15} molec/cm^2. During these 10 years, the inter-annual variations of the HCHO column concentration fluctuated greatly, with the difference between the maximum and minimum at 5.1610^{15} molec/cm^2. The NO_2 column concentration had an obvious evolutionary law during these 10 years; before 2013, there was an overall upward trend, while later it showed a downward trend; before 2014, the NO_2 column concentration was generally higher than after 2014. The reason these four pollutants in Lanzhou have shown these changes is people gained a gradual increase in environmental awareness while science and technology experienced rapid development. In addition, the Lanzhou regional government has intensified its efforts to control air pollution in recent years; it has identified key pollution control tasks such as a reduction in emissions, movement away from the use of coal, along with implementing dust abatement measures while controlling vehicle emissions, and limited the capacity for expansion. In addition, the regional government has been focusing on the management and control of key processes, while implementing linkage, scientific, targeted, engineering, and legal management plans. In addition, the Lanzhou government has prioritized control of industrial, secondary dust, motor vehicle exhaust, and coal production pollution sources in support of air pollution prevention and control. The government has implemented real-time supervision of the entire process; all employees and all grids working on air pollution prevention and control work in this area have achieved good results. The obvious control of air pollution in Lanzhou also shows that the close relationship between these four polluting gases and economic characteristics of the region can be tackled under strong environmental management.

3.3 Monthly average change in pollutants concentrations in the Lanzhou area

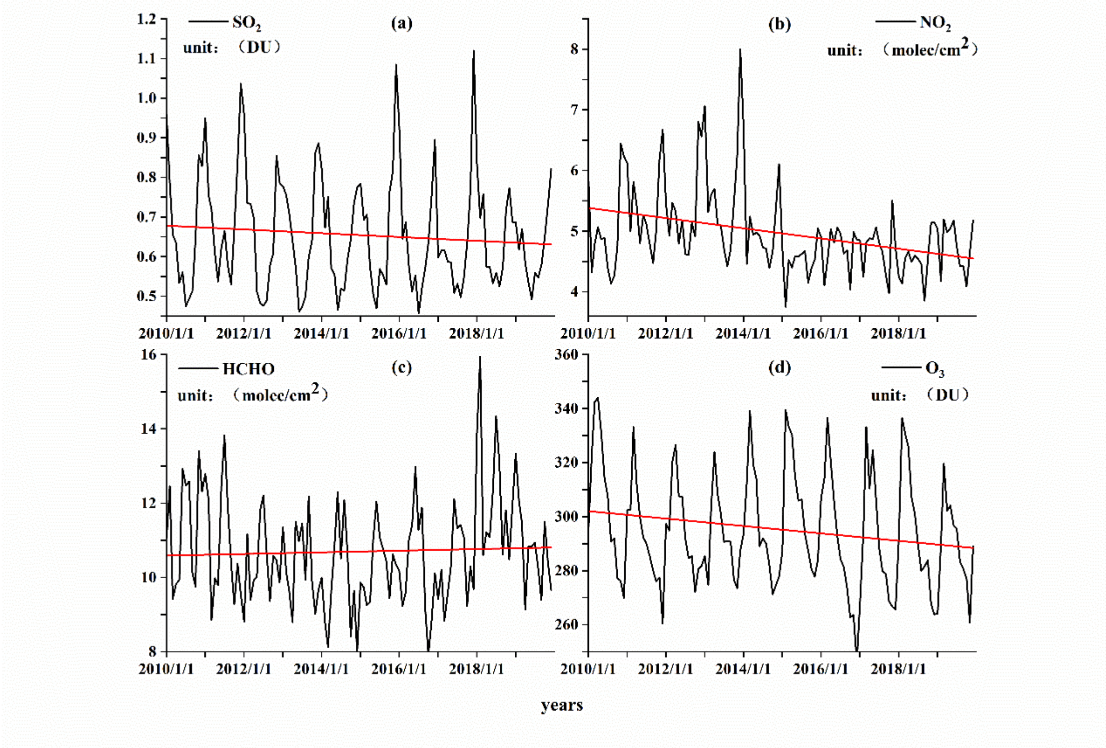

Figure 4 The average monthly changes of (a) SO_2, (b) NO_2, (c) HCHO, and (d) O_3 concentrations from 2010 to 2019

This study used Origin software to linearly fit the concentration of these four air pollution gases (SO_2, NO_2, HCHO and ozone) over 120 months in 10 years to facilitate the study of the monthly average change trends of pollutants in Lanzhou and to produce the monthly average change trend graph of the concentrations of four pollutant from 2010 to 2019 (Figure 4). This figure shows that the monthly average SO_2 and ozone column concentrations in Lanzhou show a certain regularity with large fluctuations; the difference between the maximum and minimum values were 0.66 DU and 97.79 DU, respectively. Moreover, the overall change trend of the former is gentler than that of the latter, with a decreasing trend that was not obvious. Among them, the SO_2 column concentration began to decrease in January, falling to the lowest value in July and August, then rising from September to a peak in December and January of the following year; that is, the SO_2 column concentration reached its peak, especially in January. The ozone column concentration showed obvious periodicity in the monthly average change. The concentration started to rise in January and peaked in March and April; then, the ozone column concentration began to decrease, until December and January of the next year, when the ozone column concentration reached its lowest point (Liang et al., 2021). In general, the monthly average change trends of these two pollutants were exactly opposite. That is, the trough of the ozone column concentration occurred exactly at the peak of the SO_2 column concentration, while the concentration of the former reaches its peak in March and April, the ozone column concentration reaches the highest in the spring, and the latter drops to the lowest in July and August; that is, a valley occurs in summer. However, the monthly average changes of NO_2 and HCHO column concentrations were not very obvious when compared when those of ozone and SO_2 concentrations. Among them, the NO_2 column concentration had two troughs in a year. That is, the NO_2 column concentration reached a minimum in February and August, while peaking in December. The range of changed in the NO_2 column concentration before 2015 was greater than that after 2015, while the overall trend of a change in the monthly average was decreasing. The HCHO column concentration after 2015 changed more than before 2015, and the monthly average change increased. In general, the HCHO column concentration peaked in June, and then decreased to minimums in April and October, which means that there were two troughs in each year. In general, if natural factors have a leading role in the concentrations of pollutants, then its changing trend will show a regular periodicity. However, the above four pollutants exhibited no such periodicity, meaning that the factors affecting the concentrations of pollutants in Lanzhou are mainly human factors, which are especially under the obvious influence of the concentrations of HCHO and NO_2 column.

3.4 Analysis of the stability and trend of pollutants in Lanzhou

3.4.1 Stability analysis of pollutants in the Lanzhou area

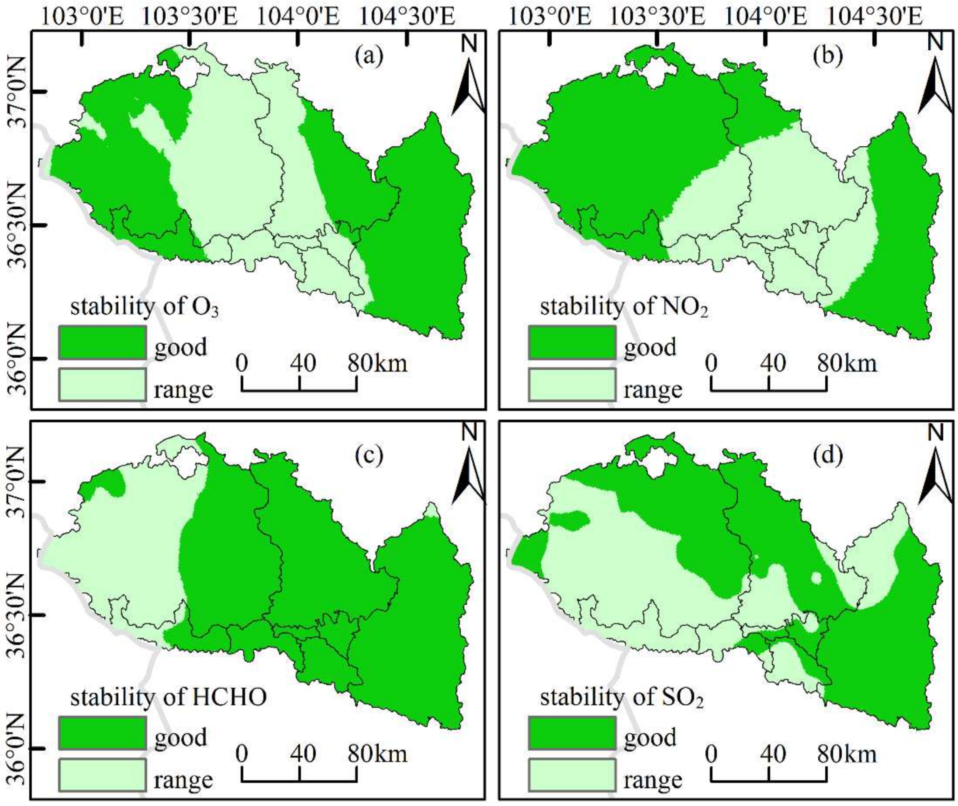

Figure 5 The distribution of stable concentrations of (a) O_3, (b) NO_2, (c) HCHO, and (d) SO_2 in Lanzhou from 2010 to 2019

A spatial distribution map of the 10-year pollutant variation coefficients in the Lanzhou area was obtained by processing data for four pollutants (ozone, NO_2, HCHO, and SO_2 column concentration) in the Lanzhou area from 2010 to 2019 to study the stability of pollutants in the Lanzhou area (Figure 5). This figure shows that the stability of the pollutants in Lanzhou improved over time with a coefficient of variation below 0.25. Among them, the largest area enclosing 42% of the Lanzhou region had a relatively low fluctuation of the ozone column concentration. This area was mainly distributed in Gaolan County, while Yongdeng County had higher ozone column concentration, with its economically developed and densely populated city-controlled areas. About 35% of the area had a fluctuating low NO_2 column concentration, with its main branches in eastern Yongdeng County, most areas of Gaolan County, and in the city-controlled areas. In addition, 26% of the study area had a low fluctuation of the HCHO column concentration, which was mainly distributed in Yongdeng County and the western part of Honggu District. Meanwhile, 38% of the study area had a low fluctuation of the SO_2 column concentration, mainly distributed in southern

Yongdeng County, northern Yuzhong County, and in most of the city-controlled areas. Figure 5 shows that the low-fluctuation area of pollutants in this study accounted for a large proportion of the study area, indicating that the spatial distribution of pollutants varies little. Except for HCHO, the city-controlled areas with the other three pollutants were lower the fluctuation area indicating that human economic activities had a certain influence on its spatial distribution, while the spatial distribution of the HCHO column concentration was greatly affected by natural factors. In general, the spatial distribution of pollutants in Lanzhou is relatively stable, affected by natural and human factors, and has relatively small fluctuations.

3.4.2 Trend analysis of pollutant concentrations in the Lanzhou area

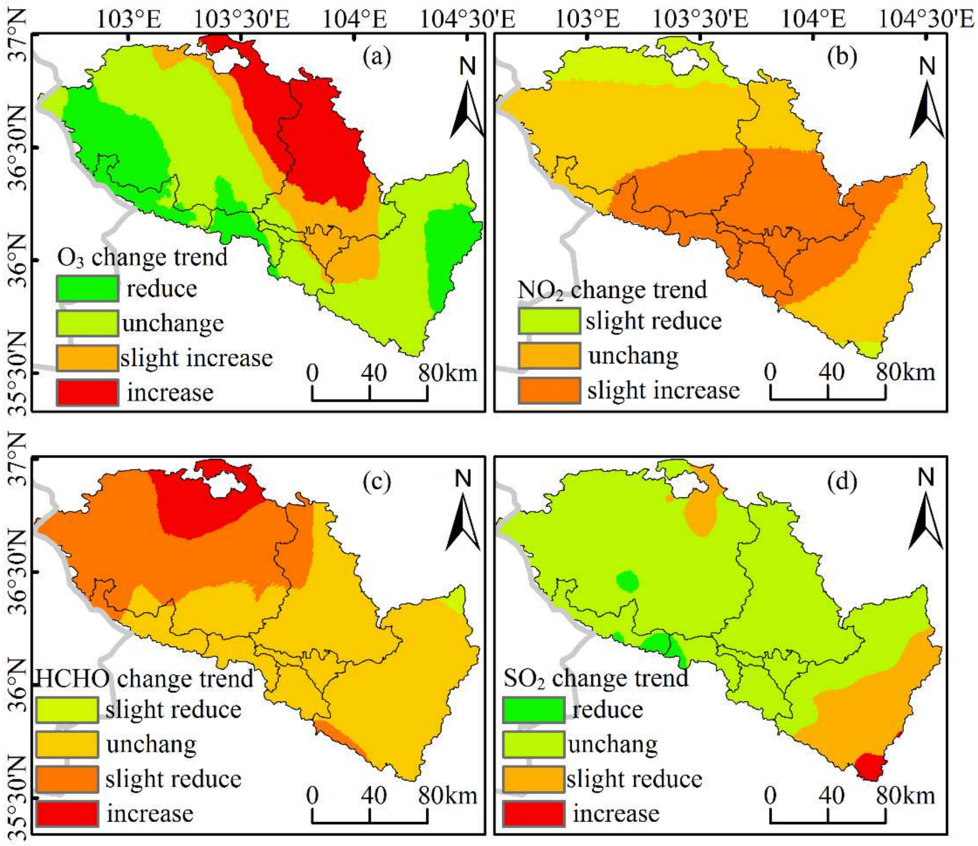

Figure 6 The trends in the spatial distribution of (a) O_3, (b) NO_2, (c) HCHO, and (d) SO_2 concentrations in Lanzhou from 2010 to 2019

The spatial distribution of the trends of change in pollutant concentrations was combined with combined trend analysis to obtain pollutant concentration data in the area from 2010 to 2019; these data were then used to study these trends in the Lanzhou area (Figure 6). In order to facilitate this type of analysis, based on the change coefficient of each pollutant trend, we divided the change trends into four categories: reduction, slight reduction, basically unchanged, and slight increase. Figure 6 shows that in northern Gaolan and Yongdeng counties the ozone column concentration was relatively high and had a significant increasing trend; meanwhile, a slight upward trend was observed in Chengguan District, while in Honggu and Xigu districts something changed. The concentration of ozone column in southwestern Yongdeng County and eastern Yuzhong County showed a clear downward trend, while in other areas the concentration of ozone did not change significantly. The NO_2 column concentration showed a slight increasing trend in the city-controlled areas with higher values, such as southern Gaolan County, southeastern Yongdeng County, and western Yuzhong County; meanwhile, NO_2 showed a slight increase in northern Yongdeng County. In the remaining areas, the concentration of NO_2 column remained basically unchanged. The HCHO column concentration in Lanzhou showed four changing trends. In northern Yongdeng County HCHO showed a clear increasing trend, while the central and northwestern parts of Gaolan County it showed a slightly increasing trend. The HCHO column concentration remained basically unchanged (except for a slight decrease in some areas) in remaining areas except for northern part of Yuzhong County. The concentration of the SO_2 column in Lanzhou remained unchanged in most areas, while it decreased in areas of the intersection between the heavy industry base (Xigu District) and Anning District; SO_2 showed a slight increase in the eastern and southern parts of Yuzhong County. The trend of SO_2 showed a clear upward trend, especially in parts of the southeast. This shows that the Lanzhou area has succeeded in controlling air pollution in recent years to some extent. The total amount of pollutants has been reduced, but some areas are still experience an increasing trend in air pollutant concentrations. The NO_2 column concentration has increased in the city-controlled areas because of changes to the regional economy. Urbanization along with increases in population and car ownership have increased year by year; as a result, car exhaust has contributed a large amount of pollutant gases into the atmosphere, causing the concentration of NO_2 column in this area to rise.

3.5 Spatial relationship among pollutants in Lanzhou area

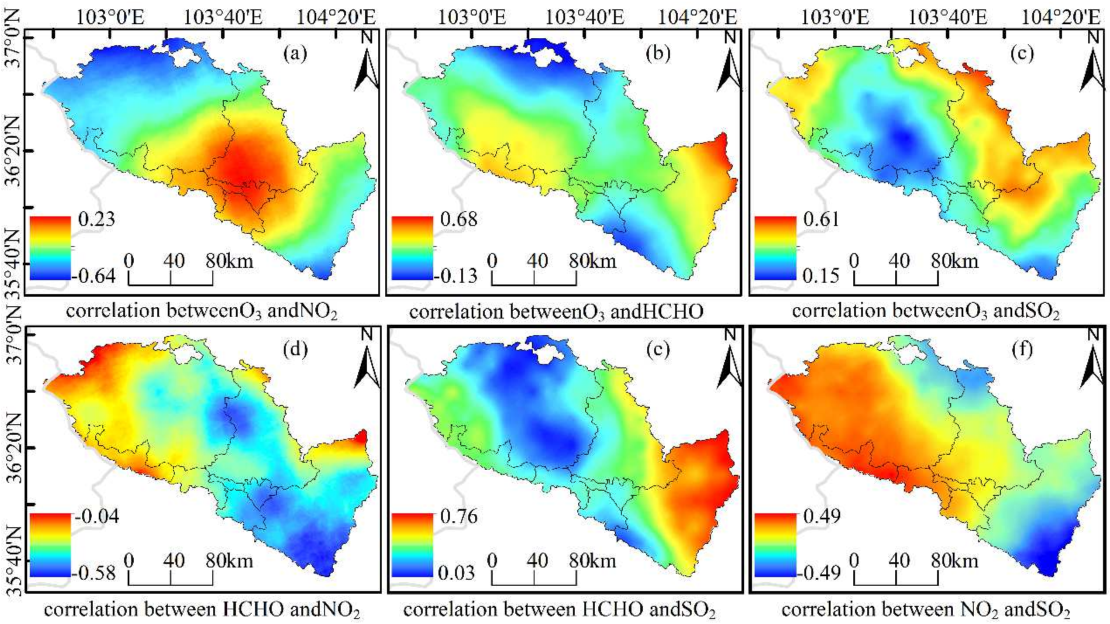

Figure 7 Spatial relationships between pollutants in Lanzhou from 2010 to 2019: correlations between (a) O_3 and NO_2; (b) O_3 and NCHO; (c) O_3 and SO_2; (d) HCHO and NO_2; (e) $HCHO_3$ and SO_2; (f) NO_2 and SO_2.

This study combined spatial pixel analysis by processing the concentration data of these four pollutants in the study area to examine the mutual influences and contributions between the pollutants in Lanzhou area. Figure 7 presents a spatial relationship diagram of the pollutant concentrations from 2010 to 2019. The NO_2 and ozone concentrations are mainly negatively correlated spatially with a negative correlation in 65% of the study area; the negative correlation coefficient was as high as −0.64. The NO_2 and ozone were mainly distributed in northern Yongdeng and Gaolan counties, and in eastern Yuzhong County. The areas with a positive correlation were mainly distributed in the city-controlled areas with higher NO_2 column concentrations, in southern Gaolan County, and in western Yuzhong County. Meanwhile, the HCHO and ozone were mainly positively correlated spatially, with a positive correlation occurring in up to 96% of the study area and having a correlation coefficient as high as 0.68. This shows that the ozone column concentration increased with an increase of the HCHO column concentration, and vice versa. The areas with a positive correlation were mainly distributed at the intersection of Yongdeng County, Xigu District, Anning District and the northern part of Yuzhong County where the concentration of both pollutants was high. Therefore, SO_2 and ozone were spatially positively correlated, with a positive correlation coefficient of 0.61; this was more obvious in the northern areas of Yuzhong and Gaolan counties where the concentrations of these two pollutants were relatively high. Both HCHO and NO_2 column concentrations were negatively correlated in space, with a negative correlation coefficient of as high as −0.58. This correlation was more obvious in the western region of Yongdeng County and in Honggu District where the two concentrations were lower. The concentration of the HCHO and SO_2 columns both realized a positive correlation spatially, with a correlation coefficient as high as 0.76, which was primarily manifested in the eastern part of the study area. The NO_2 and SO_2 column concentrations were mainly positively correlated spatially and occupied 77% of the study area; the correlation coefficient between the two was between −0.49 and 0.49. The positive correlation was primarily distributed in Yongdeng County and in Honggu and Xigu districts where the concentration of the SO_2 column was relatively high. The negative correlation was mainly distributed in the northern parts of Yongdeng and Gaolan counties as well as in the entire area of Yuzhong County, where the concentrations of both were relatively low. This shows that the concentrations of various pollutants influence and promote each other. Under certain conditions, one pollutant will transform into the precursor of another pollutant, causing it to continue to grow and fall in the atmosphere, eventually leading to changes in air quality.

4. Analysis of factors influencing the concentration of pollutant in the Lanzhou area

4.1 The influence of natural factors on the concentrations of pollutants

Table 1 Correlations between natural factors and pollutants in Lanzhou from 2010 to 2019

Correlation coefficients	SO_2	NO_2	O_3	HCHO
Temperature	−0.54	−0.89**	0.67*	−0.36
Precipitation	−0.57	−0.35	−0.49	0.42
Humidity	−0.63*	−0.56	−0.32	0.35
Sunshine	0.39	0.41	0.74**	−0.47
Year	−0.67*	−0.69*	−0.59	0.45

* $p<0.05$, significant correlation. ** $p<0.01$, significant correlation.

Origin software was used to analyze the correlation between natural factors and the concentrations of pollutants in the Lanzhou area from 2010 to 2019 using statistics. Table 1 shows the correlations between the concentrations of various pollutants and various natural factors in the study area. Table 1 shows that, except for the increase in the HCHO column concentration over time, the national binding indicators have been reduced. This shows that with the strengthening of air pollution control in Lanzhou in recent years, the air quality has improved significantly. In addition to the relatively weak relationship between temperature and HCHO, a strong correlation was observed between temperature and the other three pollutants, specifically SO_2, NO_2, and ozone, with correlation coefficients of −0.54, −0.89, and 0.67, respectively. Among them, ozone is a secondary pollutant frequently formed as a product of photochemical reactions; higher temperature will accelerate the production rate of ozone, thereby increasing the concentration of the ozone column in the atmosphere. Studies have found that a significant correlation exists between the content of nitrogen oxides in the air and the length of its life span and temperature (Ma et al., 2020). The content of NO_2 in the atmosphere in Lanzhou in winter was significantly higher than that in summer. The high summer temperatures promote photochemical reactions involving nitrogen oxides in the atmosphere and shortens its survival time, which is not conducive to the accumulation of NO_2. Low winter temperatures do not favor the conversion of NO_2 into other products, which causes it to accumulate in the atmosphere. Therefore, the concentration of NO_2 in winter is normally significantly higher than in the other three seasons. Precipitation and relative humidity have a greater impact on the concentration of the SO_2 column, with correlation coefficients of −0.57 and −0.63, respectively. With more precipitation, the humidity will increase. Rainwater will dilute some of the pollutants in the atmosphere and cause them to be removed during precipitation. This will reduce the content of some pollutants in the atmosphere, which may also be one of the reasons for the low concentrations of SO_2 and NO_2 observed in summer. In addition, a significant correlation also exists between the duration of sunshine and the ozone and HCHO column concentrations, with correlation coefficients of 0.74 and −0.47, respectively. Specifically, the longer the duration of sunshine with increased amounts of light radiation, catalyzes the formation of ozone from precursors such as VOC_S, NO_X, and HCHO, as the precursors of ozone will also consume part of those precursors as ozone is generated in the process; therefore, the number of sunshine hours also has a certain effect on the concentration of the HCHO column.

4.2 The influence of socio-economic factors on the concentrations of pollutants

Table 2 Correlations between economic factors and pollutants in Lanzhou from 2010 to 2019

Correlation coefficients	DGP	Secondary industry	Tertiary Industry	light industry	City area	Built-up area	Construction land	Raw coal consumption
SO_2	−0.67*	−0.63*	−0.66*	−0.48	−0.60*	0.59	−0.6	0.37
NO_2	−0.67*	−0.4	−0.72*	−0.41	−0.82**	−0.86**	−0.82**	0.79**
O_3	−0.5	−0.58	−0.46	−0.31	−0.34	−0.34	−0.35	0.37
HCHO	0.28	0.34	0.42	−0.56	−0.29	0.38	0.24	−0.45

* $p<0.05$, significant correlation. ** $p<0.01$, significant correlation.

Table 2 shows the relationship between economic factors and pollutant concentrations in Lanzhou from 2010 to 2019. The gross domestic product is often used to measure the economic development of a country or region in a certain period of time (Table 2). The gross domestic product had significant correlations with the column concentrations of SO_2, NO_2 and ozone, with correlation coefficients of −0.67, −0.67 and −0.5, respectively. The correlation of the gross domestic product with the HCHO column concentration was weak. The secondary industries (industries) had a significant correlation with the column concentrations of SO_2 and ozone, whereas the correlations with the column concentrations of NO_2 and HCHO were relatively weak. The tertiary industries (service industries) had a high correlation with all four types of pollution concentrations; in particular, the correlations with the SO_2 and NO_2 column concentrations and the service industry, with correlation coefficients of −0.66 and −0.72, respectively. Urban construction land, urban area, and built-up area all had obvious correlation with the SO_2 and NO_2 column concentrations, whereas the correlations with the other two pollutants were relatively weak. A significant correlation was observed between raw coal consumption and NO_2, with a correlation coefficient of 0.79. Studies have shown that a large amount of NO_X will be produced during the combustion of coal, and under certain conditions, NO_x will be converted into a precursor of NO_2, making it accumulate continuously in the air, eventually causing the NO_2 content in the atmosphere to gradually rise. The above shows that a close relationship exists between the development of industry and urbanization in Lanzhou and the concentrations of pollutants; the industries that use coal as a raw material also had a significant impact on the concentrations of pollutants (Lan et al., 2019; Cheng et al., 2019). Therefore, controlling air pollution and limiting it within a reasonable range will be necessary to better control of the use of coal and other raw materials; the purification of exhaust gas and the development of clean energy are both needed along with slowing the process of urbanization. This will reduce overall greenhouse gas emissions.

4.3 Analysis of the source of pollutants in Lanzhou

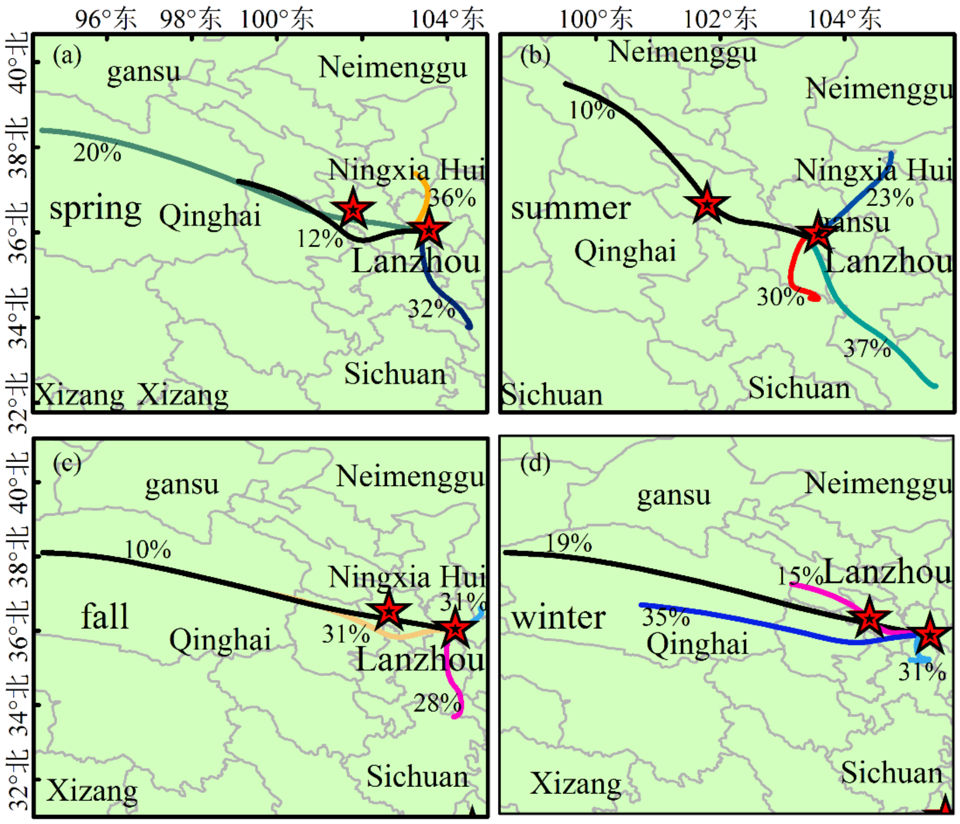

Figure 8 Sources of pollutants in (a) spring, (b) summer, (c) fall, and (d) winter in Lanzhou from 2010 to 2019

In addition to the sources of pollutants, which are closely related to human economic activities, the long-distance transportation of pollutants in the atmosphere also has a major impact on the concentration of pollutants in the studied region. The study used the atmospheric transmission model in MeteoInfo software to simulate the transmission path of pollutants in the Lanzhou area to identify the sources of pollutants more intuitively. As shown in Figure 8, the map presents the four main atmospheric motion trajectories obtained in each quarter from 2010 to 2019 using the clustering method. In spring, pollutants in the Lanzhou area primarily come from northern Wuwei city (36%), followed by Longnan City and Qinghai Province, each accounting for 32% of all air masses. This finding shows that the pollutants in the Lanzhou area in spring are primarily imported from Gansu Province, followed by Qinghai Province. The pollutants in this area in summer are mainly imported from southern Gansu Province, accounting for 67% of all air masses, followed by Shaanxi Province which accounts for 23%. In autumn, polluted air mainly came from Qinghai Province (41%), followed by Pingliang City and Sichuan Province (31% and 28%, respectively). The winter pollutants primarily come from Qinghai Province (69%), followed by the southern cities of Gansu

Province (31%). In general, the air in Lanzhou area is mainly transmitted from Gansu Province, followed by remote transmission from Qinghai Province, while the influence of Sichuan and Shaanxi provinces cannot be ignored; this also shows that long-distance atmospheric transport, a natural factor, has an increasingly prominent impact on regional pollutants.

5. Conclusions

1) Air pollutants in the Lanzhou area have multi-dimensional characteristics and a complex spatial distribution caused by variations in meteorological and other conditions that cause their formation, so that ozone concentrations decreasing from the northeast to southwest. Meanwhile, HCHO and SO_2 have the characteristics of an “inverse phase” spatial distribution; the former has a southeast phase and decreases to the northwest, while the latter decreases from northeast to southwest. In addition, NO_2 concentrations are high in the central region of the study area and low in two other areas.

2) In the past 10 years, in addition to the increase in the concentration of the HCHO column with the inter-annual changes, ozone, NO_2, and SO_2 concentrations have all decreased. With seasonal changes, both NO_2 and SO_2 concentrations peak in spring, while ozone and HCHO concentrations peak in spring and summer, respectively. In terms of changes in monthly averages, concentrations of these four pollutants (ozone, NO_2, HCHO, and SO_2) peaked in April, December, June, and January, respectively.

3) Atmospheric pollutants frequently interact with each other causing mutual transformation and promotion. Their complex characteristics make improving air quality quite difficult. The spatial correlations between these four pollutants can be specifically expressed as follows: the ozone and NO_2 column concentrations mainly show a negative correlation (correlation coefficient of −0.64; other coefficients are in parentheses below); the ozone and the column concentrations of HCHO and SO_2 are generally positively correlated (0.68 and 0.61, respectively). In addition, HCHO is negatively correlated with NO_2 (−0.58), whereas it has a high degree of positive correlation with SO_2 (0.76); SO_2 and NO_2 are mainly positively correlated spatially (between −0.49 and 0.49).

4) When analyzing the stability of pollutants in Lanzhou, areas with higher concentrations of pollutants had less stable air quality than areas with lower concentrations. In the trend analysis, it was found that the concentrations of pollutants had declined in most areas, but some areas were still

experiencing upward trends in some pollutants. The concentration of SO_2 in the Xigu District of the Industrial and Chemical Industry Base has decreased, whereas the concentration of ozone and NO_2 in Chengguan District has increased.

5) Air pollutants in Lanzhou are restricted by a variety of factors. Among the natural factors, temperature has a relatively weak relationship with HCHO, and has a greater impact on the other three pollutants. Precipitation affects all four pollutants. Relative humidity has a greater impact on SO_2 and NO_2; meanwhile, the duration of sunshine has a greater impact on ozone while also having a certain impact on HCHO and NO_2. Among the economic factors influencing air quality, these four pollutants were greatly affected by the speed of urban and economic development; in addition, a certain connection existed between HCHO and the development of light industry.

6) Through the simulation of atmospheric movement trajectory, it is found that the pollutants in Lanzhou area are mainly affected by Gansu Province. In addition, air pollutants from Qinghai, Sichuan and Shanxi provinces have been transported remotely from the atmosphere, which has exacerbated the pollution in Lanzhou.

Declarations

The data sets used or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

Tianzhen Ju is responsible for the overall control of the article's ideas and the structure of writing, Zhuohong Liang is responsible for writing the full contents of the article, Wenjun Liu: Writing - review & editing. Bingnan Li Writing - review & editing, Tunyang Geng: Investigation, RuiRui Huang: Investigation.

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The ozone column concentration, formaldehyde, nitrogen dioxide data and other economic and natural influence factors used in this article come from the following public domains:

https://disc.gsfc.nasa.gov/datasets/OMTO3_CPR_003/summary?keywords=OMI

http://www.resdc.cn/

http://www.stats.gov.cn/tjsj/ndsj/

http://tjj.lanzhou.gov.cn/

http://tjj.gansu.gov.cn/

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