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Climate and air pollution alter incidence of tuberculosis in Beijing, China

Chun Yan Zhang, BS [a], Ang Zhang, MD [b,*]

[a] Respiratory and Critical Care Medicine Ward 1, Luohe Central Hospital, Luohe, Henan, China
[b] International Joint Research Laboratory of Global Change Ecology, School of Life Sciences, Henan University, Kaifeng, Henan, China

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Purpose: This study evaluated the possible association between climate and environment and the incidence of tuberculosis and determined the characteristics of tuberculosis in different climatic and air pollution conditions.
Methods: Data on tuberculosis incidence, climate (i.e., precipitation, atmospheric pressure, relative humidity, temperature, and wind speed), and air quality (inhalable particulate matter, sulfur dioxide, and nitrogen dioxide concentrations) in Beijing from 2004 to 2016 were collected and systematically analyzed based on a structural equation model.
Results: The tuberculosis incidence was negatively correlated with the concentration of inhalable particulate matter, sulfur dioxide, or nitrogen dioxide. Precipitation, atmospheric pressure, and relative humidity had negative effects on tuberculosis incidence by indirectly lowering the concentrations of inhalable particulate matter and sulfur dioxide. By contrast, wind speed had a significant positive correlation with the incidence of tuberculosis. Temperature and wind speed had positive effects on tuberculosis incidence by improving the concentrations of inhalable particulate matter and sulfur dioxide.
Conclusions: Climate and air quality are potential regulators of the incidence of tuberculosis. The improved air quality contributes to the decline of incidence of tuberculosis in Beijing. The impact of climatic indicators on the incidence of tuberculosis was mainly regulated by the environment. Further studies are needed to formulate preventive and regulatory strategies for tuberculosis based on different climatic and air quality conditions.

Introduction

As a chronic infectious disease, tuberculosis has long threatened human health and is a major public health issue of global concern [1]. Tuberculosis continues to be at the forefront as a class A and B infectious disease, and approximately 1 million tuberculosis cases are reported each year in China [2]. According to recent statistics, tuberculosis has become the second most prevalent infectious disease in Beijing (after dysentery). As the political and economic center of China, Beijing is confronted with great challenges in the prevention and treatment of tuberculosis. The currently available approach aims to control tuberculosis and to improve its treatment because tuberculosis is highly infectious, nonattenuable, and highly drug resistant, especially in certain climates and environments [2,3].

Currently, the impact of climate on the incidence of various diseases, especially infectious diseases, is being actively investigated [4]. Previous studies have reported that precipitation, relative humidity, atmospheric pressure, and temperature are negatively correlated with the incidence of tuberculosis [5–7]. However, wind speed is positively correlated with the incidence of tuberculosis [8]. Moreover, the deterioration of urban air pollution, including increased PM_{10} (particulate matter smaller than 10 mm in diameter) [9], sulfur dioxide (SO_2), and nitrogen dioxide (NO_2), directly endangers human health by affecting the incidence of epidemic diseases, such as lung damage and tuberculosis infection [10,11]. A previous study has indicated that there was a significant positive correlation between the duration and the concentration of pollution and the risk of lung disease [12], and seasonal changes in the

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* Corresponding author. International Joint Research Laboratory of Global Change Ecology, School of Life Sciences, Henan University, Kaifeng 475004, Henan, China. Tel.: 15226092501.
E-mail address: angzhang_henu@163.com (A. Zhang).

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concentrations of various pollutants, which was consistent with changes in the population, were positively correlated with various respiratory diseases [13,14]. However, the association between the incidence of tuberculosis incidence and common climatic and environmental changes is still uncertain, which is partly due to the complex interactions between climate and environment in time and space. For instance, there is no consensus on the effects of the climate and environment on the incidence and spread of tuberculosis because there are differences in the natural environment, meteorological types, population immunity, and other social factors in different regions [15]. Therefore, further research on the internal regulatable mechanism of climate change and environment to the incidence of tuberculosis has a positive effect on understanding the incidence of tuberculosis. The active response to climate change and changes in urban environments may bring about new approaches to decrease the incidence of tuberculosis [16].

As the capital of China, studies on tuberculosis prevention and control in Beijing can be used as reference guides by other cities. To investigate climate and environment trends and the incidence of tuberculosis in Beijing, we opted to define the main climatic and air quality indicators affecting the epidemic of tuberculosis. The annual mean climate and atmospheric pollution data in Beijing from 2004 to 2016 and the data on the incidence of tuberculosis in the same period were analyzed, and the relationship between the two was studied to provide a management protocol for the effective control of tuberculosis in this city.

Materials and methods

Data source

Data on the incidence of tuberculosis in Beijing from 2004 to 2016 were obtained from "China's Health and Family Planning Statistical Yearbook" [17]. Data on the climate (i.e., annual mean atmospheric pressures and wind speeds) were obtained from "China's Meteorological Yearbook" [18] and two journal papers [19,20]. Data on the monthly mean precipitation and relative humidity were also collected from 2003 to 2016. Data on the environment were obtained from "China's Environmental Statistics Yearbook" and "China's Statistical Yearbook" [21,22]. The annual mean concentrations of inhalable particulate matter (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and air pollution were also collected from 2004 to 2016.

Statistical analysis

The annual mean precipitation and relative humidity were calculated using the monthly mean data from 12 months. Interannual regression analysis was carried out to identify changes in the climate, environment, and incidence of tuberculosis in the 13-year period. Regression analysis was carried out to identify relationships between the incidence of tuberculosis and the eight climate and air quality indicators. All data were tested for normality and homogeneity of error variance before analysis of variance. The data were analyzed using SAS V8 software. Principal component analysis was carried out to determine the contribution of the climate and air quality indicators on the incidence of tuberculosis. Multivariate statistical analysis was carried out to determine the relationships among the response variables using CANOCO 4.5 software [23].

The structural equation model (SEM) was used to examine the relationship between the climate and air quality indicators and the incidence of tuberculosis [24]. The directly observed variables (path model) were used to eliminate the latent variable's interference to the model [25]. The initial model was based on results from existing studies on the effects of the climate and environment on the incidence of tuberculosis. Before entering all variables into the model, the data were normalized to conform to a normal distribution. The initial structural equation model included direct paths from the eight climate and air quality indicators to the incidence of tuberculosis, and direct paths from five climate indicators to three air quality indicators were included in the model. We focused on the paths from the climate and air quality indicators to the incidence of tuberculosis because these paths represented the effects of the climate or the environment on the incidence of tuberculosis. The lack of data on air pollution in the initial model was due to inconsistent standards for this indicator. The χ^2 test was used to determine whether the fit between the model and the data was adequate ($P > .05$) in the final model. Each path coefficient was divided by its standard error to assess the significance. The resulting values followed a *t* distribution, which allowed *P*-values to be calculated. The coefficients with *P*-values < .05 were considered significant in this model. Thicker lines indicated stronger correlations, and the dotted lines indicated nonsignificant paths. Statistical analysis was carried out with SPSS Amos 23.0 software.

Result

The change of climate, environment, and tuberculosis incidence in Beijing from 2004 to 2016

There were significant interannual differences in the mean precipitation, relative humidity, atmospheric pressure, temperature, and wind speed, but there was no interannual trend over the 13-year period (Fig. 1A–E). Only the mean wind speed decreased significantly from 2004 to 2016 ($R^2 = 0.57$, $P < .01$), and the mean precipitation increased moderately ($R^2 = 0.22$, $P < .1$). Furthermore, the mean air quality (annual mean concentrations of PM_{10}, SO_2, and NO_2 concentrations) increased significantly from 2004 to 2016 (Fig. 1F–H), and the number of high air pollution days was higher in 2013–2016 than that in 2004–2012 due to the implementation of the new ambient air quality standards (GB3095-2012) in 2013 (Fig. 1I). Although there was no interannual trend in the number of high air pollution days, the actual air pollution declined significantly from 2004 to 2016. The mean annual incidence of tuberculosis was 58.29/100,0000 in Beijing over the 13-year period (Fig. 1J), and the incidence of tuberculosis showed a downward trend, especially after 2008.

The influence of climate and environment on the incidence of tuberculosis

Correlation regression analysis was carried out between climate and air quality indicators and the incidence of tuberculosis. There was a linear correlation between precipitation and the incidence of tuberculosis ($r^2 = 0.24$, $P < .1$, Fig. 2A). However, there was no correlation between relative humidity, temperature, or atmospheric pressure and the incidence of tuberculosis (Fig. 2B–D). There was a significant positive linear correlation between wind speed and the incidence of tuberculosis ($r^2 = 0.42$, $P < .05$, Fig. 2E), and there was a significant linear correlation between PM_{10} ($r^2 = 0.58$, $P < .01$, Fig. 2F) and SO_2 ($r^2 = 0.71$, $P < .001$, Fig. 2G) and the incidence of tuberculosis. Finally, there was a significant positive linear correlation between NO_2 concentration and the incidence of tuberculosis ($r^2 = 0.58$, $P < .01$, Fig. 2H).

Climatic and air quality indicators explained up to 86.86% of the total variability in the incidence of tuberculosis over the 13-year period (principal component analysis, $F = 3.92$, $P = .01$). The length and direction of the vectors representing each individual variable in the diagram show the relevance of the independent variable to the respective tuberculosis incidence and axis. Axes 1

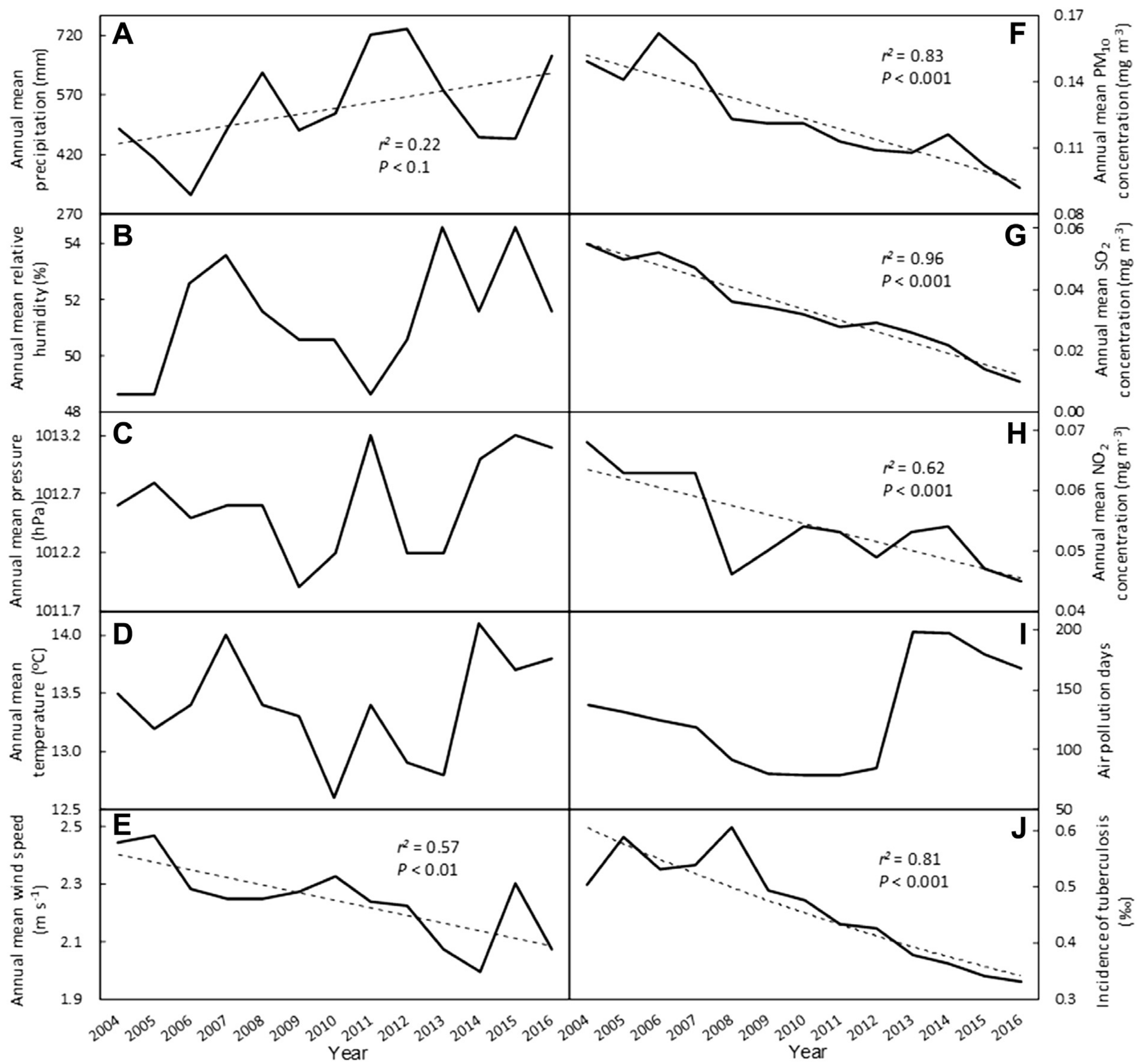

Fig. 1. Annual mean climate (precipitation, A; relative humidity, B; pressure, C; temperature, D; wind speed, E), environment (PM_{10}, F; SO_2, G; NO_2, H; air pollution days, I), and incidence of tuberculosis (J) in Beijing from 2004 to 2016.

and 2 explained 67.02% and 19.84% of the variations in the incidence of tuberculosis, respectively. The concentrations of PM_{10} and SO_2 had the strongest positive correlations with the incidence of tuberculosis (Fig. 3), but precipitation and relative humidity have the most negative impact on the incidence of tuberculosis. In other words, the incidence of tuberculosis was mainly affected by precipitation and relative humidity, although the concentrations of PM_{10} and SO_2 are more closely related to the incidence of tuberculosis.

Regulation mechanism of climate and environment on the incidence of tuberculosis

The fit between the SEM and the data was adequate for the incidence of tuberculosis ($\chi^2 = 10.06$, df = 9, $P = .35$, Fig. 4). This model was accepted because it explained 92.0% of the variations in the incidence of tuberculosis. The number of high air pollution days was not input into the initial model because the data were inconsistent with the standards in the early and late stages of the investigation. The SEM showed that the concentrations of PM_{10} and SO_2 were significantly positively correlated with the incidence of tuberculosis. The annual mean relative humidity and precipitation were significantly negatively correlated with the concentrations of PM_{10}, SO_2, and NO_2. The annual mean pressure was significantly negatively correlated with the concentrations of PM_{10} and SO_2. The annual mean wind speed was significantly positively correlated with the concentrations of PM_{10} and SO_2 and the incidence of tuberculosis. The annual mean temperature was significantly positively correlated with the concentration of PM_{10}. Therefore, the annual mean relative humidity, atmospheric pressure, and precipitation indirectly decreased the incidence of tuberculosis by reducing the concentrations of PM_{10} and SO_2, although the relative humidity, atmospheric pressure, and precipitation had no direct impact on the incidence of tuberculosis. However, the annual mean wind speed significantly directly increased the incidence of tuberculosis and indirectly increased the incidence of tuberculosis by increasing the concentrations of PM_{10} and SO_2. Finally, the annual mean temperature indirectly increased the incidence of tuberculosis by increasing the concentration of PM_{10}.

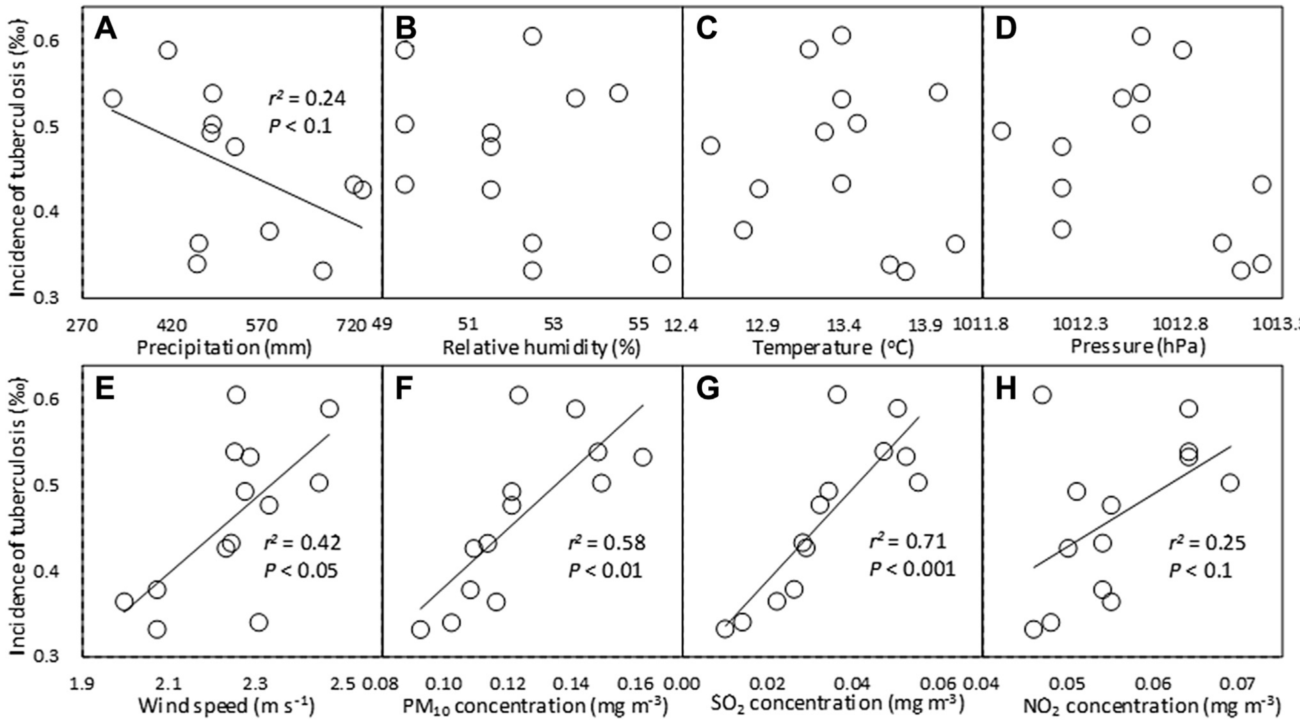

Fig. 2. Dependence of tuberculosis incidence on annual mean climate (precipitation, A; relative humidity, B; temperature, C; pressure, D; wind speed, E) and environment (PM_{10}, F; SO_2, G; NO_2, H) in Beijing from 2004 to 2016.

Discussion

Presently, the prevention and treatment of tuberculosis in China has achieved remarkable results. With the gradual implementation of tuberculosis preventive approaches and the increasing education on the disease, the overall epidemic level, not only in Beijing, shows a downward trend [3,26]. The prevention and treatment of this disease still involves enormous challenges, such as increased drug resistance [27,28], dual infection of tuberculosis and AIDS [29], and increased migrant population [30], although preventive measure has made great progress. Furthermore, urban air quality is also an important potential factor in the contribution of tuberculosis infection. Studies have suggested that tuberculosis bacilli can maintain a longer period of infectivity when they adhere to dust [8]. Air pollution increases the burden on the lungs, reduces the body's immunity, and makes tuberculosis more susceptible to erosion of alveolar macrophages, thereby increasing the chance of tuberculosis infection, although air pollution is not necessarily related to the infection rate of tuberculosis [31–33]. The positive correlation between the concentrations of PM_{10}, SO_2, and NO_2 and the incidence of tuberculosis in our study indicated that the decline of urban air quality is one of the reasons for the increase in the tuberculosis infection rate (Figs. 2F-H and 4). Therefore, our results support those of previous studies, which indicate that the air quality in Beijing has improved significantly in recent years [5]. The improved air quality may be one of the main reasons for the decline in the incidence of tuberculosis in Beijing [6].

The impact of climatic indicators on human infectious diseases requires attention because they can influence the incidence of tuberculosis [7,34]. Different climatic indicators may impact the incidence of tuberculosis differently. It is generally believed that climate change affects the incidence of respiratory diseases mainly by regulating the distribution and external latency of pathogens and affecting human immunity and pathogen transmission [35,36]. However, this research suggests that climatic factors could also affect the incidence of tuberculosis by indirectly regulating urban air quality. Climate is the most important factor affecting the incidence of tuberculosis, mainly because air quality is regulated by climate [37,38]. First, previous studies have shown that precipitation, relative humidity, and atmospheric pressure can significantly inhibit the incidence of tuberculosis [39–41], which supports our opinion, namely, that an increase in precipitation, relative humidity, and atmospheric pressure contributes to reduce the incidence of tuberculosis in Beijing by reducing air pollution. The indirect negative effect of precipitation, relative humidity, and atmospheric pressure

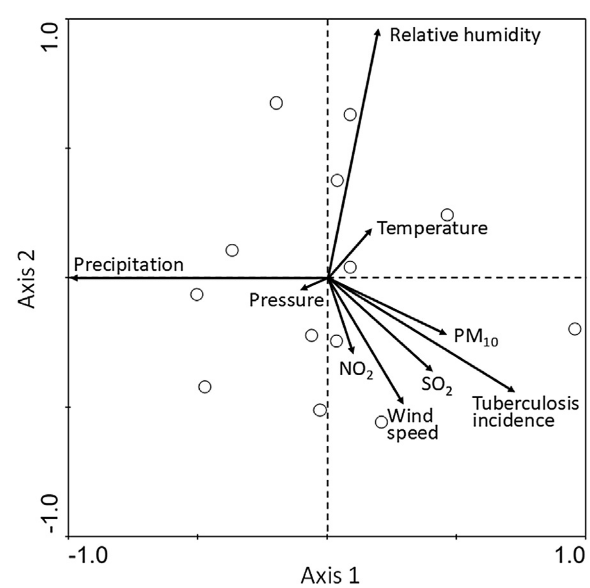

Fig. 3. Principal component analysis (PCA) of climate and environment with incidence of tuberculosis. The circle represents each year during investigated years.

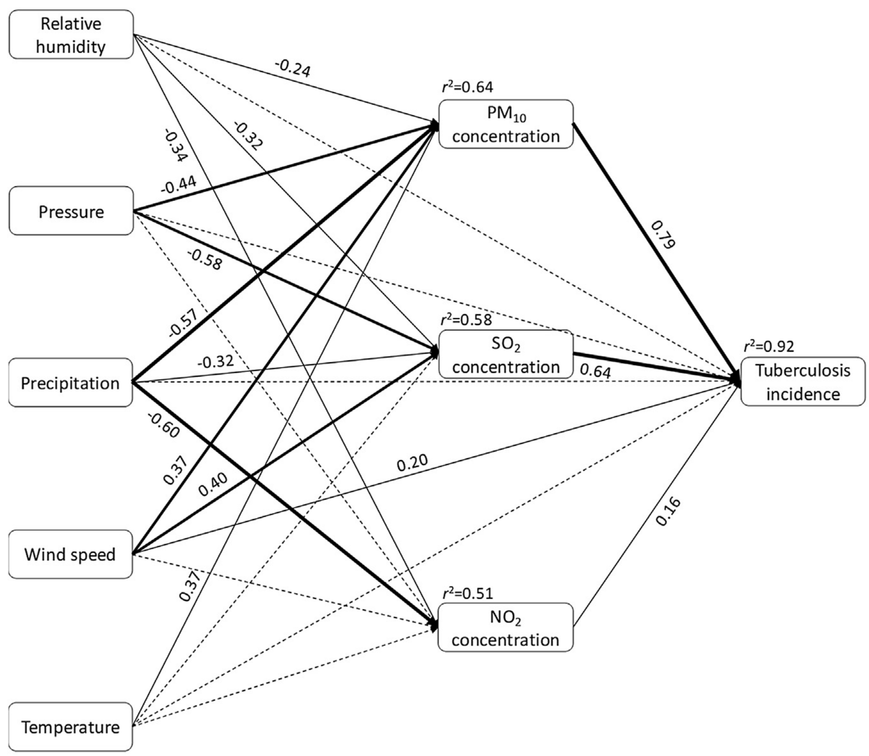

Fig. 4. The structural equation model (SEM) analysis of the regulation mechanism of climate and environment on the incidence of tuberculosis in Beijing.

on the incidence of tuberculosis infection due to the negative correlation between PM_{10}, SO_2 and precipitation, relative humidity, atmospheric pressure in this research (Fig. 4). The increased relative humidity contributed to the condensation and deposition of suspended particulate matter in the atmosphere because the suspended particulate matter in the air is adsorbed by atmospheric water vapor [42]. Drought accelerates the entry of soil particles and increases the surface dust and the PM_{10} pollutant content in the atmosphere, but precipitation has a significant clearance effect on PM_{10} [43,44]. Low-level air rises under low-pressure conditions, and surface pollutants diffuse vertically into the air, resulting in increased air pollution [45]. Therefore, the increase in the relative humidity, atmospheric pressure, and precipitation is conducive to decrease the incidence of tuberculosis in Beijing. Second, other studies have shown that temperature has a positive, negative, or neutral effect on the incidence of tuberculosis [5,14,46,47]. The results of this study suggest that temperature significantly increased the incidence of tuberculosis by indirectly increasing the PM_{10} concentration, which was mainly due to the reduced air quality. Strong vertical turbulence caused by strong atmospheric convection and rising temperature causes surface dust to enter the air, increase the PM_{10} concentration, and decrease the air quality. Third, the results of this study support previous findings that wind speed significantly increases the incidence of tuberculosis [8]. The fast diffusion of the tuberculosis virus and the bacillus may be the main reason that wind speed directly stimulated the incidence of tuberculosis in this study [8]. The peak incidence of tuberculosis is related to the peak of spring monsoon in Beijing [48], which can be used as another evidence to indicate that wind speed is one of the reasons for the increase of tuberculosis incidence. In addition, the increased wind speed may have accelerated the distribution of PM_{10} and SO_2 [42,44,45], which indirectly aggravated the incidence of tuberculosis.

In summary, the discovery and treatment of tuberculosis is not enough to prevent tuberculosis outbreaks. The prevention of tuberculosis should not only focus on blocking the transmission of the tuberculosis but also predict the possibility of an outbreak based on historical laws. Therefore, the monitoring of tuberculosis and attention to climate changes are particularly important for tuberculosis prevention and control. In addition, it is necessary to establish better prevention strategies based on the seasonal and climatic characteristics of tuberculosis infection. Presently, China is committed to establishing a prevention and treatment system that integrates hospitals, disease control centers, and community health care [49,50]. Moreover, the conclusions of this study suggest that we should pay special attention to the impact of climate and environment on tuberculosis by consolidating the existing prevention and control systems. Increasing the urban green area, protecting wetland lake areas, and expanding forest area contribute to stabilizing and improving urban microclimate in Beijing. To provide a better air quality for further reducing the incidence of tuberculosis, industrial and automobile industries should come together to control and reduce industrial dust and waste emissions, adjust industrial structures, optimize energy structures, save energy, and improve energy efficiency by improving the air quality. Finally, improving meteorological and air quality forecasting services can contribute to our understanding of the occurrence and development of tuberculosis and formulate more effective tuberculosis prevention and control strategies.

Conclusion

There is a significant correlation between climate, air quality, and the incidence of tuberculosis. The increased air quality contributes to the reduction of the tuberculosis incidence in Beijing. The impact of climatic indicators on the incidence of tuberculosis was mainly regulated by the environment. The increased precipitation, relative humidity, and atmospheric pressure has a significant inhibitory effect on the incidence of tuberculosis by indirectly reducing the concentration of air pollutants. However, the increased wind speed exacerbates the incidence of tuberculosis infection by strengthening the spread of pathogens and increasing air pollution. It is particularly important to establish preventive and regulatory approaches based on the incidence of tuberculosis in Beijing in light of the various climatic and air quality conditions across different years.

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Authors' contributions: C.Y.Z. provided ideas and wrote the original manuscript. A.Z. collected and analyzed data and reviewed the manuscript. C.Y.Z. and A.Z. equally contributed to this work.

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