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Effects of dust storm events on weekly clinic visits related to pulmonary tuberculosis disease in Minqin, China

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HIGHLIGHTS

• There is a clear link between the population dynamics of PTB and dust storms.
• The onset of PTB epidemics and dust storms occurred in almost the same mean week.
• Particulate matter may be the cause of the PTB outbreak on dust storm days.
• Reduction of the PTB epidemic was linked to improvements in the local environment.

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ABSTRACT

Pulmonary tuberculosis (PTB) is a major public health problem in China. Minqin, a Northwest county of China, has a very high number of annual PTB clinic visits and it is also known for its severe dust storms. The epidemic usually begins in February and ends in July, while the dust storms mainly occur throughout spring and early summer, thereby suggesting that there might be a close link between the causative agent of PTB and dust storms. We investigated the general impact of dust storms on PTB over time by analyzing the variation in weekly clinic visits in Minqin during 2005–2012. We used the Mann–Whitney–Pettitt test and a regression model to determine the seasonal periodicity of PTB and dust storms in a time series, as well as assessing the relationships between meteorological variables and weekly PTB clinic visits. After comparing the number of weekly PTB cases in Gansu province with dust storm events, we detected a clear link between the population dynamics of PTB and climate events, i.e., the onset of epidemics and dust storms (defined by an atmospheric index) occurred in almost the same mean week. Thus, particulate matter might be the cause of PTB outbreaks on dust storm days. It is highly likely that the significant decline in annual clinic visits was closely associated with improvements in the local environment, which prevented desertification and decreased the frequency of dust storm events. To the best of our knowledge, this is the first population-based study to provide clear evidence that a PTB epidemic was affected by dust storms in China, which may give insights into the association between this environmental problem and the evolution of epidemic disease.

1. Introduction

It is known that Asian dust storms (ADS) occurring in the spring mainly originate in the Gobi and Takla Makan deserts of Mongolia and western China, and they can be transported eastward to China (Chen et al., 2003), Japan (Fan et al., 1996; Figen Var et al., 2000), Korea (Chung and Yoon, 1996), Taiwan (Chen et al., 2004), and

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sometimes the western coast of North America (Duce et al., 1980; R. B. Husar et al., 2001). Minqin County (102.9591°E, 38.6071°N) is an administrative district in Gansu, China, which is part of the Wuwei prefecture, and its population was 300,000 people in 2006. Minqin symbolizes China's battle with desertification because this small agricultural region with 300,000 inhabitants is now threatened by the spread of the Badan Jaran and Tengger Deserts, which are two natural deserts that are gradually meeting in the middle. Its location means that dust storms are a major environmental problem in Minqin (Fig. 1). The number of severe dust storm events (visibility $\leq$ 200 m, instantaneous maximum wind velocity $\geq$ 20 m/s) each year has increased by over 10 times in the past 50 years (Qian et al., 2002, 2006). Moreover, floating dust weather events often occur in the spring and early summer.

Several studies have shown that the presence of desert dust in the atmosphere is associated with increased concentrations of cultivable bacteria, cultivable fungi, and fungal spores in downwind areas relative to the background levels, or days with clear atmospheric conditions (Chen et al., 2010; Griffin et al., 2001, 2003, 2006, 2007, Griffin et al. 2007; Ho et al., 2005; Kellogg et al., 2004; Schlesinger et al., 2006). The levels of particulate air pollution, such as total suspended particulates (TSP) (Chung and Yoon, 1996) and particulate matter with an aerodynamic diameter < 10 mm (PM_{10}) (R.B. Husar et al., 2001; Lin, 2001; Var et al., 2000), can rise significantly in affected urban areas during dust storm periods. Based on growing evidence from epidemiological studies, increases in deleterious health effects, including respiratory diseases, have recently attracted much attention during dust storm days in downwind areas (Bell et al., 2008; Chan et al., 2008; Chang et al., 2006; Chen et al., 2004; Chen and Yang, 2005; Chien et al., 2012; Yang et al., 2005a, 2005b). However, previous health studies have provided no consistent evidence that adverse health effects correspond to increases in particulate pollution. Using mortality data as health outcomes, two previous studies reported insignificant effects of ADS on mortality in Korea and Taiwan. Kwon et al. (2002) reported that ADSs during 1995–1998 were not associated with deaths due to cardiovascular and respiratory diseases in Seoul, Korea (Kwon et al., 2002). Hsieh and Liao (2013) reported that ADS events are seasonally-based meteorological phenomena that exacerbate chronic respiratory diseases (Hsieh and Liao, 2013).

Although relatively efficient treatments have existed for pulmonary tuberculosis (PTB) for decades, this disease remains one of the leading causes of mortality attributed to an infectious disease. PTB has affected China for centuries and it has the world's second largest tuberculosis epidemic (after India). During 2004–2012, the Centers for Disease Control (CDC) in China registered 950,000 to 1250,000 disease cases per year, where about 0.08% resulted in death (CDC, 2013). Minqin has one of the highest annual clinic visitation rates for PTB in China (Fig. 2). CDC datasets from China show that the highest annual number of clinic visits for PTB in Xinjiang province (0.193%) occurred in 2006, but the rate was 0.191% in the same year in Minqin county, which is very close to Xinjiang province. Therefore, PTB is now a major public health concern in Minqin (Yang and Men, 2008; Yang et al., 2008).

PTB is an infection of the lung caused by the bacterium *Mycobacterium tuberculosis*, which induces chronic infection with a very high rate of mortality in Chinese populations. The agent is highly contagious and person-to-person aerial transmission occurs via respiratory and throat secretions (Konstantinos, 2010). Interactions between different environmental parameters (e.g., immune

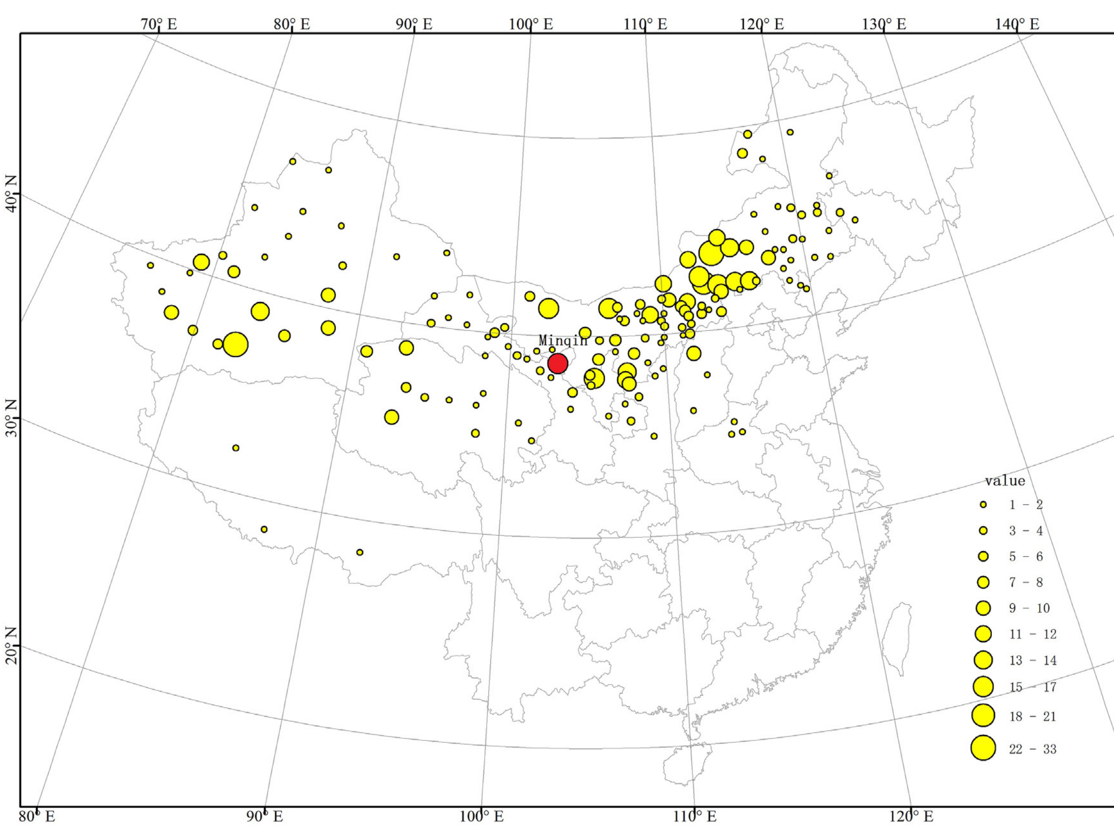

Fig. 1. Frequency of dust storm events in China during 2006 based on 753 atmospheric observation stations. The size of each circle represents the number of dust storm events. The red circle indicates the frequency of dust storm events in Minqin.

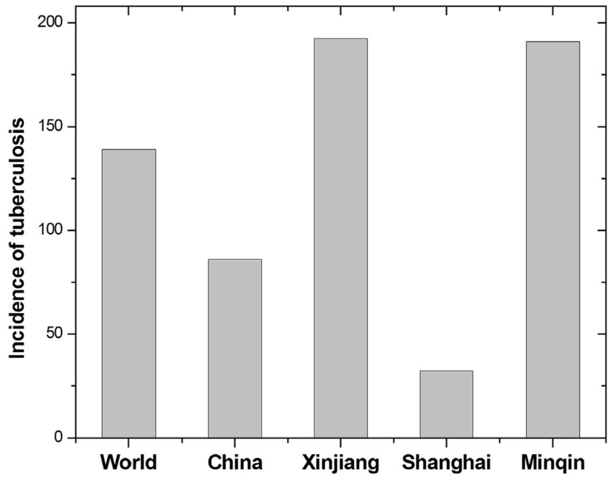

Fig. 2. Incidence of PTB in the world (139), China (86.2), Xinjiang province (192.6), Shanghai (32.4), and Minqin county (190.9) during 2006 (per 100,000 people). In China, the incidence of PTB was highest in Xinjiang and lowest in Shanghai during 2006.

receptivity of individuals, low socioeconomic level, transmission of more virulent serotypes, social interactions [such as pilgrimages, tribe migrations, and meetings], and specific climatic conditions) may contribute to PTB disease outbreaks and their spread within local populations (Lawn and Zumla, 2011).

Favorable environmental conditions are related to the resurgence and dispersion of the disease, and specific climatic conditions can induce periodic fluctuations in the disease incidence. Recent studies of the population dynamics of some infectious diseases have also clearly demonstrated the crucial importance of climate (Pascual et al., 2000; Rodo et al., 2002; Sultan et al., 2005). To understand the general impact of dust storms on the PTB epidemic, we used population-based data related to weekly clinic visits for PTB in Minqin during 2005–2012. We employed these data to predict the co-occurrence in both space and time of PTB disease cases and dust storm events, thereby suggesting that the incidence of PTB might be related to seasonal meteorological events. Very few previous studies have tried to establish potential links between climate events and PTB outbreaks. Thus, the aim of the present study was to document the dust storm-related context of PTB disease outbreaks and population dynamics in the highly affected Northwestern Chinese county of Minqin.

2. Materials and methods

2.1. Epidemiological data: weekly reports CDC for Gansu

The diagnosis of active PTB relies on radiology (usually chest X-rays), as well as microscopic examinations and microbiological culture of body fluids. If a smear is positive, PCR or gene probe tests can distinguish *M. tuberculosis* from other mycobacteria. Even if a sputum smear is negative, tuberculosis must be considered and it can only be excluded after negative cultures. This diagnosis forms the basis of disease surveillance and case reporting studies using the standard case definition for PTB, which can be implemented in any healthcare setting. The treatment of PTB is complex and it requires the administration of multiple antibiotics over a long period of time. Social contacts are also screened and treated if necessary. Prevention relies on screening programs and vaccination with the Bacillus Calmette–Guérin vaccine.

In general, the CDC in Gansu province began preparing systematic reports of infectious diseases in 2004, following the outbreak of SARS in China during 2003. In 2005, the survey started in Minqin. The CDC in Gansu contacted all of the public hospitals in the province and established a research database using standard procedures to ensure the accuracy and quality of the data collected. PTB reports are included in the weekly reports of clinic visits and they are aggregated from the health center level to the county level. The present study was based on the database of weekly reports for all clinic visits collected by Gansu CDC's Department of Communicable Disease Surveillance, from which we extracted PTB-related visits during 2005–2012 in Minqin.

2.2. Onset of the epidemic

We determined the temporal correlation in the epidemic based on weekly clinic visits for PTB in Minqin during 2005–2012 using the Mann–Whitney–Pettitt test (Pettitt, 1979), which is a nonparametric test used to detect a “change point” in a time series. A change point is defined as a point where the average values on either side are higher or lower than the other data points. For the time series considered in this study $Xy(w)$ (weekly number of cases in the year y), we computed $Uy(w)$ as

$$U_y(w) = U_y(w-1) + V_y(w), \tag{1}$$

where $2 \le w \le 53$ and $Uy(1) = Vy(1)$, where $Vy(w)$ is defined by

$$V_y(w) = \sum_{j=1}^{53} sign\left(X_y(w) - X_y(j)\right). \tag{2}$$

Thus, the most significant change point in the year y is the point when the value $|Uy(w)|$ is maximized. The probability $Py(w)$ of a given week being a change point is defined by

$$P_y(w) = 1 - \exp\left(\frac{-6U_y^2(w)}{T^3 + T^2}\right), \tag{3}$$

where $T = 53$ (the length of the time series in weeks). Therefore, the Mann–Whitney–Pettitt test was used to estimate the influence of large-scale climate variability on the disease patterns (Sultan et al., 2005).

2.3. Atmospheric data: China meteorological data sharing service system

In the late winter and spring, as cold and dry continental polar air masses from northern latitudes move southward or south-southeastward to exchange heat and moisture with warm and moist air masses at lower latitudes, the two different air masses meet in Mongolia or Inner-Mongolia in China to form a cold front or cold air outbreak (Sun et al., 2001; Wang et al., 2008). Given suitable atmospheric conditions, the strong surface winds associated with the baroclinic system of the cold front lift dust from the dry sandy surfaces of the deserts in western China to produce ADSs. The seasonal progression can be documented using weekly field surface wind speed data obtained from the China meteorological data sharing service system, which provides gridded atmospheric parameters (CMA, 2013).

The China Meteorological Administration (CMA) has produced complete severe dust storm datasets for China (CMA, 2013), which were derived from 753 atmospheric observation stations (Fig. 1). The dust storm events identified in the CMA database were based on a reanalysis of the national observational network of meteorological variables (wind, temperature, geopotential height, humidity on pressure levels, surface variables, and flux variables such as the precipitation rate) by performing data assimilation from 1954 to the present. This analysis allowed us to avoid the problems caused by previous numerical weather prediction analyses due to changes in techniques, models, and data assimilation. In the present study, we used severe dust storm datasets for the 8 years covering 2005–2012 in Minqin (red circle in Fig. 1), and we averaged these daily means per week to obtain weekly values. We applied the Mann–Whitney–Pettitt test to the weekly dust storm event values observed at Minqin station.

We analyzed clinic visit data for PTB in Minqin where the time series indicated that there was a close relationship between dust storm events and PTB epidemics with the same "active phase" in Minqin. In order to estimate the influence of particulate matter from dust storm events on the PTB epidemics, we generated a regression model to determine the correlations between three atmospheric variables (visibility, duration, and wind speed) and clinic visits during 2-week periods. It has been reported that dust storms can affect respiratory health in children based on analyses of dust storm events on weekdays to post-dust storm weekdays (the week after the dust storm event) (Chien et al., 2012), thereby justifying the use of data related to clinic visits and the number of dust storm events every 2 weeks (the weeks during and after dust storm events) in these models.

3. Results

3.1. PTB epidemic seasonality in Minqin

The weekly average number of PTB clinic visits varied in Minqin before, during, and after dust storm events in 2005–2011 (there were no dust storm events in 2012) (Table 1), and there was only one dust storm event in 2011. The weekly mean (±SD) number of visits during days with dust storm events ranged from 7.3 ± 6.9 in 2010 to 17.0 ± 3.9 in 2006. In most years, there were low weekly averages during pre-dust storm weeks, except in 2008. The weekly average numbers of visits during post-dust storm weeks were higher than those during dust storm weeks, except in 2009 and 2011, and they were all higher than those during pre-dust storm weeks. The greatest increase in visits from pre-dust storm weeks to dust storm event weeks occurred in 2011 (nine visits), and the greatest increase in visits from dust storm weeks to post-dust storm weeks occurred in 2007 (5.3 visits).

The weekly number of PTB clinic visits varied throughout the study period, where the weekly PTB records for 2005–2012 allowed us to determine the seasonal evolution of PTB epidemics in Minqin (Fig. 3). For each year, we determined the week when the onset of the epidemic occurred based on the breaking slope in the annual cycle of the number of cases (data not shown). In order to reduce the effect of high variability among years during 2005–2011 (there were no dust storm events in Minqin during 2012), we computed the average standardized anomalies in the number of cases (bars in Fig. 3) to represent the typical seasonal pattern of the PTB epidemic. To improve the description of the seasonal pattern of the epidemic and to reduce noise due to interannual variability in the onset date, we determined the composite mean of the number of cases during 2005–2011 based on the week when the epidemic onset occurred in each year. During 2005–2011, the maximum change in the number of PTB cases occurred between week 5 and week 31, which is the main active phase, i.e., from early spring to summer (Fig. 3). We detected another short active phase from week 44 to week 50.

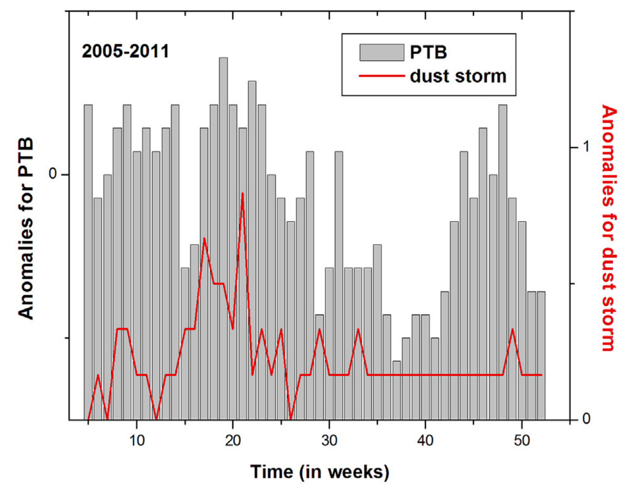

Fig. 3. Seasonal patterns of PTB epidemics and dust storms. Mean seasonal pattern in the number of PTB cases during 2005–2011 in terms of standardized anomalies (bars). The red curve represents the seasonal pattern of dust storms during 2005–2011.

3.2. Atmospheric events during PTB epidemics in Minqin

We studied the relationship between dust storms and the seasonal course of the PTB epidemic in Minqin using a regional index that summarized the temporal evolution of the low-layer occurrence (Fig. 3). This index was obtained from the dominant mode detected by the Mann–Whitney–Pettitt test (see Materials and Methods), which was applied to weekly dust storm occurrence data during 2005–2011 in Minqin (Fig. 3) The seasonal pattern showed that the dust storm outbreak varied with an almost regular synchronized rhythm, which was approximately the same as the active phase of the PTB epidemic dynamics, i.e., from week 7 to week 34. There were several dust storm events in December during 2008–2011, as well as another short active phase from week 48 to week 50. The epidemic active phase of the PTB epidemic coincided with the dust storm events in Minqin (Fig. 3).

Table 1
Weekly average clinic visits for PBT in Minqin during 2005–2011 (mean ± SD).

Time	Frequency of severe dust storms	Pre-dust storm week visits	Dust storm week visits	Post-dust storm week visits
2005	10	11.2 ± 4.3	11.9 ± 7.2	15.5 ± 10.0
2006	14	16.2 ± 1.5	17.0 ± 3.9	17.5 ± 0.7
2007	9	13.3 ± 3.5	14.4 ± 5.4	19.7 ± 8.0
2008	7	12.4 ± 5.0	10.8 ± 4.1	15.0 ± 5.4
2009	6	6.5 ± 2.5	11.3 ± 3.4	11.0 ± 7.0
2010	8	5.0 ± 2.2	7.3 ± 6.9	8.3 ± 1.2
2011	1	6	15	3

3.3. Effects of dust storm events on weekly PTB clinic attendance

There were close statistical links between PTB cases and the visibility, duration, and wind speed of single dust storm events during 2005–2011 (Fig. 4), thereby suggesting that there was a positive regression relationship between the duration of single dust storm events and the PTB epidemic during 2005–2011 in Minqin, i.e., dust storm events with a longer duration were associated with more epidemic cases of PTB (Fig. 4B, $p < 0.01$). There was also a positive relationship between the wind speed in single dust storm events and the number of PTB cases, i.e., higher wind speeds during dust storm events were associated with more epidemic cases of PTB (Fig. 4C, $p < 0.01$). However, there was a negative relationship between the visibility in single dust storm events and the number of PTB cases, i.e., lower visibility during dust storm events was associated with more epidemic cases of PTB (Fig. 4A, $p = 0.519$). Particulate matter is present in the total suspended particles and the amount of total suspended particles is related to the visibility, i.e., lower visibility indicates a larger amount of total suspended particles, and we found that a higher amount of particulate matter during single dust storm events was associated with more PTB clinic visits in Minqin. In addition, the total amount of suspended particulates might be related to the duration of events and the wind speed of single dust storms.

Although the number of years considered in this study was low, there was a close relationship between the number of PTB cases and days when dust storms occurred during the dust storm season (between week 7 and week 34), where the dust storm occurrence days explained >68% of the variance in PTB epidemic cases during the dust storm season in Minqin, i.e., a higher number of dust storm events was associated with more cases of epidemic PTB (Fig. 5). We analyzed the case data for the dust storm season to exclude the effect of seasonal variations in PTB, instead of analyzing the number

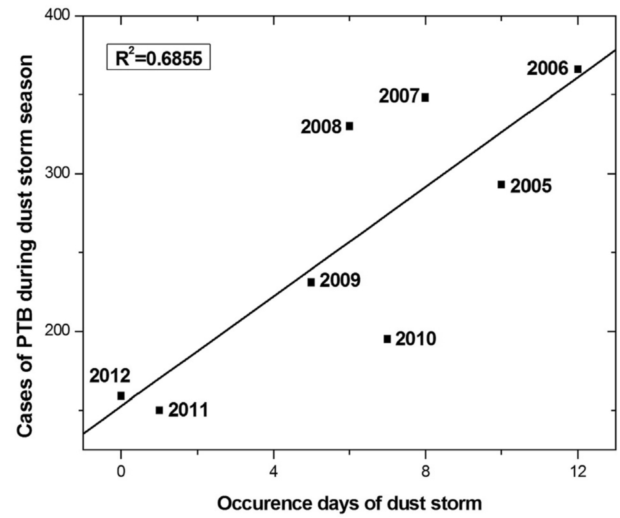

Fig. 5. Relationship between all of the PTB clinic visits during the dust storm season (from week 7 to week 34) and the number of days with dust storms in Minqin during 2005–2012.

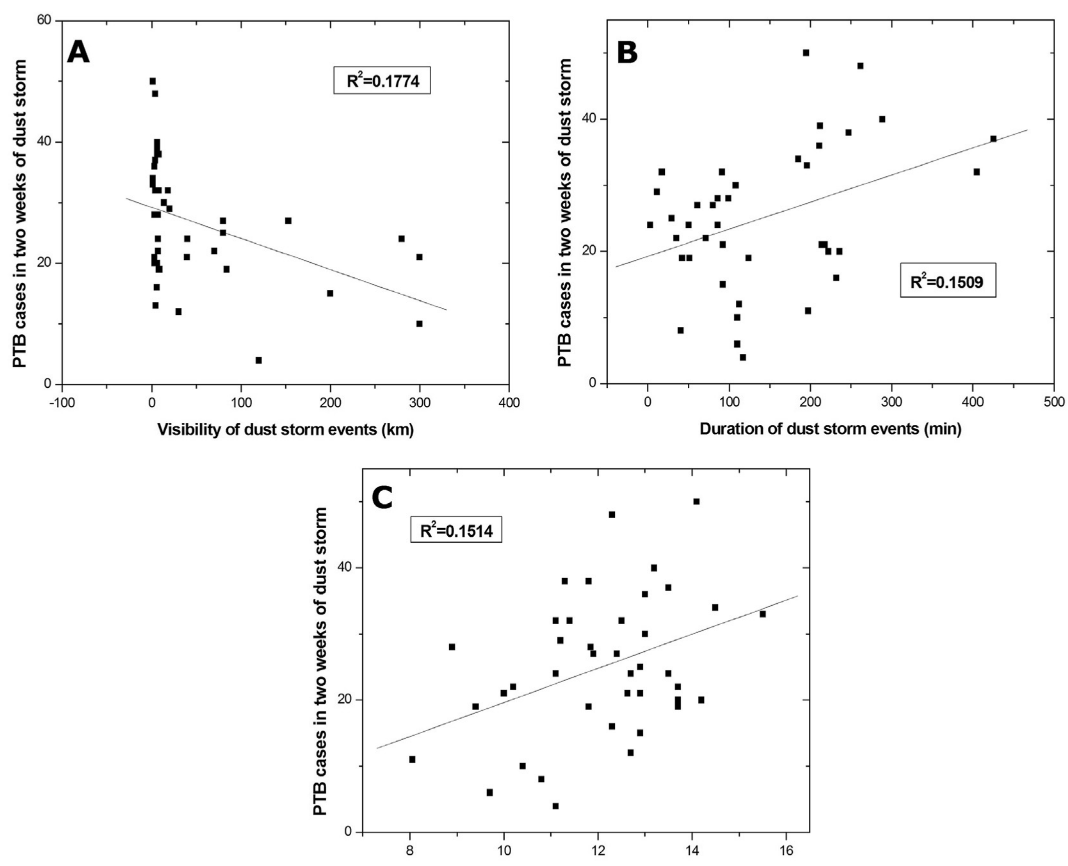

Fig. 4. Relationship between metrological variables, i.e., visibility (A), duration (B), and wind speed (C), during dust storm events and weekly PTB clinic visits during 2005–2011 (if more than two dust storm events occurred in one week, the average values of the three metrological indexes were employed in this regression analysis).

of PTB cases throughout the whole year.

In recent decades, the local government of Minqin has introduced several measures to prevent desertification and to control the occurrence of dust storms. Thus, the number of dust storm events decreased gradually during 2005–2011, and there were even no dust storm events in 2012, probably because the annual precipitation increased significantly in the local desert. The annual records of PTB cases in Minqin also decreased significantly during 2005–2012 (Fig. 6). Due to the development of the social economy and improvements in healthcare, the annual number of PTB cases has decreased gradually in China (data from CDC of China) as well as other countries (data from WHO), but the decrease in PTB clinic visits in Minqin was higher than the global trend.

4. Discussion

In this study, based on the relationship between the weekly number of PTB cases in Minqin and the large-scale atmospheric index of dust storms, we obtained clear evidence of a strong connection between climate and the seasonal patterns of PTB cases in Minqin. The onset of the disease outbreak was characterized by a clear active phase in the seasonal cycle of the number of PTB cases between week 5 and week 31. The atmospheric index calculated based on dust storms in Minqin showed that this active abrupt shift also occurred at almost the same time each year, which corresponded to the dry winter and the presence of strong surface winds.

It is possible that the pathophysiological connection between dust particles and the respiratory system is attributable to alveolar inflammation due to the inhalation of particles. This may also exacerbate existing lung disease and the autonomic function of the heart (Chuang et al., 2005; Esmaeil et al., 2014; Middleton et al., 2008; Stone and Godleski, 1999), as well as contributing to a systemic inflammatory state. These effects may then activate haemostatic pathways, impair vascular function, and promote atherosclerosis (Seaton et al., 1995). Previous studies has shown that the level of particulate air pollution, e.g., TSP and PM_{10}, can increase significantly in affected urban areas during dust storm periods, while particulate matter with a diameter of <2.5 mm ($PM_{2.5}$) can also affect the lung pathology in PTB, compromise a host's ability to handle ongoing pneumococcal infections and support the epidemiological findings of increased pneumonia-related deaths in ambient PM-exposed elderly individuals (Chung and Yoon, 1996; Jassal et al., 2013; Seaton et al., 1995; Var et al., 2000; Zelikoff et al., 2003). Recent studies provide more direct evidence of the correlation between fine particulate matter (PM) levels and smear-positive PTB. PM inhibits the expression of antimicrobial peptide genes and thus protein production in respiratory alveolar type II epithelial (A549) cells (Schwander et al., 2014), so exposure to PM2.5 or PM10 deregulates the ability of A549 cells to express the antimicrobial peptides human β-defensin 2 and 3 (HBD-2 and HBD-3) after infection with *M. tb* and this promotes increased intracellular growth by *M. tb* (Rivas-Santiago et al., 2013). The induction of senescence and the downregulated expression of HBD-2 and HBD-3 in respiratory PM-exposed epithelial cells lead to increased *M. tb* growth, and these mechanisms may allow exposure to air pollution PM to increase the risk of *M. tb* infection and PTB development (Rivas-Santiago et al., 2015).

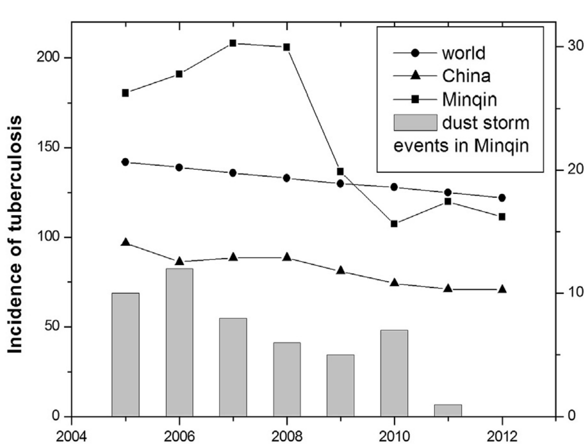

Fig. 6. Inter-annual evolution of PTB in the world (circle), China (triangle), and Minqin (square), and the inter-annual trends in dust storm events in Minqin during 2005–2012.

There is no evidence to suggest that *M. tb* bacteria might be attached to dust particles and inhaled by humans, although microorganisms have the ability to survive on the surfaces of dust particles and they can be transported over long distances (Griffin, 2007; Yamaguchi et al., 2012). We also analyzed 50 topsoil samples from the Badan Jaran and Tengger Deserts using a real-time quantitative polymerase chain reaction (qPCR) assay, but the pathogen responsible for PTB, *M. tb*, was not detected in any of the samples (data not shown).

However, regardless of the climatic index used, this analysis did not allow us to correlate the intensity of the epidemic (the annual number of cases) with the intensity of dust storms in terms of absolute humidity and surface wind speed. This lack of a relationship may be due to the time series length, where the number of years may have been insufficient to study interannual variations. Alternatively, climatic effects might only explain the occurrence of the seasonal cycle of the epidemic and its geographical range distribution, but not its intensity. Although these climatic indices failed to forecast the intensity of the epidemic, their correlations with the onset and the seasonal course of the PTB epidemic in Minqin provide an important tool for disease monitoring and prediction in China.

The Takla makan Desert Index and Gobi Desert Index time series have exhibited decreasing trends since the mid-1980s, probably because of an enhanced geopotential height over the Mongolian plateau and the middle Siberian region, as well as an anomalous shift in the phase and intensity of the stationary wave over Eurasia (Wang et al., 2008). In the context of global change, human activities caused mainly by governmental polices have improved the regional changes in the eco-environment. Huang et al. (2014) subjected historical documents, remote sensing, hydrology, vegetation, and socio-economic data to statistical analysis to clarify the characteristics of eco-environmental change in Minqin during the past 60 years, where they analyzed the internal driving force from the perspective of policy. They showed that the eco-environment quality in Minqin decreased initially during this period and it then improved. The switching points occurred mainly around 1980, 2000, and 2007 (Huang et al., 2014), where 2007 represented an abrupt switching point in the reduction of PTB cases in Minqin (Fig. 6). It was also considered that other reasons might explain the reduction of PTB during 2005–2012 in Minqin, such as improvements in medical care and personal health habits. However, the improvement in Chinese medical care has been a gradual process and thus the incidence of PTB in China has also declined gradually (Fig. 6). The annual clinic visitation rates for PTB in the provinces with a relatively high incidence but without high dust storm disturbances have also decreased gradually as medical care has improved (Fig. S1). Thus, we conclude that the significant reduction in PTB clinic visits in Minqin during 2005–2012 was associated mainly with improvements in the local environment, which prevented desertification and decreased the frequency of dust storm events (except in 2010). These changes were closely related to the implementation of the “Food Program,” “Reform and Opening,” and “Ecological Protection” policies (Huang et al., 2014).

Next, we consider some explanations for the specific data obtained in 2010, as shown in Fig. 6. (1) We used the number of dust storm events to represent the approximate severity of dust storms, which might have excluded the effects of other atmospheric factors related to dust storms on the incidence of PTB. (2) The dust storm outbreak was concentrated in 2010, where three dust storm events occurred in week 11 and two in week 16. The overlap between dust storm events might have reduced the effects of their incidence relative to PTB in the statistic analysis. (3) The visibility in the dust storm events was fairly high (data not shown), which means that the particulate matter content was lower than that in other years. The lower particulate matter of dust storms in 2010 might also explain the reduced effect on the PTB epidemic. It should be noted that this study was not a controlled indoor experiment, and thus many other factors could have affected the results obtained. Overall, if we exclude the data from 2010, we may conclude that the significant reduction of PTB clinic visits in Minqin during 2005–2012 was closely associated with improvements in the local environment, which prevented desertification and decreased the frequency of dust storm events.

We also acknowledge that our study had some limitations. First, due to the lack of an air quality monitoring system in Minqin station to determine the particulate matter concentration, we had to use visibility data to explain the influence of particulate matter on PTB epidemics. Thus, particulate matter might be the cause of the PTB outbreaks related to dust storm days. Previously, it was shown that the power functional relationships between PM_{10} and visibility among various regions generally had a good correlation ($r^2 = 0.90$), especially in ADS source regions (Wang et al., 2007). However, visibility is still a subjective measure and it is not sufficiently accurate to represent the particulate matter content. Second, particulate matter might have been a main cause of the PTB epidemics related to dust storm days, but not the only cause. For example, dust storms were often accompanied by a drop in temperature in Minqin. The sudden change in temperature might also have affected the PTB epidemic to some extent. Both of these reasons might lead to non-significant results in Fig. 4A. However, it should still be noted that there was a negative relationship between the visibility in single dust storm events and the number of cases of PTB. Third, weekly reports might not be sufficiently accurate for estimating the influence of dust storms on the PTB epidemic. The public hospital in Minqin only aggregated and reported the weekly clinic visits data to the CDC of Gansu up to 2012, but information about this disease could support a large-scale analysis of the influence of climate on PTB. Fourth, although the result of the correlation analysis between PTB cases and the dust storm occurrence days was highly significant (Fig. 5), the low R2 value was due partly to the low number of years considered (only 8 years), which is the main limitation of our analysis. Finally, we cannot exclude confounding effects that may have led to reductions in the number of PTB cases during this period, such as the development of the local economy and improved healthcare. Minqin is a county in the northwest of China and the rate of social improvement is below the average level for China, but there was a major decline in the PTB epidemic after the prevention of dust storms by the government, whereas the total epidemic cases of PTB in China have only decreased slightly.

5. Conclusions

Regardless of these limitations, we believe that our overall results support the conclusion that dust storms affect PTB epidemics and that particulate matter might be the cause of PTB outbreaks on dust storm days. It is highly likely that the significant reduction in annual clinic visits in Minqin during 2005–2012 was closely associated with improvements in the local environment, which prevented desertification and decreased the frequency of dust storm events. The insights obtained in this study may help us to understand the association between this environmental problem and the evolution of epidemic disease, as well as supporting national and international public health institutions and policy makers to improve the control of PTB disease in Northwest China.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.12.041.

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