Meteorological and Environmental Causes of an Autumn Thunderstorm Asthma Event in Northern Shaanxi

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Abstract Based on the number of asthmatic children in the Children's Hospital of Yulin City, the monitoring data of daily pollen concentration, and routine meteorological and environmental monitoring data of Yulin City from 2020 to 2022, the meteorological and environmental conditions of a thunderstorm asthma event in Yulin City in northern Shaanxi on September 9, 2022 were analyzed. The results show that the strong convective weather was accompanied by a strong thunderstorm, lightning, gusts, short-time heavy precipitation and small hail, and the convective activity lasted for nearly 7 h. The short-term abrupt change of allergenic substances such as artemisia pollen caused by lightning, gusts and precipitation, the sudden drop in temperature, the inversion near the surface and the stimulation of cold air were the key meteorological conditions for the subsequent outbreak of asthma. In early September in 2022, the daily average pollen concentration in Yulin City was up to 1 067.9 particles/1 000 mm^2, which was 113.3% and 41.2% higher than that of the same period in 2021 and 2020, respectively. The day before the thunderstorm, the pollen concentration soared to 2 680 particles/1 000 mm^2, reaching the maximum of the year. The synergistic effect of the thunderstorm event and the sharp increase in pollen concentration on the previous day provided the background of heavy pollen pollution for this outbreak of thunderstorm asthma. O_3 concentration was consistently high on the day of thunderstorm and the day before, and the peaks of O_3 and PM_{10} concentration appeared subsequently in the afternoon of the day, which became the background of air pollution for the asthma outbreak.

Key words Thunderstorm asthma; Severe convective weather; Sudden drop in temperature and cold stimulus; High concentration of artemisia pollen; O_3 pollution

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In recent years, with the rapid development of industrialization and urbanization, the impact of adverse meteorological and environmental conditions on human health has received increasing attention due to the multiple influence of intensified climate change and an increase in extreme weather and climate events[1-3]. Previous studies[4-5] reveal that climate change is associated with the occurrence of allergic respiratory diseases and asthma. For instance, Wu Qianpeng *et al.*[6] believed that weather and climate change are the main causes of respiratory diseases. That is, the cold stress effect of winter monsoon leads to a fluctuating increase in the number of patients with respiratory diseases among related populations, and temperature, humidity, wind and air pollution jointly affect the incidence of respiratory diseases. Besides, various air pollutants such as particulate matter and ozone, as well as meteorological conditions such as lightning, temperature, humidity and strong winds, have a combined effect on respiratory diseases[7-8]. Zhang Leilei *et al.*[9] studied the meteorological conditions of climate health care, and proposed that human comfort is dominated by temperature. Wei Xiaoyu *et al.*[10] found that the impact of temperature on respiratory and circulatory system diseases is characterized by immediacy at high temperatures and by lag at low temperatures, that is, the "cold" effect is dominant. Jian Wanlin *et al.*[11] found that dry and cold environments may lead to an increase in the number of residents admitted to hospital because of respiratory diseases.

With the intensification of climate change and the increase in the probability of extreme weather, severe convective weather has become more frequent and stronger, and thunderstorm asthma has attracted more and more attention. In 1983, thunderstorm asthma was first reported in the Birmingham area of the United Kingdom. In 2016, the largest thunderstorm asthma event occurred in the Melbourne area of Australia. It is believed that thunderstorms cause pollen to burst and form a large number of fungal spores and other allergens[12-14]. Zhang Jinjin *et al.*[15] suggested that the main predisposition factors to thunderstorm asthma include pollen, fungal spores, unstable cold air and high humidity. In recent years, there have been multiple thunderstorm asthma incidents in places such as Ningxia, Inner Mongolia, and Yulin, Shaanxi Province. On September 12, 2018, a relatively serious mass outbreak of thunderstorm asthma occurred in Yulin City, Shaanxi

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Province[16], which drew great attention from the local government, the scientific and technological community, and the general public.

Thunderstorms are intense atmospheric discharge phenomena in the troposphere. Severe thunderstorm weather is often accompanied by severe weather conditions such as short-term strong winds, hail, and heavy precipitation, and meteorological elements such as temperature and air pressure also undergo drastic changes, becoming the causes of certain diseases[17]. However, there are few studies on the influence mechanism of short-term exposure of weather and environmental conditions on allergic diseases such as asthma. In this paper, based on the monitoring data of pollen concentration and environmental factors, conventional meteorological data, as well as the monitoring data of new detection equipment such as Doppler weather radar, wind profiling radar, and microwave radiometer in Yulin City, the meteorological and environmental causes of asthma outbreak under the influence of strong convective weather on September 9, 2022 were studied to provide a reference for the protection against thunderstorm asthma.

1 Data and methods

Yulin City, which is located in the transitional zone between the Mu Us Desert and the Loess Plateau in the north of Shaanxi Province, has a temperate continental arid and semi-arid monsoon climate. The annual average temperature is 10.0 ℃. The extreme maximum temperature in summer is 42.6 ℃, and the extreme minimum temperature in winter is −30.0 ℃. The annual precipitation is 455.1 mm, and the annual average relative humidity is 42%. The annual average wind speed is 2.3 m/s. In winter, it is cold and dry, and there is little rain or snow due to the influence of the Mongolian high pressure. In summer, it is hot and rainy, and thunderstorms and other convective weather happen frequently owning to the impact of the continental high pressure and subtropical high pressure. Spring and autumn are transitional seasons with changeable weather and significant fluctuations in temperature. Asthma, a common disease in Yulin area, appears frequently from August to September. In recent years, the number of patients suffering from asthma has increased, and their age has decreased. Children's Hospital of Yulin City, which is situated in the center of the urban area of Yulin City, is a comprehensive general hospital, and mainly treat patients in the city and Yuyang District. The data of cases used in this paper is derived from the number of registered visitors to the asthma outpatient department recorded by this hospital from 2020 to 2022. The environmental data include the monitoring data of pollen concentration in Yulin City and six elements of air quality in the urban area of Yulin. The meteorological monitoring data contain the data of various meteorological monitoring stations in Yulin City and the detection data of the new generation of weather radar and microwave radiometer in Yulin City.

2 An overview of the thunderstorm asthma event

From 13:00 to 15:00 (Beijing time, the same below) on September 9, 2022, severe thunderstorms, lightning, strong winds, precipitation and small hail occurred in the main urban area of Yulin City. As a result, many local students suddenly suffered from asthma, and were taken to the hospital by their parents for treatment. Subsequently, the thunderstorm system moved southward away from the urban area. From 17:00 to 19:00, it moved northward to cause thunderstorm gales again in the urban area of Yulin, so that the number of asthma patients increased again, but was less than that in the afternoon. After 21:00, the convective weather system weakened, so the number of the patients persisted slightly and then gradually decreased.

Table 1 shows the number of asthma patients visiting Children's Hospital of Yulin City every hour from 08:00 to 24:00 on September 9, 2022. A total of 633 patients visited the hospital, and the number was 10.1 times that of the previous day. Among the patients, there were 415 males and 218 females, with a gender ratio of 1.9 ∶ 1. The conclusion that there were more male patients than female patients was contrary to that of Makrufardi F *et al.*[13] and Clayton-chubb D *et al.*[14], but it was similar to that of Liu Fang *et al.*[16].

The number of asthma patients visiting the hospital hourly rose abnormally since 15:00 when thunderstorms had already occurred. From 16:00 to 17:00, the number of asthma patients reached 118, and the disease was the most severe. During 17:00 – 18:00, the number of asthma patients reduced but was also large. The number of asthma patients was relatively small from 18:00 to 20:00, and a small peak appeared again from 20:00 to 23:00. Overall, the number of asthma patients during 14:00 – 23:00 was up to 433, accounting for 68.4% of the total number of asthma patients on that day. The concentrated outbreak of asthma overlapped highly with the time of thunderstorm activities. In terms of patients of different ages on that day, the number of primary school students aged 7 – 12 was the largest (up to 269), accounting for 42.5% of the total number. The number of children aged 4 – 6 was up to 171, accounting for 27.0% of the total number. The number of children aged 0 – 3 and young adults aged 20 – 40 accounted for 11.5% and 11.4%, respectively. The proportion of the rest was less than 5%. Therefore, primary school students and children entering kindergartens were the main patients, followed by young adults and infants. It can be known from living habits that men and students spend a long time outdoors, and the immunity of children is relatively poor, so these two groups of people suffered from thunderstorm asthma frequently. In this article, the short-term exposure processes of meteorological conditions and the atmospheric environment as well as their causes during this thunderstorm asthma event were mainly discussed.

Table 1 Hourly number of asthma patients visiting the hospital from 08:00 to 23:59 on September 9, 2022

Time	Total	Male	Female	Age						
				0 – 3	4 – 6	7 – 12	13 – 19	20 – 40	40 – 60	>60
08:00 – 08:59	51	35	16	4	12	29	0	4	2	0
09:00 – 09:59	45	32	13	8	17	16	0	3	1	0
10:00 – 10:59	30	18	12	6	6	9	1	6	2	0
11:00 – 11:59	17	13	4	5	6	3	1	2	0	0
12:00 – 12:59	0	0	0	0	0	0	0	0	0	0
13:00 – 13:59	3	2	1	1	1	1	0	0	0	0
14:00 – 14:59	34	26	8	4	10	14	1	4	1	0
15:00 – 15:59	73	51	22	2	22	34	4	8	3	0
16:00 – 16:59	118	76	42	12	33	47	9	12	4	1
17:00 – 17:59	73	43	30	12	19	30	5	7	0	0
18:00 – 18:59	14	11	3	1	1	10	1	1	0	0
19:00 – 19:59	12	8	4	1	1	7	0	2	0	1
20:00 – 20:59	41	23	18	3	10	18	1	7	2	0
21:00 – 21:59	45	27	18	5	9	18	2	7	2	2
22:00 – 22:59	49	30	19	8	15	21	1	3	1	0
23:00 – 23:59	28	20	8	1	9	12	0	6	0	0
Total	633	415	218	73	171	269	26	72	18	4

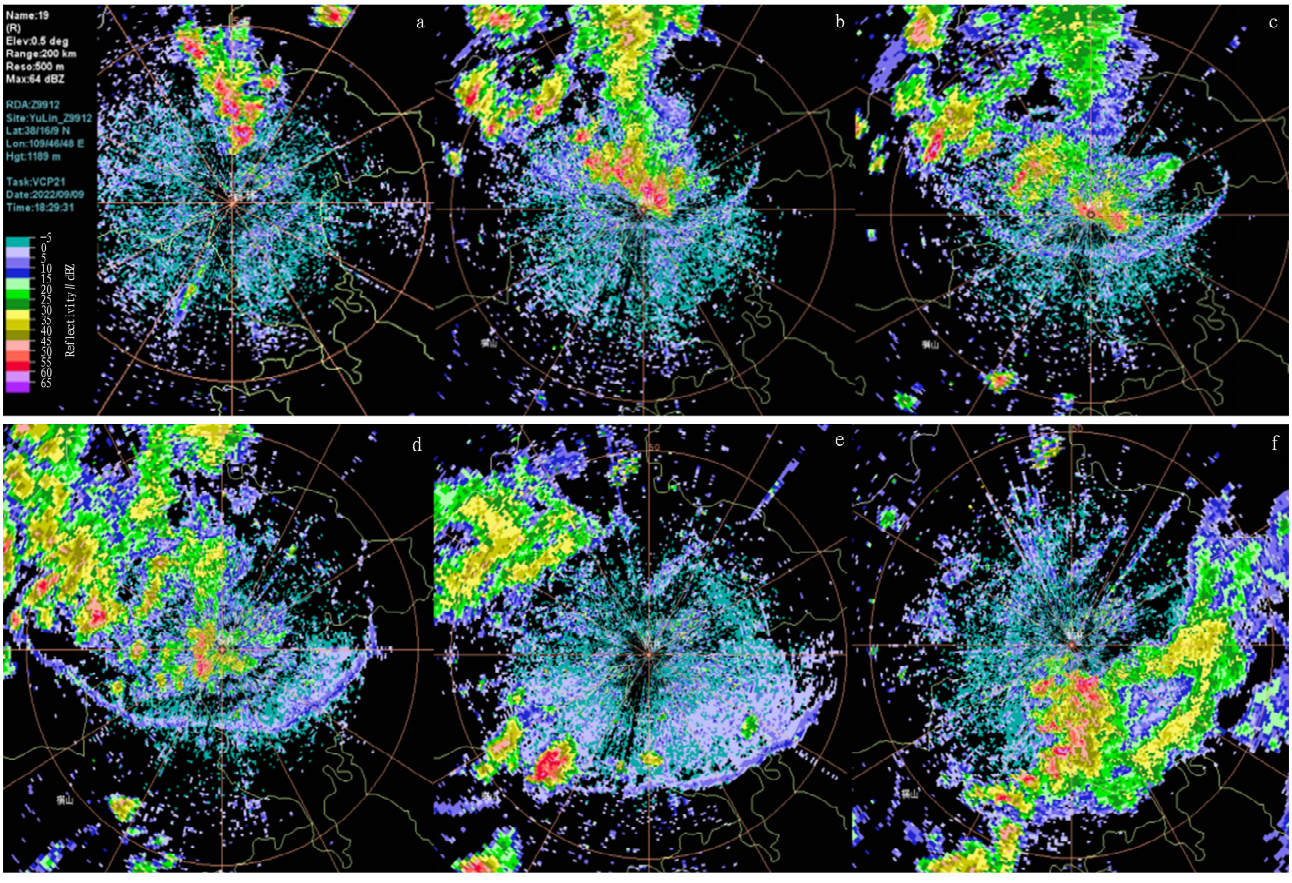
3 Analysis of the exposure of meteorological conditions

3.1 Causes of thunderstorm weather and characteristics of radar echoes

3.1.1 Causes of thunderstorm weather. From the 500 hPa weather map (omitted) at 08:00 on September 9, 2022, it can be seen that the East Asian circulation was zonal circulation. The subtropical high pressure over the western Pacific extended westward to connected with the Qinghai – Tibet high pressure, forming band-like high pressure. The 588 dagpm line was roughly located between 30° and 40° N. A cold low vortex was formed in Hetao area to the north of the subtropical high. Yulin was located in the trough area at the bottom of the low vortex. The air flow on the east and west sides of the trough line was northerly and easterly, respectively. At 850 hPa, there was an east – west convergence area in the west of Yulin, and there were northeast and southwest winds on both sides of the convergence line. The high- and low-altitude circulation pattern and stratification configuration were conducive to the development of strong convection in Yulin. On the ground weather map, there was high-pressure circulation over the west of Shaanxi Province, and Yulin was in a uniform pressure field. At 11:00, with the increase of ground temperature and decrease of air pressure, the dew point temperature difference of the Loess Plateau and the Mu Us Sandy Land on the Shaanxi – Mongolia border increased to form the main line. The dew point temperature difference on both sides was 3 – 5 ℃, and the thunderstorm weather system was formed during the southward movement of the main line.

3.1.2 Characteristics of strong convective echoes. As shown in the 0.5° elevation map (omitted) of Yulin Weather Radar Station at 11:56, locally generated strong convective echoes were approximately circular 36.4 km away from the north of the radar station. The horizontal range of the echo area with the reflectivity intensity of above 45 dBZ was less than 10 km, and the maximum echo intensity reached 60 dBZ. At the same time, there was divergence in the lower layer and convergence in the middle and upper layer on the velocity map. Afterwards, the echoes moved southward, and new convective monomers were generated on the front and back sides of the moving direction. At 12:42, a single convection developed into north – south linear convective echoes (Fig. 1a). The front part was about 10 km away from the station, and the maximum reflectivity intensity was >65 dBZ. The low-level divergence increased, and radial wind speed reached 16 m/s. At this time, lightning had been detected on the ground in Yulin City. At 14:09, convective cloud echoes approached Yulin Radar Station (above the urban area) (Fig. 1b). It is seen that multiple strong convective individual echoes were distributed from northwest to southeast in a linear pattern, and reflectivity intensity was >65 dBZ. In front of the moving echoes, a gust front was formed by the thunderstorm's outflow. On the radial velocity map (omitted) at the same moment and elevation angle, strong convective echoes corresponded to a divergent wind field. The maximum radial wind speed near the measurement station was up to 16 m/s. At this time, the first strong wind appeared in the urban area of Yulin, with the extreme wind speed of 10.8 m/s. There was thunder over the urban area of Yulin. From 14:32 to 14:42, the main body of convective clouds moved over the urban area of Yulin (Fig. 1c), with the maximum reflectivity intensity of >55 dBZ. The gust front in front of strong echoes was clearly visible in an arc shape, and intense lightning was accompanied by strong winds, hail and heavy precipitation. The second strong wind appeared in the urban area of Yulin, and the extreme wind speed reached 12.6 m/s. At 15:01, there were still convective clouds over Yulin (Fig. 1d), and there was no significant change in echo intensity. The gust front still remained, and ground precipitation began to weaken. At

16:22, convective clouds above Yulin Station dissipated, but the gust front triggered the formation of new and more scattered convective clouds, and the maximum reflectivity intensity was > 60 dBZ 20 – 25 km away from the southwest of Yulin Station (Fig. 1e). Thunderstorms still occurred in Yulin. At 18:29, convective echoes generated on the east side of Yulin moved westward to the observation station (Fig. 1f). Thunderstorms and southerly strong winds happened again in the urban area of Yulin, with the extreme wind speed of 12.2 m/s. The convective weather system weakened after 21:00.



Note: a. 12:42; b. 14:09; c. 14:32; d. 15:01; e. 16:22; f. 18:29.

Fig. 1 Basic reflectivity at an elevation of 0.5° at Yulin Radar Station from 12:42 to 18:23 on September 9, 2022

3.2 Sudden changes in lightning activities and meteorological elements Yair Y *et al.* [18] studied thunderstorm asthma caused by a severe thunderstorm in Israel, and believed that the occurrence of high flash speed and strong electric fields during thunderstorms, as well as the presence of high humidity and rainfall, might damage pollen membranes and enrich the air with respirable allergens accompanied by other aerosol particles already present in the environment.

3.2.1 Changes in lightning and surface meteorological elements and possible inducing mechanisms. Fig. 2 shows changes in the number of asthma patients and the frequency of lightning in the urban area of Yulin as well as hourly temperature and extreme wind speed monitored by the meteorological monitoring station at Century Square in the center of Yulin from 09:00 to 23:00 on September 9, 2022. As shown in Fig. 2, lightning happened from 13:00 to 20:00, namely lasting for nearly 7 h. It appeared frequently in two periods. From 14:00 to 15:00, the frequency of lightning was the highest, reaching 143. After that, the thunderstorm weakened, and the frequency of lightning sharply declined. During 18:00 – 19:00, it was up to 108, and the intensity of thunderstorms was weaker than that of the first period. In the first high-incidence period of lightning, meteorological elements changed significantly, such as thunderstorm gales, short-term precipitation and a sudden drop in temperature. Temperature declined most obviously between 14:00 and 15:00, decreasing from 24 ℃ to 13 ℃, with a drop of 11 ℃ within 1 h, reaching the cooling standard for a strong cold wave in winter. Meanwhile, wind speed increased most obviously, surging sharply from 5.8 m/s at 13:00 to 12.6 m/s at 15:00. According to the records from various meteorological monitoring points, precipitation occurred from 14:00 to 15:00, with a precipitation of 7.5 – 15 mm. The maximum precipitation in the suburbs appeared in Jinchitan Town in the north of the city, up to 29.5 mm. Ground pressure fluctuated with the change of thunderstorm activities. Pressure was the highest before the thunderstorm, up to 900 hPa. It dropped to 897 hPa after the thunderstorm began, with a daily variation of 3.0 hPa.

From the comparison of the time nodes of severe convective weather and the onset of asthma, it is found that the frequency of

lightning, which characterizes the intensity of thunderstorms, peaked during 14:00 – 15:00. The number of asthma patients began to increase sharply at 15:00, reaching a peak of 118 from 16:00 to 17:00. During 18:00 – 19:00, the frequency of lightning and gusts increased again, which was accompanied by a weak drop in temperature. The number of asthma patients rose again after 20:00. There was a lag of about 2 h between the peaks of the two lightning activities and asthma patients.

The possible changes in the morphology of pollen films caused by thunderstorms, lightning, gusts and short-term heavy precipitation, as well as the stimulation of cold air caused by the sudden drop in temperature at the level of a strong cold wave, were the key meteorological factors for inducing the subsequent large-scale outbreak of asthma.

3.2.2 Vertical variations of meteorological elements and their possible influences. Ground-based microwave radiometers have the advantage of all-weather continuous observation, which can make up for the shortcomings of long detection time intervals and incomplete detection information in sounding, providing the possibility of capturing fine changes in mesoscale systems[19-20]. The TK001 microwave radiometer installed in the artificial rain enhancement base in the northern suburb of Yulin City is 14 km (straight-line distance) away from the meteorological monitoring station at Century Square in Yulin City. The vertical profiles of detected temperature (the figure is omitted) indicates that at 13:00 before the occurrence of strong convection, temperature declined in vertical direction. At a height of 1.5 m, temperature was 27.3 ℃, and vertical decrease rate was 0.5 ℃/100 m. Since 14:00, thunderstorm activities intensified as the convective cloud body approached the urban area. Temperature dropped to 21.9 ℃ at a height of 1.5 m and 22.3 ℃ at a height of 50 m. An inversion layer began to form between 1.5 and 50 m near the surface layer, with a temperature difference of 1.2 ℃. The height ranging from 50 to 230 m was an isothermal layer. At 14:20, heavy precipitation accompanied by hail occurred in the urban area, and temperature continued to drop to 18.8 ℃. The height of the inversion layer expanded upward to 300 m. As precipitation approached the precipitation landing station, ground temperature declined rapidly (14:10 – 14:30), and the vertical temperature difference between ground temperature and the top of the inversion layer reached 4.5 ℃. During 14:30 – 15:00 (from the later stage of precipitation to its end), ground temperature first decreased and then rose, but the inversion layer always existed. The height of the inversion layer dropped from 600 to 400 m, and it continued until night.

From the vertical profiles of relative humidity in the lower troposphere (0 – 1.5 km) from 13:00 to 15:00 (the figure is omitted), it can be seen that relative humidity was between 30% and 32% in the lower troposphere before convection occurred. From 14:00 to 14:10, thunderstorms and precipitation began, and relative humidity near the ground gradually increased. At an altitude of 0.25 – 0.5 km, relative humidity rose to around 80% due to the influence of the precipitation. The altitude was basically consistent with that of the inversion layer top in Fig. 3a. From 0.5 to 1.5 km (the upper part of the boundary layer), drying and wetting alternated. During 14:20 – 14:40, relative humidity was high at an altitude of 0.1 – 0.65 km, and drying and wetting alternated near the surface layer and in the boundary layer. The profiles indicate that the large values of relative humidity were associated with precipitation. The alternation of drying and wetting was the result of turbulent exchange in the boundary layer, and the alternation of drying and wetting near the surface layer was related to strong winds on the ground. After the precipitation ended at 15:00, relative humidity became stable.

The profiles of temperature and humidity show that during the strong convection, a continuously strengthened inversion layer was formed near the surface layer, so that allergens such as water vapor and pollen accumulated near the surface layer for a long time, and cannot be effectively diffused.

When thunderstorm weather occurs under the background of low-pressure controlled circulation, the strong vertical movement of cold and warm air within clouds leads to intense lightning activities. The cold air within clouds is transmitted to the ground along with thunderstorm winds and precipitation, causing a sudden drop in temperature to reach the standard of a strong cold wave. Meteorological elements such as strong winds also undergo sudden changes, and the ground air pressure fluctuates, causing an instantaneous change in the pressure difference between the inside and outside of the human body. Moreover, an inversion layer is formed in the lower troposphere, making it difficult for allergens to spread and causing respiratory discomfort in susceptible populations. These factors might be meteorological causes of thunderstorm asthma.

4 Analysis of the exposure of pollen pollution

The public believes that artemisia pollen may be the main cause of the frequent occurrence of allergic rhinitis and asthma in Yulin City in summer and autumn. There are currently five monitoring points of pollen concentration in Yulin City, and they are located respectively in the main urban areas of Shenmu City in the north, Dingbian County in the west, Yulin City in the middle, Jia County in the east, and Suide County in the south. The monitoring data of daily pollen concentration in each monitoring station from 2020 to 2022 were collected, and a total of 1 338 samples were obtained. In order to compare the annual variations of pollen concentration during the same period and eliminate the influence of missing data from monitoring stations, the data of all monitoring stations from July 11 to October 9 in each year were averaged to represent the average pollen concentration of the whole city (the figure is omitted). During 2020 – 2022, the pollen concentration in Yulin City was relatively low from July to middle August, and began to increase in late August. It reached the peak from early to middle September, and the date of the peak fluctuated slightly from year to year, but the difference did not exceed 7 d. The peaks of the average concentration over the three years were 1 227, 1 015, and 2 493 particles/1 000 mm^2, respectively. The difference between the peaks in 2020 and 2021 was not significant, but the peak in 2022 was abnormally high, about twice that of the previous two years. The daily average of pollen concentration in early September, 2022 was up to 1 067.9 particles/1 000 mm^2, which

was 113.3% and 41.2% higher than that of the last year and the previous year. From the number of asthma patients during the same period, it is found that the high-incidence period of asthma and the peak period of pollen concentration highly overlapped, that is, they peaked in early September.

The changes in pollen concentration in the main urban area of Yulin City before and after the outbreak of asthma on September 9 were further analyzed. Fig. 3 shows the daily changes in pollen concentration and the number of asthma patients in the main urban area of Yulin City during September 1 – 20, 2022. From September 1 to 7, pollen concentration increased slowly day by day, reaching 860 particles/1 000 mm^2 on September 7. According to the local classification for the prevention and control of pollen allergy, it was extremely high. On September 8, the weather was sunny and hot, and pollen concentration suddenly rose to 2 680 particles/1 000 mm^2, reaching the maximum within the year. It was 3.12 times that of the previous day and 2.44 times that of the last year. It can be seen that pollen concentration was usually high in early and middle September, and there was a significant increase in pollen concentration on September 8. The superimposed effect of the two provided the background condition of heavy pollen pollution for the outbreak of thunderstorm asthma on the next day.

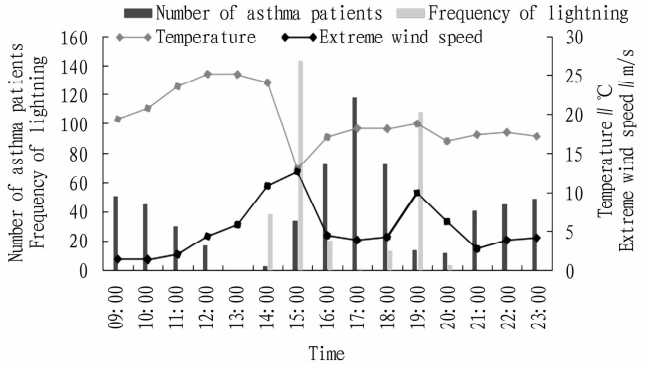


Fig. 2 Hourly changes in the frequency of lightning, ground temperature, wind speed and the number of asthma patients in Yulin City from 09:00 to 23:00 on September 9, 2022

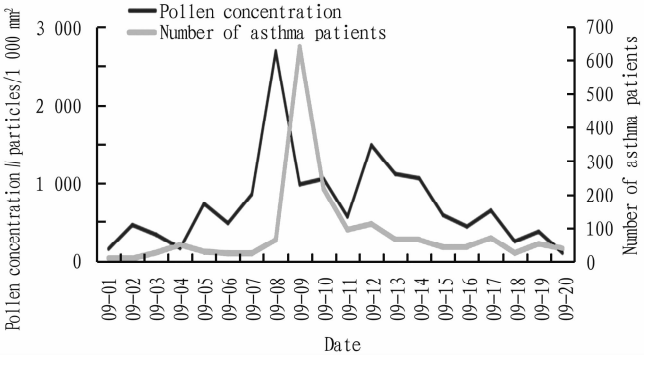


Fig. 3 Daily variations in the number of asthma patients and pollen concentration at the monitoring station in the urban area of Yulin from September 1 to 20, 2022

5 Analysis of the exposure of air pollution

Tian Yu[21] and Chen Chen *et al.*[22] hold that there was a statistically significant correlation between the number of hospital visitors and short-term exposure of ozone. Zhang Hong *et al.*[23] suggested that short-term exposure of ozone in the warm season would increase the risk of patients visiting hospital. Ruan Fangfang *et al.*[24] proposed that when ozone concentration was >100 $\mu g/m^3$, the risk of death rose by 0.39% with the increase of ozone concentration by 10 $\mu g/m^3$. Therefore, the higher the ozone concentration, the greater the impact on respiratory health risks. Two days before the thunderstorm (from September 7 to 8), ozone concentration rose continuously. On September 8, $O_{3-8\,h}$ (the daily maximum 8-h average concentration of O_3) reached 149.1 $\mu g/m^3$, approaching the pollution threshold and exceeding the upper limit 100 $\mu g/m^3$ of $O_{3-8\,h}$ recommended in the *Guidelines on Global Air Quality* issued by the World Health Organization. At 14:00 on September 8, the concentration reached the maximum in early September, up to 163 $\mu g/m^3$. The ozone concentration on September 8 was relatively high, and there was an exposure risk and a lag effect of 1 d. On September 9 when the asthma happened suddenly, ozone concentration decreased compared to the previous day but remained at a relatively high level. It dropped below 100 $\mu g/m^3$ after September 19. Hence, the asthma outbreak on September 9 was related to ozone exposure, which was consistent with the conclusion of Zhang Wenjing *et al.*[25].

Fig. 4 reveals the hourly distribution of ozone concentration, PM_{10} concentration and the number of asthma patients in Yulin City on September 9, 2022. O_3 concentration rose rapidly since 11:00, and reached 101 $\mu g/m^3$ at 12:00. At 13:00, cloud cover increased, and lightning intensified, but O_3 concentration continued to rise. O_3 concentration was up to the daily maximum of 152 $\mu g/m^3$ at 14:00. Due to the continuous appearance of lightning and the occurrence of convection at noon, surface temperature was the highest, and vertical temperature difference was the largest. During this period, weather phenomena such as hail, precipitation and strong winds also appeared. The exchange of heat and water vapor formed by turbulence between the ground and the atmosphere near the surface layer was more active, and lightning produced atmospheric photochemical reactions, which led to rapid and complex changes in the composition of the near-surface atmosphere. O_3 concentration did not drop rapidly with the reduction of sunlight, but decreased slowly, and increased again from 18:00 to 20:00

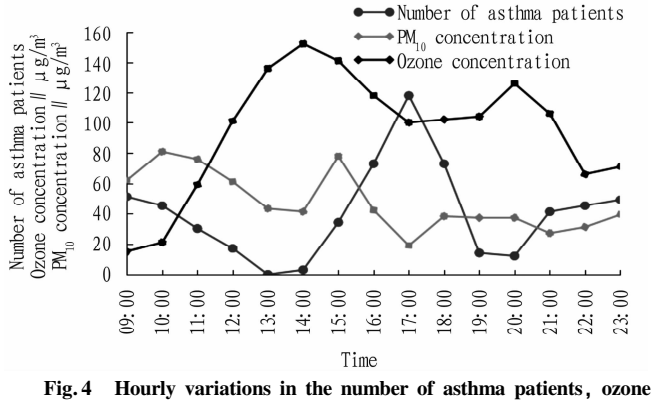


Fig. 4 Hourly variations in the number of asthma patients, ozone concentration, and PM_{10} concentration in Yulin City from 00:00 to 23:00 on September 9, 2022

when there was no sunlight at all. It can also be seen from their daily variations that there was a lag of 1 – 3 h between the peaks of O_3 concentration and the number of asthma patients. In addition, owing to the transmission of upstream sand and dust, PM_{10} concentration reached 81 μg/m^3 at 10:00 on September 9. Under the direct influence of thunderstorms and strong winds, it was up to 78 μg/m^3 at 15:00. In a word, PM_{10} concentration was relatively high on September 9. In conclusion, the successive occurrence of the peaks of O_3 and PM_{10} concentration in the afternoon became the background conditions of air pollution for the subsequent large-scale outbreak of asthma.

6 Conclusions and discussion

In this paper, the sudden changes in meteorological elements and the characteristics of air pollution during the severe convective weather process accompanied by the strong outbreak of thunderstorm asthma in Yulin City, Shaanxi Province on September 9, 2022 were analyzed according to the number of asthma patients in the hospital. The main conclusions are as follows.

(1) On September 9, 2022, the circulation background of the severe convective weather in Yulin City was that the subtropical high pressure over the western Pacific extended westward to connected with the Qinghai – Tibet high pressure, forming band-like high pressure. Yulin was located in the trough area at the bottom of the low vortex in Hetao to the north of the subtropical high. The ground main line triggered the occurrence of convection, which was accompanied by severe thunderstorms, lightning, gusts, short-term heavy precipitation and small hail. A gust front was formed in front of the convective system, and lasted for a long time. Moreover, it triggered new convection cells to repeatedly affect Yulin area.

(2) From 08:00 to 24:00 on September 9, a total of 633 asthma patients visited the Children's Hospital of Yulin City, and the number was 10.1 times that of the previous day. From 14:00 to 23:00, the number of asthma patients reached 433, accounting for 68.4% of the total number of asthma patients on that day. During 16:00 – 17:00, the number of asthma patients was up to 118, accounting for 18.6%. The concentrated outbreak of asthma coincided with thunderstorm activities. The ratio of male to female patients was 1.9 ∶ 1, and primary school students and children entering kindergartens were the main patients.

(3) The thunderstorm within convective clouds and cloud-to-ground lightning lasted for 7 h. The thunderstorm and strong winds repeatedly affected the urban area of Yulin. From 14:00 to 15:00, the thunderstorm was the strongest, and the maximum force of gusts was up to 6. Temperature dropped by 11 ℃ within 1 h, which reached the standard of a strong cold wave in winter. The daily variation range of air pressure was 3.0 hPa. The outflow of cold air from thunderstorm clouds caused drastic fluctuations in temperature and air pressure, leading to unstable pressure differences between the inside and outside of the human body. Moreover, precipitation and temperature drop created near-surface temperature inversion, so that it was difficult for allergens to spread. The combined influence of these meteorological factors reduced the emergency response function of the respiratory system in susceptible populations, becoming a cause of the asthma attack. There was a lag of about 2 h between the peaks of asthma patients and thunderstorms.

(4) In early September, the concentration of artemisia pollen and asthma incidence in Yulin City are high. In early September of 2022, the daily average concentration of artemisia pollen was up to 1 067.9 particles/1 000 mm^2, which was 113.3% and 41.2% higher than that of the same period in 2021 and 2020, respectively. The pollen concentration soared to 2 680 particles/1 000 mm^2 the day before the thunderstorm, which was the maximum within the year. The synergistic effect of the thunderstorm event and the sharp increase in pollen concentration on the previous day provided the background of heavy pollen pollution and the material basis for the induction of this outbreak of thunderstorm asthma.

(5) $O_{3-8\,h}$ was up to 149.1 μg/m^3 the day before the thunderstorm, approaching the pollution threshold. At 14:00, the concentration reached 163 μg/m^3, which was the maximum in early September. During the thunderstorm on September 9, the peaks of O_3 and PM_{10} concentration occurred successively, becoming the background conditions of air pollution for the large-scale outbreak of asthma.

The causes of thunderstorm asthma are complex. In this paper, only a case of thunderstorm asthma was analyzed based on the number of asthma outpatients and the main meteorological and environmental factors during thunderstorm weather. The conclusions have a certain reference value. The influence of meteorology and atmospheric environment on human health has received increasing attention, and further data accumulation is needed for more detailed analysis and research.

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