



Air pollution characteristics, health risks, and source analysis in Shanxi Province, China

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Abstract China is confronting an unprecedented air pollution problem. This study discussed the characteristics of air pollution and its risks on human health and conducted source analysis combined with local development in Shanxi Province in 2016 and 2017. Results demonstrated that the air pollution situation in Shanxi was deteriorating, with Taiyuan, Yangquan, Changzhi, Jincheng, Jinzhong, and Linfen being heavily polluted districts. Particulate matter (PM) was considered the major pollutant, but nitrogen dioxide and ozone showed a dominant trend recently. Furthermore, the health risks evaluated on the basis of a comprehensive air quality index (AAQI) and an aggregated risk index revealed a relatively high-risk level in Shanxi. Among the pollutants, the largest contributor was PM, followed by sulfur dioxide and ozone. Southern Shanxi had the largest pollution level and health risks, whereas Datong was the least polluted region. Source analysis suggested that the main driving forces of air pollution, besides natural factors, were urbanization, population size, civil

vehicles, coal-based heavy industries, and high-energy consumption. Therefore, strengthening urban greening, vigorously adjusting and optimizing the industrial structure, and formulating a multi-domain cooperative control regime on air pollution, especially PM and ozone, should be promoted.

Keywords Air pollution characteristics · Health risks · Source analysis · Local development

Introduction

With the acceleration of urbanization and industrialization in China, air pollution has become a major environmental issue and drawn broad attention. The characteristics of air pollution have become evident since this developing country transitioned from coal-burning to complex conditions (Aunan et al. 2018). Studies on air pollution have focused on spatial and temporal distribution characteristics, relationship between meteorological conditions, source apportioning, and influencing factors (Chai et al. 2014; He et al. 2016, 2017; Sun and Zhou 2017; Zhang et al. 2015; Zhou et al. 2017). However, information on the association between atmospheric pollution characteristics and local socioeconomic development is limited.

Over 50 years, the relationship between air pollution and its corresponding human health effects has been a concern for the World Health Organization

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(WHO) (Motesaddi et al. 2017). Numerous previous studies have confirmed that exposure to air pollutants endangers public health (Brunekreef and Forsberg 2005; Brunekreef and Holgate 2002; Burnett et al. 2000; Shang et al. 2013). For this reason, many guidelines and standards have been established to protect human health from the adverse effects of air pollutants. For example, the Technical Regulation on Ambient Air Quality Index (AQI; on trial; HJ 633-2012) has been issued and applied worldwide to notify the public about the air pollution status and related health risks (Ministry of Ecology and Environment of the People's Republic of China 2012). However, some previous studies only analyzed a single pollutant (Anderson et al. 2012; Christakos and Vyas 1998; Dergham et al. 2015; Gong et al. 2016), thereby ignoring the damage caused by various air contaminants on human health. Correspondingly, other studies have proposed novel indicators for health risks assessment by considering the spatiotemporal heterogeneity of air contaminants in different regions. Kyrkilis et al. (2007) established a comprehensive air quality index (AAQI) based on the combined influences of multiple pollutants. Wong et al. (2013) developed a risk-based, multi-pollutant air quality health index (AQHI) that solves a major disadvantage of reliance on one dominant pollutant in the calculation and demonstrated an improvement when it was applied in Hong Kong. Furthermore, to effectively reflect the contribution of each air pollutant to human health, Cairncross et al. (2007) put forward an aggregated risk index (ARI) to link the total excess risk of human mortality to the exposure to each common air pollutant. Thus, studies should adopt comprehensive evaluation methods to provide more detailed information about the measures necessary to protect public health. At present, the practice and academic research on atmospheric pollution treatment in China mostly focus on the Beijing–Tianjin–Hebei area and the surrounding regions, which are the most polluted parts of the country. In Shanxi Province, which is similarly affected by air pollution, research achievements are still limited and mostly conducted from a meteorological perspective (Lv et al. 2018; Wang et al. 2014b).

In this research, we selected Shanxi Province as a case study. As an important national base for energy generation and the largest coal-producing province in China, Shanxi is experiencing an atmospheric

environmental pollution that is becoming increasingly serious. To address this problem, the Shanxi government has taken control actions in accordance with the national policy and the energy efficiency transformation of the province. After years of efforts, the emission of major pollutants has been effectively brought under control, and air quality has improved notably. However, the concentration of pollutants, especially PM, remains high, and the 8 h-averaged O₃ concentration has increased yearly (Du et al. 2019). As such, discussing air pollution characteristics, assessing related human health risks, and determining the main driving factors in Shanxi are valuable tasks that can help raise public awareness about the need to balance economic development with environmental protection. These tasks can also provide evidence enabling local governments to control air pollution to a certain extent.

Materials and methods

Study area

Shanxi (34° 34'–40° 43' N, 110° 14'–114° 33' E), an important province in northern China, is located on the east bank of the middle reaches of the Yellow River, bordering Hebei in the east, Shaanxi in the west, Henan in the south, and Inner Mongolia in the north. Shanxi covers a total area of 156,700 km², and it consisted of 11 prefecture-level cities in 2017. The geographical distribution is illustrated in Fig. 1. As shown, the central part of the province is the capital city of Taiyuan (TY, with a population of 4.38 million and 271 enterprises). The 10 other cities from north to south are Datong (DT, 3.44 million and 113), Shuozhou (SZ, 1.78 million and 67), Xinzhou (XZ, 3.17 million and 32), Yangquan (YQ, 1.41 million and 54), Lvliang (LL, 3.88 million and 24), Jinzhong (JZ, 3.37 million and 134), Changzhi (CZ, 3.46 million and 69), Jincheng (JC, 2.33 million and 39), Linfen (LF, 4.48 million and 53), and Yuncheng (YC, 5.34 million and 78), covering all urban areas in the province (Fig. 1). Shanxi has a temperate continental monsoon climate characterized by seasonal changes and sufficient sunshine. It is characterized by a landform of narrow valleys and covered with a crisscrossing network of ravines, hills, and mountains. The mountainous area constitutes 80.1% of the total area, and

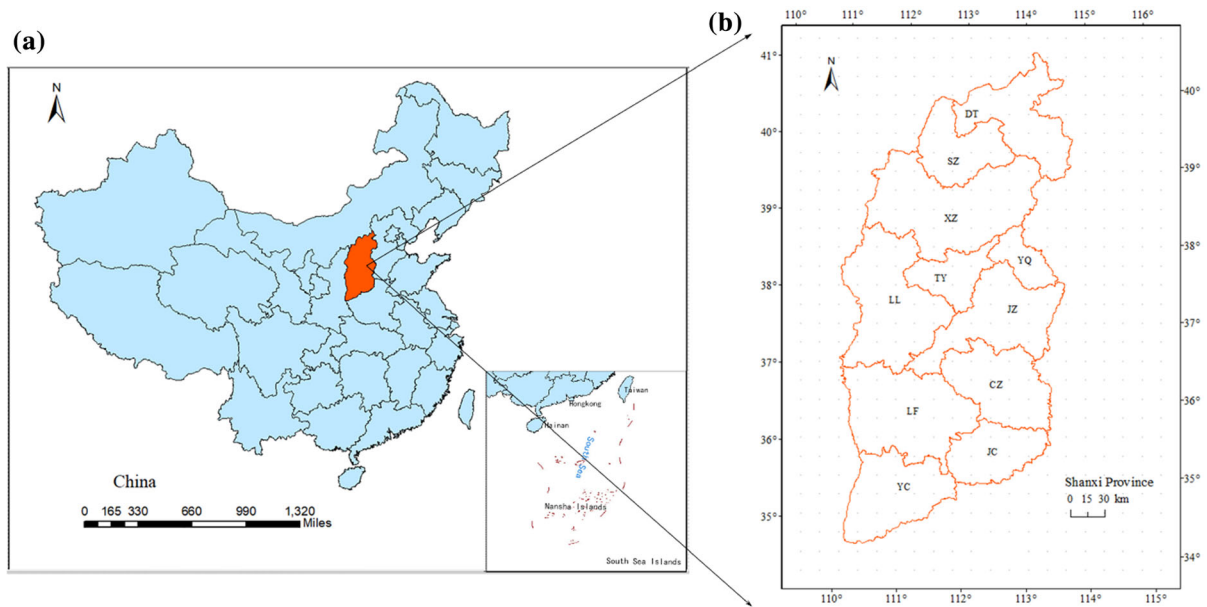


Fig. 1 Study area: **a** location of Shanxi Province in China and **b** geographical distribution of 11 prefecture cities in the province

commercial and residential areas are centralized in basins and valleys. The special terrain accounts for a relatively closed atmospheric system coupled with adverse weather conditions, such as local circulation and temperature inversion, which are not conducive to the diffusion of pollutants (Du et al. 2019).

Data sources and processing

The relevant environmental data for each city in 2016 and 2017 were collected from China Statistical Yearbook on Environment and Report on the State of Environment in Shanxi. The statistical data ranging from 1997 to 2018 were obtained from the Statistical Yearbook of Shanxi Province (Shanxi Provincial Bureau of Statistics 1997–2018). Microsoft Excel 2016, ArcGIS 10.5, and Adobe Photoshop CC were used for data processing and graphic drawing.

Methods

Previously, PM₁₀, PM_{2.5}, SO₂, NO₂, CO, and O₃, which pose the greatest threat to human, have been identified as the world’s six criteria pollutants to quantify air pollution levels (Chen et al. 2004; Hu et al. 2015; Ruggieri and Plaia 2012). These pollutants are comprehensively assessed in the present study.

Air quality index

A sub-AQI for each pollutant was calculated with Eq. (1). Then, the maximum sub-AQI of all pollutants was explained as the overall AQI, as shown in Eq. (2).

$$AQI_i = \frac{AQI_{i,j} - AQI_{i,j-1}}{(m_{i,j} - m_{i,j-1})} \times (m_i - m_{i,j-1}) + AQI_{i,j-1}, \quad j > 1$$

$$AQI_i = AQI_{i,1} \frac{m_i}{m_{i,1}} \quad j = 1, \tag{1}$$

$$AQI = \max(AQI_1, AQI_2 \dots AQI_n), \quad n = 1, 2, \dots, 6, \tag{2}$$

where *i* represents the pollutant *i*; AQI_{*i*} is the index for each pollutant *i*; *m_i* is the monitored concentration of pollutant *i*; *j* is the health category index; *m_{i,j}* and *m_{i,j-1}* are the upper limit reference concentrations for pollution *i* corresponding to the *j*th and *j-1*th health categories, respectively; and *n* is the number of pollutants. The reference pollutant concentrations, health categories, and corresponding risks are listed in Table S1.






Aggregate AQI (AAQI)

As the atmospheric pollution in China is usually characterized by high concentrations of multiple air contaminants rather than a single pollutant, the AQI system may depend on the exposed risks of one major pollutant. Moreover, studies have applied different indices to evaluate air quality and have shown that the AQI likely underestimates the comprehensive health risks of exposure to various air pollutants in many cases, especially when serious pollution occurs; by comparison, the AAQI can be used to evaluate the exposure more effectively (Hu et al. 2015; Motesaddi et al. 2017; Shen et al. 2017). Consequently, the AAQI method was adopted in this study to consider the combined impacts of all criteria pollutants, as defined in the following formula (Kyrkilis et al. 2007; Swamee and Tyagi 1999):

$$AAQI = \left(\sum_{i=1}^n (AQI_i)^\rho \right)^{\frac{1}{\rho}}, \quad (3)$$

where ρ is a pollutant with an irrelevant empirical constant in the range of $[1, \infty]$. Some previous studies suggested that ρ values should be between 2 and 3 (Khanna 2000; Ruggieri and Plaia 2012; Swamee and Tyagi 1999). However, the optimal choice of ρ value remains an open scientific concern. Hu et al. (2015) compared the mean and standard deviations of AAQI/AQI ratios by using four different ρ values (i.e., 1.5, 2.0, 2.5, and 3.0) and found that the ratios exhibit small variations in the changes of ρ , and the value of $\rho = 2$. Thus, in this study, we also selected 2 as the value of ρ . As presented in Table 1, in comparison with the AQI, the AAQI was converted into the same scale of 0–500 and health categories (Motesaddi et al. 2017).

Table 1 Classification of the AAQI and the corresponding health risks

AAQI	Color	Health categories
0–100		Good–moderate
101–150		Unhealthy for sensitive groups
151–200		Unhealthy
200–300		Very unhealthy
300–500		Hazardous

Aggregate risk index (ARI)

To effectively reflect the human health impacts of multiple air contaminants and further consider the exposure–response relationships between various air pollutants and health risks, Cairncross et al. (2007) proposed an ARI based on the relative risks of increased daily mortality related to the exposure to common air pollutants. According to the definition, the total risk of human health associated with several air pollutants is the sum of the risks caused by the exposure of each air pollutant, as expressed in the following:

$$ARI = \sum_{i=1}^n PSI_i = \sum_{i=1}^n a_i \times C_i, \quad (4)$$

where PSI_i is the individual contribution of the contaminants to the total health risks, C_i is the measured concentration of the pollutants, and a_i is a coefficient proportional to the incremental risk values. Studies have found that the relative risk (RR) value of PM_{10} is significant, and constant $a_{PM_{10}}$ is determined by the health endpoints (Pyta 2008; Sicard et al. 2011). The health breakpoint value between the “good” and “moderate” categories (WHO 2001) for PM_{10} is $50 \mu\text{g}/\text{m}^3$ (Table S1). At the 24-h mean PM_{10} concentration of $50 \mu\text{g}/\text{m}^3$, the relative risk is 1.014 ($RR_{PM_{10}} = 1.014$) (Sicard et al. 2011). Thus, according to its risk subindex value (Table S2), the constant of $a_{PM_{10}}$ can be calculated by Eq. (4) at this exposure level. For other pollutants, a_i is calculated as follows:

$$a_i = \frac{a_{PM_{10}} \times (RR_i - 1)}{RR_{PM_{10}} - 1}, \quad (5)$$

where the concept of the relative risk of the mortality for each pollutant (RR_i) is adopted and given as follows:

$$RR_i = \exp[\beta_i(C_i - C_0)], \quad C_i > C_0, \quad (6)$$

where β_i is the exposure–response coefficient that represents the excess health risks associated with an increase in a per-unit pollutant. For every $1 \mu\text{g}/\text{m}^3$ increase, the β values of $PM_{2.5}$, SO_2 , NO_2 , and O_3 are 0.032%, 0.081%, 0.13%, and 0.048%, respectively, and for every $1 \text{mg}/\text{m}^3$ increase in CO, the β value is 3.7% (Shang et al. 2013). C_0 is the limit concentration, which refers to the threshold values of CAAQS Grade

II in this study. When C_i is lower than C_0 , no obvious excessive effects on human health are observed (i.e., $RR_i = 1$).

Results

Characteristics of air pollution in Shanxi

The average annual concentrations of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , O_3 , and CO in Shanxi Province in 2017 were $59 \mu\text{g}/\text{m}^3$, $109 \mu\text{g}/\text{m}^3$, $56 \mu\text{g}/\text{m}^3$, $42 \mu\text{g}/\text{m}^3$, $186 \mu\text{g}/\text{m}^3$, and $3 \text{mg}/\text{m}^3$, respectively (Table 2). The SO_2 , CO, and NO_2 concentrations reached or approached the upper limit of Grade II, and the concentrations of $PM_{2.5}$, PM_{10} , and O_3 obviously exceeded the standard.

In 2017, TY, YQ, CZ, JC, JZ, and LF were the most PM-polluted regions (including $PM_{2.5}$ and PM_{10}), and they were listed as the first batch of “4 + 2” cities for the total coal consumption control in Shanxi (Department of Ecology and Environment of Shanxi Province 2017). Only DT met the CAAQS Grade II standard for $PM_{2.5}$ and slightly exceeded that of PM_{10} in 2017. The highest levels of $PM_{2.5}$ and PM_{10} were $79 \mu\text{g}/\text{m}^3$ in LL and $131 \mu\text{g}/\text{m}^3$ in TY, and the standard-exceeding multiples were nearly 1.26 and 0.87, respectively. In 2016, only 2 out of 11 cities (DT and XZ) met the

concentration standard of SO_2 , but only 3 cities (JZ, LF, and LL) exceeded the standard in 2017, implying the significant improvement in the SO_2 concentration. With regard to NO_2 , O_3 , and CO, the CO concentration remained comparatively low or stable except in JC, YC, and LF. However, the spatial variation in NO_2 and O_3 concentrations displayed an upward trend, and the O_3 concentration increased rapidly, reaching the maximum value of $218 \mu\text{g}/\text{m}^3$ in JC.

Figure 2a shows the days when the standard of ambient air quality (i.e., the concentrations of six pollutants included in the evaluation and satisfied the air quality standard) was reached in each city. In 2017, the average number of days with air quality standard in 11 prefecture-level cities in Shanxi was 200, indicating a 10.8% decrease compared with the number in 2016 (249 days). The average numbers of days with air quality standards in DT, LL, SZ, and XZ were 301, 245, 242, and 213, respectively, which were higher than the provincial average. The number of days in LL, YC, JC and TY decreased dramatically from 244, 252, 237, and 232 in 2016 to 128, 161, 166, and 176, respectively, which was far below the average, and the air quality continues to deteriorate. Although the air pollution in LF and YC remained the most predominant and the maximum number of days of severe pollution ($AQI > 200$) exceeded 30 days, the number of days with severe pollution in each city declined.

Table 2 Annual average concentrations of six principal air pollutants in 11 cities of Shanxi Province in 2016 and 2017, respectively

City	Description	$PM_{2.5}$ ($\mu\text{g}/\text{m}^3$)		PM_{10} ($\mu\text{g}/\text{m}^3$)		SO_2 ($\mu\text{g}/\text{m}^3$)		NO_2 ($\mu\text{g}/\text{m}^3$)		O_3 ($\mu\text{g}/\text{m}^3$)		CO ($\mu\text{g}/\text{m}^3$)	
		2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
TY	Taiyuan	66	65	125	131	68	54	46	54	140	185	3.3	2.5
DT	Datong	37	36	78	73	48	44	29	32	134	154	2.7	3
YQ	Yangquan	63	61	131	116	62	49	48	48	168	198	2.7	2.5
CZ	Changzhi	69	60	114	103	61	43	40	41	155	188	3.7	3.1
JC	Jincheng	62	62	111	117	70	47	40	45	128	218	4.1	4.3
SZ	Shuozhou	57	48	97	99	67	46	33	34	160	168	2	1.8
JZ	Jinzhong	62	59	109	112	88	84	36	44	142	190	3.1	2.8
YC	Yuncheng	65	69	108	116	67	51	36	35	110	205	4	4
XZ	Xinzhou	56	58	103	102	49	49	39	43	138	181	3.5	2.8
LF	Linfen	74	79	120	122	83	79	34	37	136	214	5	4.1
LL	Lvliang	49	55	98	112	62	68	25	46	106	150	3.1	2.6
Average		60	59	109	109	66	56	37	42	138	186	3.4	3
CAAQS Grade II		35		70		60		40		160		4	

The Grade II standard value refers to the Ambient Air Quality Standard of China (CAAQS) (GB 3095-2012)

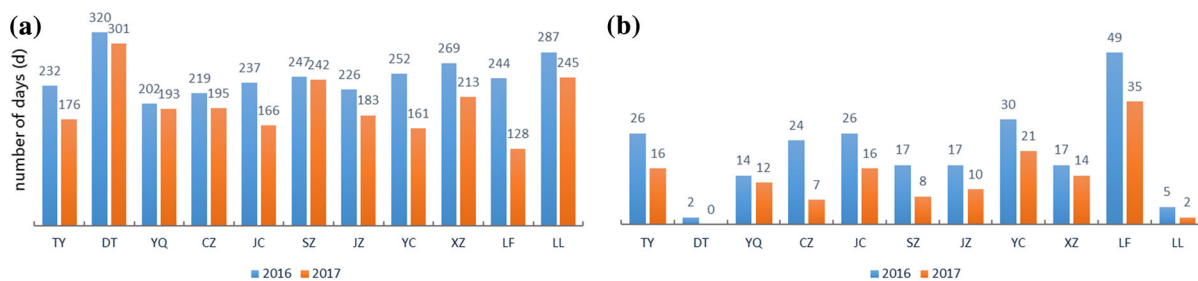


Fig. 2 Number of days with **a** air quality standard and **b** severe pollution in 11 cities of Shanxi in 2016 and 2017

The provincial average was 13 days, which represented a 1.9% decrease compared with the rate in 2016, as presented in Fig. 2b, especially in DT and LL, which had average numbers of days of 0 and 2, respectively.

To reflect the overall contamination degree of air pollution in Shanxi, we presented the comprehensive pollution index values in Fig. 3 and observed that the air pollution degree in the province had aggravated over the past 2 years. In 2017, the comprehensive index ranged from 5.31 to 8.60, and the cities could be sorted from high to low as follows: LF > JC > TY > JZ > YC > YQ > LL > CZ > XZ > SZ > DT.

Moreover, the air pollution in southern Shanxi was more severe than that in other areas. According to the classification of the comprehensive pollution index (Table S3), the pollution degree in all cities was between moderate and severe. The synthetic index of SZ, CZ, and YQ decreased in 2017 compared with that in 2016, whereas those in the eight other cities

increased and their air quality deteriorated. LF was the only city with heavily contaminated air, and its comprehensive index value exceeded that of the eight cities in 2016 and 2017. Furthermore, as shown in Fig. S1, PM was the largest contributor to the comprehensive index, accounting for nearly half of the total value. By contrast, SO₂ ranked second, especially in LF and JZ. The effects of NO₂ and O₃ on air quality also increased.

Health risk assessment

AAQI

Figure 4 presents the spatial distribution of the average AAQI categories for Shanxi Province in 2016 and 2017. Generally, all people in 11 cities were exposed to “polluted” air (AAQI > 100). In 2016, only DT was categorized as “unhealthy for sensitive groups” (100 < AAQI < 150), and other cities were mostly under moderate pollution that was unhealthy (150 < AAQI < 200). However, LF had serious pollution (200 < AAQI < 300). In 2017, the health risks further increased, and their AAQI was higher than 150 in all the cities. The lowest AAQI (156.83) still occurred in DT, and people in 6 out of 11 cities (TY, YQ, JZ, LF, YC, and JC) lived with “very unhealthy” air (200 < AAQI < 300), which would cause certain symptoms even among healthy persons.

ARI

In this study, ARI was applied to integrate the mortality effects of all air contaminants on human health, and the spatial distribution of ARI values in Shanxi is shown in Fig. 5. The spatial distribution of high ARI values showed similar changes in the distribution patterns of previous evaluation results.

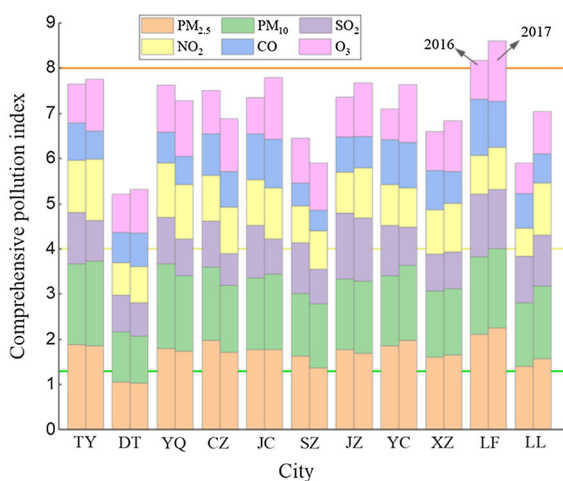


Fig. 3 Distribution of comprehensive air pollution index in 11 cities in 2016 and 2017

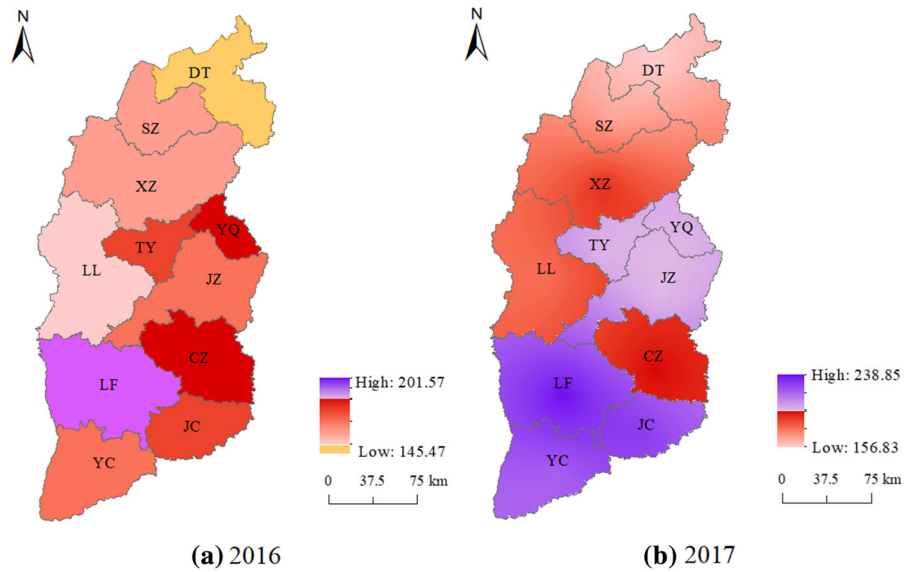


Fig. 4 Spatial distribution of the average AAQI categories for Shanxi in 2016 and 2017

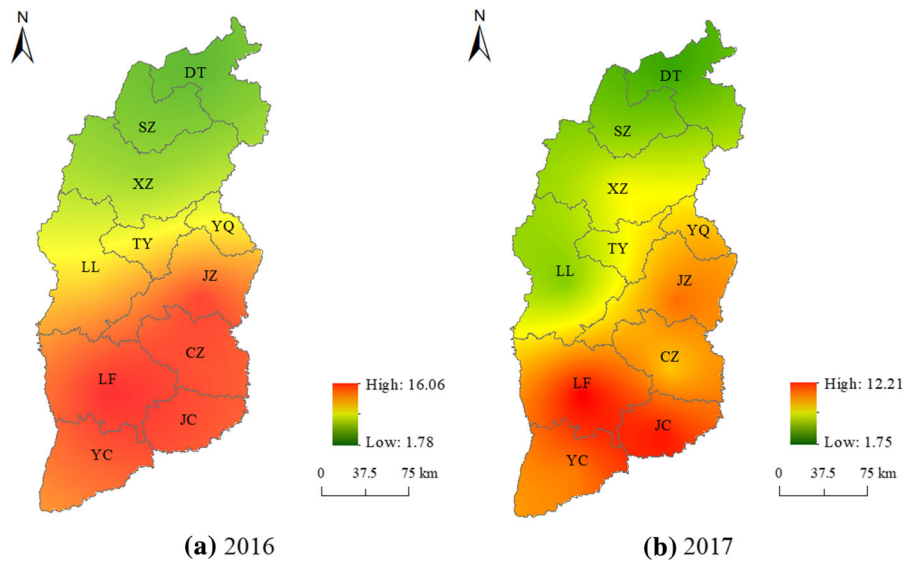


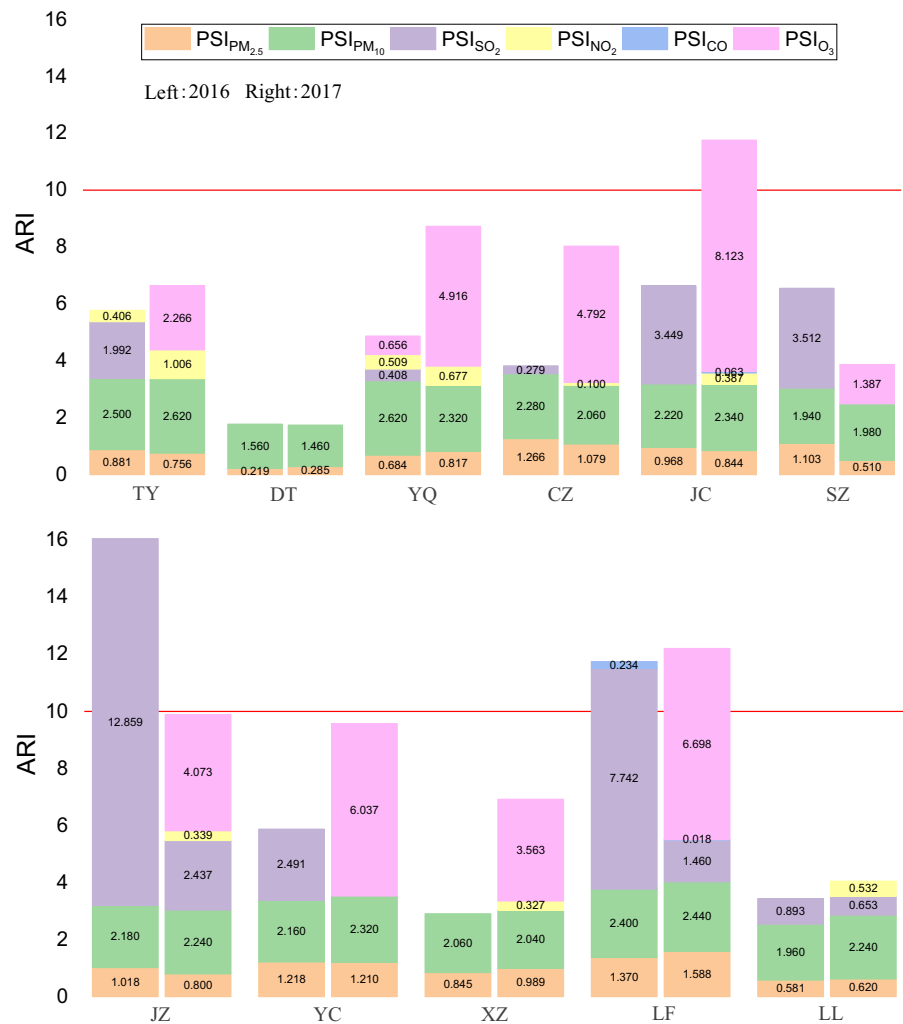
Fig. 5 Spatial distribution of average ARI values of 11 cities in **a** 2016 and **b** 2017

This result indicated that the southern part of Shanxi was exposed to a high health risk of mortality. However, the health risk level mortality rate in 2017 decreased compared with that in 2016 at a provincial scale.

The impact of air pollution on human health is due to the exposure to multiple air pollutants, so Fig. 6 further describes the ARI values for each pollutant in 11 cities in 2016 and 2017. The data might provide

insights into the major contributors to the health problems. In JC, JZ, and LF, the ARI values are greater than 10, which corresponds to the highest health risk in these areas (Sicard et al. 2011). People were the most easily exposed to PM among the various air pollutants studied. Notably, in 2016, some cities, such as TY, JC, SZ, JZ, YC, and LF, exhibited very high-risk subindices of SO₂ due to the high concentration of this pollutant; in JZ and LF, the subindices reached

Fig. 6 Contribution of each pollutant to the total health risks in cities in 2016 and 2017



12.86 and 7.74, respectively. Fortunately, SO₂ was effectively controlled in 2017. Moreover, O₃ poses a significant effect on human health. In 2017, the contribution of this pollutant to the total health risks in JC, YC, and LF was approximately between 6 and 8, indicating a high threat.

Discussion

Overview of air contamination in Shanxi

Overall, the air quality in Shanxi has not improved remarkably in the past 2 years. According to the Ministry of Ecology and Environment of the People's Republic of China (2017), the ambient air quality in

TY, the capital city of Shanxi, ranked fifth to the last among 74 key cities in China. Meanwhile, in the first quarter, the air quality of four-channel cities (i.e., CZ, TY, JC, and YQ) in the Beijing–Tianjin–Hebei region and its surrounding “2 + 26” cities ranked 7th, 9th, 13th, and 15th from the bottom, respectively, and their comprehensive index was greater than 8 (Table S4). These findings emphasized the severe air pollution in Shanxi. Among the common pollutants, PM had the most serious pollution level, which might be partially attributed to the coal-dominated industrial energy consumption structure in Shanxi, as discussed in Sects. “Industrial structure evolution” and “Energy consumption structure”. The influence of extra coal consumption for winter civil boilers in northern regions is also an important source (Li et al. 2008).

Although SO₂ pollution has been alleviated, severe pollution still exists in some areas, especially JZ and LF, which seem to be the districts with the highest SO₂ density; LF also exhibits the smoke lock-in incident of a high SO₂ concentration that severely exceeds the standard level. Large coal-fired power plants are regarded as the main emission sources of SO₂ in Shanxi (Department of Environmental Protection of Shanxi 2005). Furthermore, the significant improvement in SO₂ is probably attributed to the wide application of flue gas desulfurization devices and the introduction of tighter discharge standards (Song and Yang 2014; Xue et al. 2013). To the best of our knowledge, SO₂ is a respiratory stimulant and bronchoconstrictor, which may increase the mortality risk even under short-term exposure, thereby causing crucial effects on human health (Chen et al. 2007, Chen et al. 2012; Tunnicliffe et al. 2001). Thus, stringent measures should be implemented to reduce the high SO₂ emissions still existing in Shanxi and prevent them from rebounding in areas such as LL and JZ. In addition, the influence of NO₂ and O₃ on air quality should not be overlooked because their concentrations have also increased. Previous studies indicated that power plants, as well as fossil fuel combustion, vehicle emissions, biomass open burning, and biogenic sources are mostly the major contributors to O₃–NO_x in Shanxi (Liang et al. 1998; Wang et al. 2019). These findings also implied that air contamination in major cities has changed from single coal-burning to vehicle-exhaust-related pollution or a combination of both, but coal smoke pollution is the dominant type (Li 2017).

Health risks through exposure to air contaminants

The mean AAQI values in 11 cities were higher than 100, suggesting that all people in Shanxi were exposed to polluted air. In fact, the local government has taken typical measures to enhance air quality, including dispatch orders on heavily polluted weather, key projects for clean heating in winter, staggered production of industrial enterprises, and relocation of heavy-polluting companies (Department of Environmental Protection of Shanxi 2017; Sun 2018). The results underscored that the high health risks caused by air pollution in Shanxi have accumulated over many years, and these risks cannot be successfully addressed in a single day. According to ARI values, the mortality

risk in 2017 was lower than that in 2016, which might confirm that government policies and effective environmental protection could translate into meaningful health benefits (Tang et al. 2014). Overall, the health risks in the southern cities of Shanxi were higher than those in the other cities, and PM exerted the greatest adverse effects on human health; these observations were consistent with previous results and epidemiological reports (Pope and Dockery 2006). The leading coal producers in Shanxi are southern cities, such as LF, where economic development is driven by the extensive coal mining industry, coupled with the basin topographical condition that limits diffusion (Gu and Shi 2019). It is worth mentioning that the risks caused by O₃ have gradually emerged. Exposure to a high O₃ concentration may have acute health effects, such as cardiovascular and respiratory diseases (Li et al. 2015; Wang et al. 2019). Therefore, future strategies on controlling and managing air pollution should pay close attention to O₃.

Source analysis based on local socioeconomic development

Urbanization

Shanxi has experienced tremendous economic growth and achieved continuous improvement on people's standard of living for over nearly two decades (Table 3). Rapid urbanization has occurred with economic growth, and the rate of urban population growth increased from 30.41% in 1996 to 57.34% in 2017 with an average annual growth rate of 1.28%. At the same time, the province has shown consistent demand trends in transportation. The number of civil motor vehicles has increased nearly 15-fold since 1996, i.e., it increased from more than 38 million in 1996 to 589.61 million in 2017. Furthermore, the rapid urban expansion with an inconsistent overall planning pace caused heavily polluted areas (such as industrial and mining enterprises) that used to be in the periphery of an urban area to gather close to the edge of a city or even be surrounded by it (Li 2017). Population accumulation and industrial agglomeration also create environmental hazards (Li et al. 2012). Some studies have found that the highest concentration of air pollutants is detected in the Beijing–Tianjin–Hebei–Shandong–Shanxi–Henan regions, which have local characteristics of high population density, urban

Table 3 Urban development situation of Shanxi from 1996 to 2017

Year	GDP (100 million yuan)	Household consumption expenditure (yuan/person)	Urbanization rate (%)	Population (10,000 persons)	Civil vehicles (unit)
1996	1292.11	1880	30.41	3109.26	384,126
2000	1845.72	2037	35.88	3247.80	550,148
2005	4246.91	4172	42.11	3355.21	1,074,350
2010	9240.80	8159	48.05	3574.11	2,478,905
2015	12,793.44	14,364	55.03	3664.12	4,665,842
2017	15,528.42	18,132	57.34	3702.35	5,896,070

transportation, economic growth, and rapid urban expansion (Lin et al. 2014; Wang et al. 2014a; Zhou et al. 2017).

Industrial structure evolution

For 22 years, Shanxi's GDP has grown significantly; for instance, it increased from 1292.11 (100 million yuan) in 1996 to 15,528.42 (100 million yuan) in 2017 (Table 3). As shown in Fig. 7, the proportion of the primary industry was stable even though it slightly declined, whereas the proportions of secondary and tertiary industries were likely to vary symmetrically. From 1996 to 2011, the annual variation in the secondary and tertiary industries showed a wide fluctuation. However, the secondary industry was more dominant than the tertiary industry. After 2002, the gap between the two industries broadened continually and peaked in 2011. During this period, the industrial efficiency of the secondary industry was

mainly driven by industrial development (Table S5). The crucial economic pillar estates were centralized in coal, electricity, metallurgy, chemicals, machinery, and coking, which were high-energy consumption and high-pollutant emitting enterprises; consequently, they caused tremendous environmental pressure. Subsequently, the proportion of the primary industry declined, whereas the proportion of the tertiary industry increased. Until 2015, the proportion of the tertiary industry (53.2%) exceeded that of the secondary industry (41.1%) for the first time, thereby forming a “321” industrial pattern. In 2017, the proportion of the three industries evolved to 4.6%, 43.7%, and 51.7%, respectively, with the tertiary industry occupying a leading place. This result indicated that the industrial structure in Shanxi was continually upgraded, resulting in advancement and rationalization. However, this structure did not reach the optimal condition and needed further restructuring. In addition, Shanxi as a province characterized by heavy industrialization prioritizes the development of resource-intensive industries (Du et al. 2019).

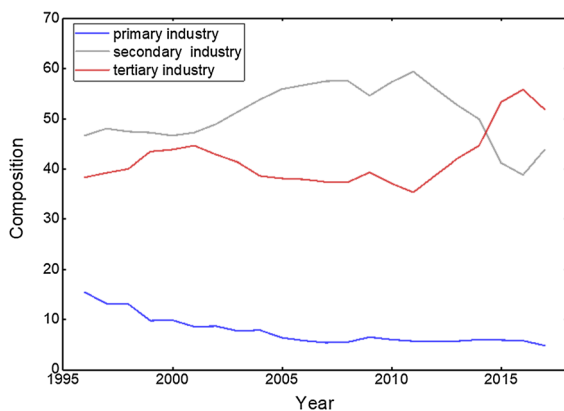


Fig. 7 Three-industry composition of gross domestic product in major years (from 1996 to 2017)

Energy consumption structure

As shown in Tables 4 and S6, energy consumption involves a variety of fields from industries to residential living. The total energy consumption increased from 68.0383 (10,000 tons of SCE) in 1996 to 200.5723 (10,000 tons of SCE) in 2017 and showed a sharp increasing trend yearly. The major source of energy was still coal, followed by electricity and coke. With regard to usage, heavy industries such as coal mining, metallurgy, chemical, electricity, petroleum, and coking were the main direction. The energy consumption structure in Shanxi was mainly

Table 4 Energy product usage distribution in Shanxi from 1996 to 2017

Year	Energy (10,000 tons of SCE)		Coal (10,000 tons)				Electricity (100 million kwh)				Coke (10,000 tons)				
	Total	Light industry	Heavy industry		Transport		Residential		Light industry	Heavy industry		Transport		Residential	
			Light industry	Heavy industry	Light industry	Heavy industry	Light industry	Heavy industry		Light industry	Heavy industry	Light industry	Heavy industry	Light industry	Heavy industry
1996	6803.83	385.92	12,743.09	50.50	614.80	25.45	342.35	12.72	31.71	62.35	966.35	1.85	128.60		
2000	6727.70	406.28	11,362.64	61.60	610.00	26.89	388.54	14.76	39.23	66.00	944.30	2.00	132.60		
2005	12,311.92	198.00	21,261.90	68.00	865.70	32.37	701.22	31.07	71.82	0.51	2039.99	–	25.00		
2010	16,808.03	157.84	26,193.54	54.94	1082.46	28.43	1161.58	45.63	105.48	0.24	2586.48	–	1.18		
2015	19,383.45	439.36	27,390.13	69.26	1152.29	39.64	1316.84	54.31	223.56	0.02	2082.49	–	–		
2017	20,057.23	213.78	30,291.84	75.38	1218.8	34.89	1510.28	66.76	272.86	0.22	1955.23	–	–		
Year	Gasoline (10,000 tons)				Diesel oil (10,000 tons)										
	Light industry	Heavy industry		Transport	Residential		Light industry	Heavy industry		Transport	Residential				
		Light industry	Heavy industry		Light industry	Heavy industry		Light industry	Heavy industry		Light industry	Heavy industry			
1996	6.78	27.10	35.73	8.30	0.93	18.41	18.60	1.4							
2000	5.00	24.54	36.80	8.05	0.82	21.92	28.60	1.54							
2005	0.94	14.89	46.01	15.42	0.59	55.08	148.30	6.46							
2010	1.28	16.12	103.15	34.31	0.34	55.12	324.13	4.53							
2015	0.76	9.26	108.85	50.05	0.39	79.78	375.43	10.85							
2017	0.33	28.39	115.53	61.16	0.42	86.91	389.76	1.82							

composed of energy sources and raw materials, and it was highly dependent on coal, with typical characteristics of primary and resource-based (Han 2019). According to the preceding analysis, it was comparable with issues on the oversized heavy-industry proportion and high-energy consumption in the industrial structure. Since 2005, the consumption of coal in residents' living has continued to increase most likely because of the long period of coal heating in winter. Furthermore, with the great increase in the number of vehicles since 2010, the consumption of gasoline and diesel in transportation has also increased and gradually become a key factor in environmental pollution.

Conclusions and suggestions

This study discussed the characteristics of air pollution, assessed the corresponding human health risks by using AAQI and ARI, and analyzed the potential sources based on the local development in the 11 prefecture-level cities of Shanxi Province. The main conclusions were as follows:

1. The average concentrations of six criteria air pollutants are at a high level. PM is found as the major pollutant whose concentration exceeds the standard and needs to be further controlled. Although the SO₂ concentration has dropped strikingly, it has to be prevented from rebounding. Moreover, NO₂ and O₃ contamination has gradually aggravated, and the overall air quality in Shanxi is deteriorating. Areas with serious air pollution are mainly located in TY, YQ, CZ, JC, JZ, and LF, which are the key areas where governments should strengthen the comprehensive control and supervision of air pollution in the future.
2. The risk assessment results reveal that the health risks in southern Shanxi are higher than those in the northern part. According to the AAQI, the health risks in 2017 further increased compared with that in 2016. All cities were mostly above the moderate level, which were severely polluted. However, the ARI is related to mortality; the overall trend of health risks and the contribution of each pollutant, especially SO₂, have decreased. This discovery demonstrates that pollution abatement countermeasures have certain effects, but PM is still a major contributor to health problems, and the risks caused by O₃ have gradually increased. Similarly, the next treatment target should focus on changes in O₃ during the strengthening of the control of PM.
3. The severe air pollution in Shanxi depends less on natural elements than on the accumulative effects of anthropogenic activities. The rapid urbanization in Shanxi and its industrial structure with an oversized heavy-industry proportion and a high-energy consumption structure has resulted in inefficient resource utilization and environmental problems. Coupled with the rapid development of the high-tech industry and white-hot market competition in Shanxi, coal-fired pillar industries have begun to suffer a dramatic decline (Zhang 2000). Therefore, Shanxi needs to exert great efforts to speeding up the “new” urbanization process (Lu and Yu 2018) and developing clean energy sources (such as nuclear power and wind power), high-tech industries, and modern services with high quality and efficiency to meet the needs of the optimal industrial and energy consumption structure. Green growth path and improving energy efficiency are essential for sustainable development (Sun et al. 2019). The results also show that air pollution is the result of the combined effects of industrial production, urban construction, residents' lifestyle, and other factors. Indeed, if air pollution treatment plans were limited to only a single industry or field, no remarkable achievements would be made; as such, local governments should establish a multi-domain cooperative control regime to create a healthy balance (Sun et al. 2020). Generally, 2016 was the first year of the 13th Five-Year Plan, and 2017 was the key year for the Prevention and Control of Atmospheric Pollution (Zhang 2018). Thus, building a green city in Shanxi will take time.

This study has several limitations, and further research is needed. For example, more studies on health damage related to the interaction between air pollutants should be conducted. Socioeconomic development and atmospheric environment systems are complex. We will consider more factors and explore the causal coupling relationship between systems in depth by establishing detailed models and combining

qualitative and quantitative evaluation methods. In addition, future research should identify the principal pollution areas and key drivers at a county or pixel level to promote urban green development.

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