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Severe weather disasters to epidemics in China during low and high solar activities from 1 to 1911 Common Era

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Abstract

Historical records truthfully document human life and activities associated with climate and environmental changes. Based on the official historical records for the years 1–1911 Common Era (i.e., a period of 1911 years), we examine how the 408 epidemic events, occurring in 282 years, are related to solar activity, geographical locations, seasons, and natural disasters of anomalous temperature and irregular precipitation, in China. The epidemics occur more frequently during the low solar activity period. The inland area and area north to the climate boundary of Qinling–Huaihe Line along 35° geographic latitude, in particular, suffer epidemics more often during low solar activity periods. In fact, 45% or more epidemics occurred in summer, while less than 9% occurred in winter. The infection is highly related to social distancing, and therefore the epidemics also occur likely in areas with high-density population or heavy traffic. Statistical tests further demonstrate that natural disasters owing to anomalous temperature and irregular precipitation act as mediators which significantly cause the epidemics in ancient China.

Keywords Epidemics, Solar activity, Temperature

Introduction

Historical records faithfully document human life, climate, and environmental changes in the past. China has long official historical records, which continuously document human life and activities over the approximately four thousand years up to 1911 CE (Common Era, equivalent to Anno Domini, AD) (Song 1992). Based on these historical records, scientists examined relationships of populations–epidemics (Morabia 2009), transportation routes–plagues (Xu et al. 2014), climate–diseases (Patz et al. 2005; Zhang et al. 2007; Xu et al. 2014; Pei et al. 2015), places–epidemics (Gong et al. 2020), seasons–epidemics (Gong et al. 2020) temperature–epidemics (Lee et al. 2017; Gong et al. 2020) and precipitation–epidemics (Lee et al. 2017; Gong et al. 2020) in ancient China. Meanwhile, long-term variations in solar activity and global climate show that changes in the solar irradiance are important (Reid 1987; Friis-Christensen and Lassen 1991; Tinsley 1996; Mann et al. 1998; Rind 2002). Reduced solar irradiances could lower global temperature (Eddy 1976), increase the global low cloud cover (Svensmark and Friis-Christensen 1997; Carslaw et al. 2002), and affect precipitation (Verschuren et al. 2000; Kniveton and Todd 2001). Anomalous temperature of extremely cold or hot and irregular precipitation of heavy rain/snow/hale or severe dry might cause natural disasters (Liu et al. 2022) and further result in epidemics.

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Since the Han dynasty [206 BC (before Christ)–220 CE], there are 25 official Chinese historical books, dynastic histories. The accuracy or reliability of the 25 Chinese historical books has been warranted by the head/life of history officers and double checked by their successive dynasties (Sima 1961). Based on the 25 official Chinese historical books, and cross checking with general historical records, important county annals, ancient medical books, ancient irrigation books, and other historical texts, Song (1992) edited and published "Chronicle of Severe Natural Disaster and Anomaly in Ancient China", which summarizes severe natural disasters and anomalies occurring in China spanning the approximately four thousand years up to 1911 CE. In the chronicle (Song 1992), each event listing includes the original statements in the historical books, the lunar month and year of the occurrence in terms of the Gregorian calendar and the Chinese imperial era, the location of the historical prefecture together with the corresponding current province, the human and animal casualties, property and environmental damage, the size of the area affected, and the duration.

This paper statistically investigates the relationship between epidemics and geographic locations, solar activities, seasons, as well as natural disasters owing to anomalous temperature and irregular precipitation in China during the period of 1–1911 CE. Here, epidemic and disaster occurrence locations correspond to 22 current provinces, lunar months stand for seasons, and sunspot history records and/or the solar minimums correspond to the solar activity (Stuiver and Braziunas 1989; Pang and Yau 2002; Usoskin et al. 2003; Knudsen et al. 2009; Steinhilber et al. 2012). In total, 9 solar minimums occurred during 107–1825 CE (Stuiver and Braziunas 1989; Pang and Yau 2002; Usoskin et al. 2003; Knudsen et al. 2009; Steinhilber et al. 2012; Liu et al. 2022). We examine the correlation between the epidemic occurrence and solar activity by considering the minimum as low solar activity (LSA) periods and the period between two adjacent minimums as a high solar activity (HSA). Statistical analyses of 80% confidence interval (CI) are constructed to assess the difference in epidemic proportions between the periods characterized by LSA and HSA. Contingency tables are further employed to depict the binary responses associated with epidemic events and natural disasters resulting from anomalous temperature or irregular precipitation. All the details will be discussed in the following sections.

Method

Data conversion and arrangement

Disasters and anomalies in the chronicle (Song 1992) are classified into many items, which are grouped into 9 categories: astronomy including sunspots, geology, seismology, meteorology, hydrology, ocean, plant, animal, and human. The epidemic events are under the category of human. Natural disasters associated with severe cold temperature including cold winters, cool equinoxes/summers, frosty/icy plants, frozen and wells/lakes/rivers, as well as severe hot temperature comprising harsh hot summers, and warm equinoxes/winters are quantified from the meteorology (Liu et al. 2022). On the other hand, natural disasters owing to irregular precipitation of wet (i.e., heavy precipitation) associated with torrential rain, heavy snow, and heavy hail, as well as of dry of severe drought events are extracted from the meteorology and hydrology category (Liu et al. 2022).

Qualitative historical records of the epidemics and natural disasters are herein converted into quantitative data by denoting years with epidemics and disasters, respectively, by "1" and those without by "0". We then statistically investigate how the occurrence of epidemics related to locations, seasons, solar activities, and natural disasters due to anomalous temperature of extremely cold/hot and irregular precipitation of severe wet/dry during 1–1911 CE. To do so, the epidemics denoted by "1" are also marked with their associated lunar months and locations of the corresponding current province. To avoid double counting, however, if the same event was recorded by multi-historical records, overlapped years, lunar months or locations, it will be simply counted by one time only. Although there are 408 epidemic event records isolated from the 25 official Chinese historical books during 1–1911 CE, the statistical study is based on binary responses of 282 (229) event years and 1629 (1490) non-event years during 1–1911 CE (107–1825 CE). We further compute the count of inter-event time of epidemics and find that the epidemics tend to occur in cluster. More than 52% (=147/282) of epidemics occur within 1–2 years of other epidemics.

Solar activity

There are 9 solar minimums, Second-Century Minimum (107–203 CE), Fourth-Century Minimum (332–365 CE), Fifth-Century Minimum (462–526 CE), Medieval Minimum (580–820 CE), Oort Minimum (980–1070 CE), Wolf Minimum (1280–1350 CE), Sporer Minimum (1410–1590 CE), Maunder Minimum (1645–1715 CE) and Dalton Minimum (1795–1825 CE), during 1–1911 CE (Stuiver and Braziunas 1989; Pang and Yau 2002; Usoskin et al. 2003; Knudsen et al. 2009; Steinhilber et al. 2012; Liu et al. 2022). If considering the Minimum as a low solar activity (LSA) period and the period between two adjacent minimums as a high solar activity (HSA), in total, there are 9 LSA and 8 HSA periods. Table 1 illustrates 9 LSA and 8 HSA periods together with the number of event years in each LSA and HSA periods. During 107–1825 CE, the durations of the LSA and HSA periods are 882 years and 837 years, respectively. Figure 1a depicts years of the epidemics and the disasters during the LSA and HSA periods of 1–1911.

Location and season

Figure 1b displays locations of the epidemics in the 22 current provinces, which are further subdivided into 2 areas of northern versus southern areas (i.e., provinces) by the climate boundary of the Qinling–Huaihe Line at about 33° N (Gao et al. 2019; Liu et al. 2020) or 2 areas of coastal versus inland areas (i.e., provinces). Seasons of the epidemics are classified as, spring (February–April; lunar month 1–3), summer (May–July; lunar month 4–6), autumn (August–October; lunar month 7–9), and winter (November–January; lunar month 10–12).

Figure 2 displays in total, 408 epidemic event records and 282 (229) event years that have been isolated during 1–1911 CE (107–1825 CE). When an event was reported in multiple provinces or areas in the same year, the event is treated as an individual one and the percentage computed accordingly in each province or area. For the overall study period of 1–1911 period, there 377 out of the 408 records are individually identified for the area study, and 263 out of 377 are denoted with the associated seasons. Similarly, for the occurrence year study, an event occurring in multiple areas and months but in the same year is considered as an individual one. Therefore, 280 out of 408 records are denoted with the occurrence months and 263 out of 280 are recorded with location information. On the other hand, for the solar activity study, there are 229 epidemic event years during 107–1825 CE.

Table 1 List of epidemic year counts in the LSA and HSA period

Cycle	Minimums	LSA (CE)	Lyr[a] (#)	HSA (CE)	Hyr[a] (#)
1	Second-century	107–203	10	204–331	22
2	Fourth-century	332–365	1	366–461	4
3	Fifth-century	462–526	2	527–579	1
4	Medieval	580–820	14	821–979	5
5	Oort	980–1070	5	1071–1279	27
6	Wolf	1280–1350	4	1351–1409	12
7	Sporer	1410–1590	39	1591–1644	11
8	Maunder	1645–1715	31	1716–1794	23
9	Dalton	1795–1825	18		
	Total duration (years)	882	124	837	105

[a] Lyr and Hyr are number of event years in each LSA and HSA periods, respectively

Difference between two proportions

To see whether the epidemic is related to solar activity, the 80% confidence interval (CI) for the difference between the proportions of epidemics in the LSA and HSA periods is constructed (Agresti 1996). Let P_{L} and P_{H} be the proportions in LSA and HSA periods, respectively. The 80% CI for the true difference between the two proportions is then given by:

$$\mathrm{CIs} = \left[P_{\mathrm{L}} - P_{\mathrm{H}} - 1.28\sqrt{\frac{P_{\mathrm{L}}(1-P_{\mathrm{L}})}{N_{\mathrm{L}}} + \frac{P_{\mathrm{H}}(1-P_{\mathrm{H}})}{N_{\mathrm{H}}}}, P_{\mathrm{L}} - P_{\mathrm{H}} + 1.28\sqrt{\frac{P_{\mathrm{L}}(1-P_{\mathrm{L}})}{N_{\mathrm{L}}} + \frac{P_{\mathrm{H}}(1-P_{\mathrm{H}})}{N_{\mathrm{H}}}}\right].$$

The 80% lower bound of $P_{\mathrm{L}} - P_{\mathrm{H}}$ is then use to test if P_{L} is larger than P_{H}. On the other hand, the associated upper bound is used to test if P_{H} is larger than P_{L}. When the lower (upper) bound is positive (negative), P_{L} (P_{H}) is claim to be greater than P_{H} (P_{L}) under significance level 0.10. During 107–1825 CE, the numbers of years involved in the LSA and HSA periods are $N_{\mathrm{L}}=882$ and $N_{\mathrm{H}}=837$, respectively.

Association between epidemics and disasters

We investigate the relationship between epidemics and disasters related to temperature anomalies or precipitation irregularities. There are, in total, 242 anomalous temperature disaster years, 419 irregular precipitation disaster years, and 282 epidemics event years during 1–1911 CE. The contingency tables are constructed to illustrate the binary responses of epidemic event and natural disasters owing to anomalous temperature or irregular precipitation. Two binary variables are considered to be positively associated if most of the data fall along the diagonal cells. By contrast, two binary variables are considered to be negatively associated if most of the data fall in the off-diagonal cells. Hence, the Phi correlation coefficient(s) (Conover 1999), ϕ, is employed to examine the association between the occurrences of epidemics and disasters. Let n_{ij} be the number in the cell (i,j), $i,j = 0,1$. Set $n_{i\cdot}=n_{i0}+n_{i1}$, $n_{\cdot j}=n_{0j}+n_{1j}$ and $n = n_{00}+n_{01}+n_{10}+n_{11}$. The Phi coefficient is then obtained as:

$$\phi = (n_{11}n_{00} - n_{10}n_{01}) \Big/ \sqrt{n_{0\cdot}n_{1\cdot}n_{\cdot 0}n_{\cdot 1}}.$$

If the occurrences of epidemics and disaster are independent, the statistic

$$\chi^2 = n\phi^2$$

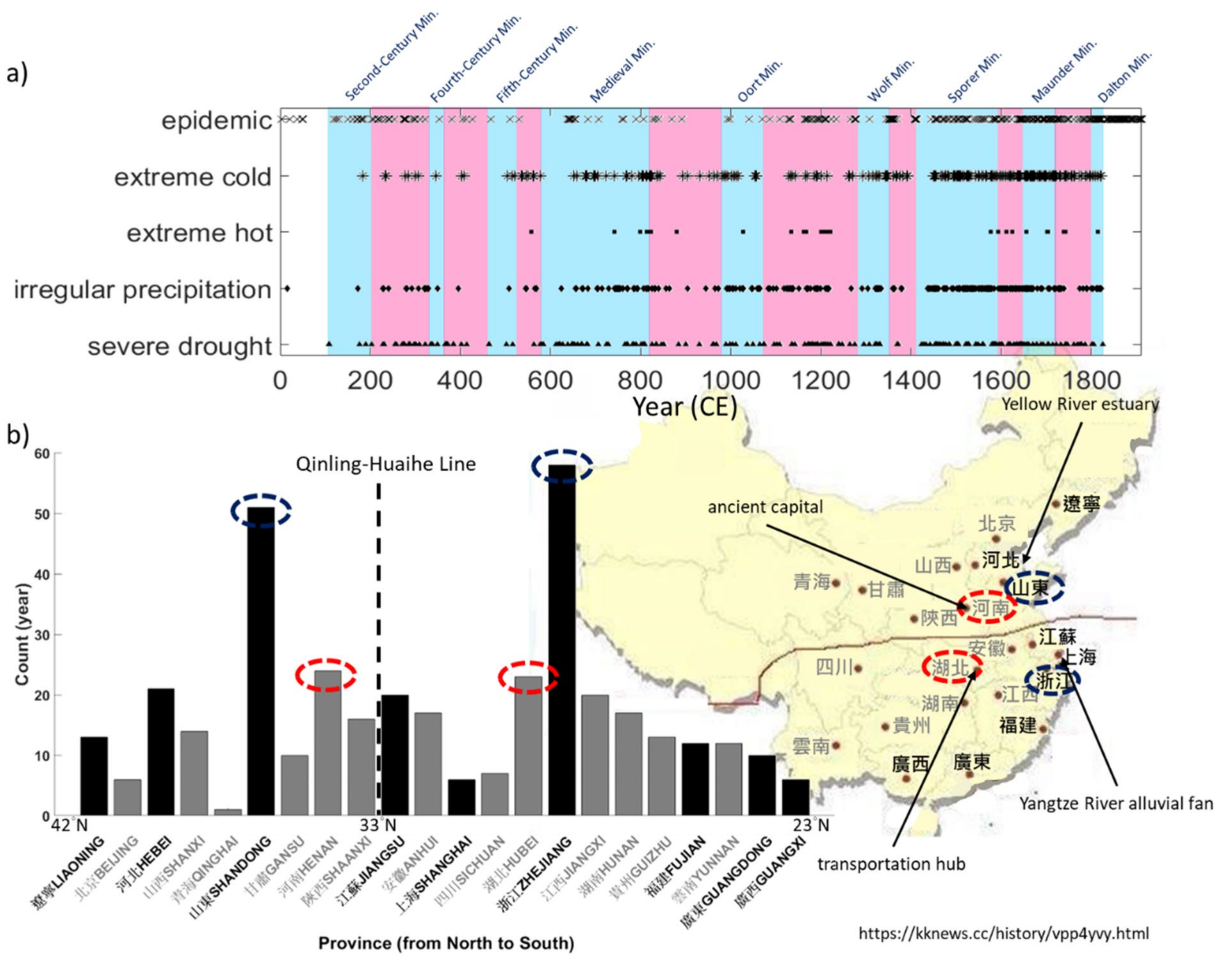

Fig. 1 Occurrence years and locations of 224 epidemics as well as disasters owing to anomalous temperatures and irregular precipitations in China between 1 and 1911 CE. **a** There are 9 solar minimums, low solar activities (LSA; blue bars), and 8 high solar activities (HSA; red bars) during the 1–1911 CE. Years of the epidemic (cross symbols) as well as disasters due to cold (star symbols), hot (square symbols), precipitations (diamond symbols), and droughts (triangle symbols) are denoted. Nine LSA periods: 107–203 CE (second-century minimum), 332–365 CE (fourth-century minimum), 462–526 CE (fifth-century minimum), 580–820 CE (Medieval minimum), 980–1070 CE (Oort minimum), 1280–1350 CE (Wolf minimum), 1410–1590 CE (Sporer minimum), 1645–1715 CE (Maunder minimum) and 1795–1825 CE (Dalton minimum). Red and blue denote HSA and LSA periods, respectively. **b** The epidemic locations are defined using the 22 current provinces, and subdivided into either northern versus southern area by the climate boundary of the Qinling–Huaihe Line (dark brown curve) at about 33° N or coastal (black characters/bars) versus inland provinces (gray characters/bars). The top two provinces of epidemic occurrences in costal (black dashed ecliptics) and inland (red dashed ecliptics) areas are denoted

is distributed according to a Chi-square distribution with one degree of freedom, denoted by χ_1^2. Let $\chi_{1,\alpha}^2$ be the upper αth percentile of χ_1^2. If $\chi^2 > \chi_{1,\alpha}^2$, we then claim that, under significance level α, there is an association between the occurrences of epidemics and the disaster. Note that the significance level α is the probability that the association is erroneously claimed for two independent events. Therefore, a small value of α is preferred, for example, $\chi_{1,0.001}^2 = 10.83$. In fact, the Chi-square test can also be used to test for the independence between the epidemic at year t and disaster at year $t+k$ for possible lag time $|k| \leq 3$. Therefore, the total number of observations is $n = 1911 - |k|$.

Results

Geographical locations

Figure 1a illustrates the occurrence year of the epidemics and disasters due to anomalous temperatures of severe cold or extreme hot and irregular precipitations of heavy precipitation (i.e., wet) or severe dry in various LSA and HSA periods, while Fig. 1b depicts the occurrence count of the epidemics in 22 provinces between 23 and 42° N geographic latitudes during the period of 1–1911

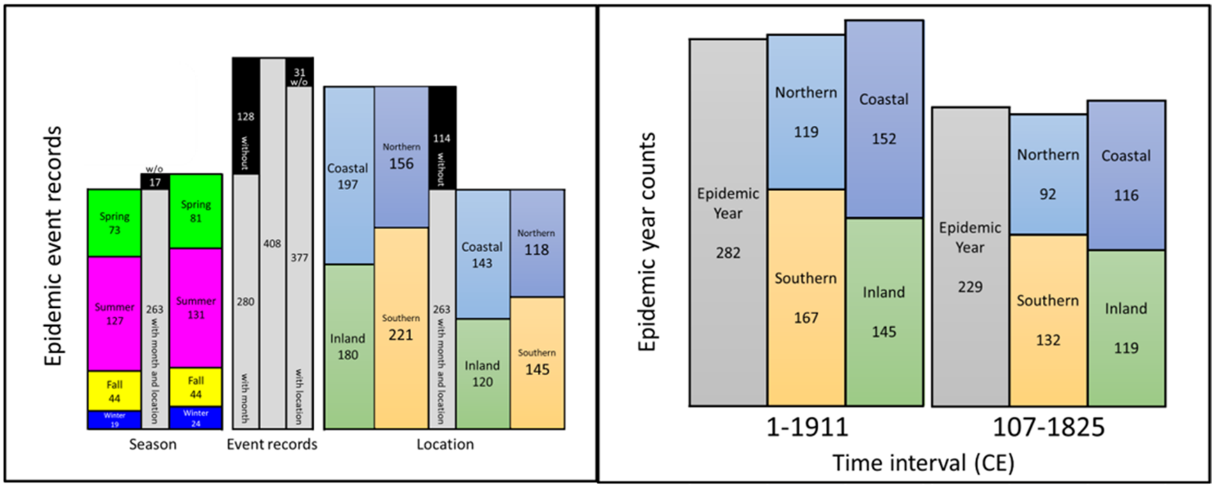

Fig. 2 Epidemic events in various seasons and locations. Left panel: epidemic event records in seasons (months) and locations during 1–1911 CE. Right panel: epidemic year counts in locations during 1–1911 CE (left side) and 107–1825 CE (right side)

CE. These provinces are further divided into either the northern versus southern areas to the climate boundary of the Qinling–Huaihe Line at about 33° N or coastal versus inland provinces. In Fig. 2, the epidemic occurrence rates in the inland/coastal and northern/southern areas to the total of 377 are 0.52/0.48 and 0.41/0.59, respectively, which suggest that the frequency of epidemics in the four areas are similar during the entire study period of 1–1911 CE. However, the geographic distribution of the epidemics corresponding to the 22 current provinces shows that the coastal provinces of Shandong and Zhejiang and the inland provinces of Henan and Hubei, close to the climate boundary line around 33° N, suffer more frequently from epidemics (Fig. 1b). The epidemic occurrences in Shandong and Zhejiang are about 5 times more likely than the average, which might be due to the fact that the former is nearby the Yellow River estuary and the latter is within the Yangtze River alluvial fan. The Henan province was home to the capitals of several ancient dynasties while the Hubei province has been the most important transportation hub for several centuries. These suggest that high-density population and heavy traffic could enhance the spreading of epidemics.

Solar activities

Figure 1a depicts years of the epidemics during the LSA and HSA periods during 107–1825 CE. To study the effect of solar activity on the occurrence of epidemics, we compute the proportion, namely, the number of epidemic years in each LSA or HSA period divided by the total years under study in the overall or different areas. Figure 3 illustrates that the subtotal proportion of LSA is greater than that of HSA in the overall and the four areas, which indicates that the epidemics tend to occur during the solar minimum. Table 2 depicts that in the overall China and each area, the proportion of epidemics during the LSA period is larger than that during the HSA period, and the 80% CIs further indicate that the epidemics particularly in the inland or northern area occur tend to occur more often in the LSA period. This again shows that the epidemics frequently occur during the LSA periods. We further examine the proportion difference between LSA and HSA in the coastal provinces of Shandong and Zhejiang, where yield the top 2 occurrence of epidemics and about 5 times more than the average of the 22 provinces. The bottom two panels in Table 2 show that the epidemic in the northern coastal provinces of Shandong occurs significantly in the LSA period, while that in the southern coastal provinces of Zhejiang is vice versa in the HSA period. This indicates that response of the epidemics in coastal areas to the solar activity could be dependent on the climate boundary of the Qinling–Huaihe Line.

Seasonal variations

The occurrence percentages of epidemic events in each area during the 4 seasons are examined. In each area, the percentage of epidemics is defined as the number of epidemic years in a certain season during the LSA or HSA period being derived by the total number of epidemic years. Figure 4 shows that the epidemics in the four areas most frequently occur in summer at which the frequency of 45–51% is about two times greater than the four-season average of 25%, especially in the inland and the northern areas. The second most frequent season are in

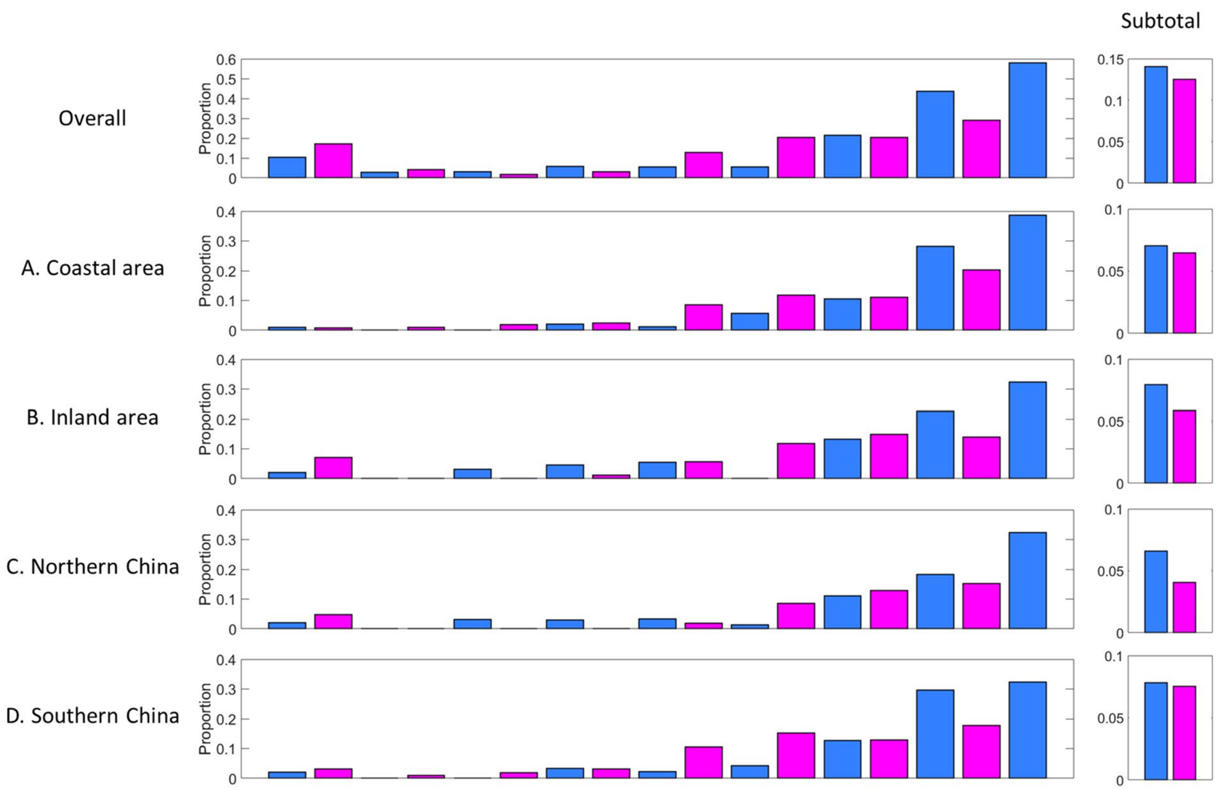

Fig. 3 Proportions of the epidemic occurrences in the overall, costal, inland, Northern, and Southern areas in each solar activity periods. The proportion is computed by epidemic year counts divided by the year counts of the period. The proportion of LSA (blue bars) and HSA (red bars) periods are denoted

Table 2 Proportions and confidence interval of P_L–P_H

Area/province	P_L	P_H	(LB, UB) (80%)
Overall	0.1406	0.1254	(− 0.006, 0.036)
Coastal area	0.0703	0.0645	(− 0.010, 0.021)
Inland area	0.0794	0.0585	**(0.005, 0.036)**
Northern China	0.0658	0.0406	**(0.011, 0.039)**
Southern China	0.0782	0.0753	(− 0.014, 0.019)
Shandong province	0.0215	0.0131	**(0.0004, 0.016)**
Zhejiang province	0.0193	0.0335	**(− 0.024, − 0.004)**

Bold numbers stand for meeting the statistical significance level of 0.10

P_L and P_H are the proportions in LSA and HSA periods, respectively

LB, and UB are lower bound and upper bound of 80% confident interval, respectively

spring. In contrast, the epidemics least frequently occur in winter, which has a frequency of about 6–9%, and is about one-third of the overall average of 25%. These show that the epidemics peaked in summer and diminished in winter in ancient China.

It is interesting to find that in each season, the epidemic occurrence percentage of the LSA period is greater than that of the HSA period, expect in summer and spring at the costal and the southern areas (pie chart in Fig. 4). The exceptions again suggest that the climate boundary of the Qinling–Huaihe Line and inland/coastal effects are important. Nevertheless, the epidemic occurrence percentage of the LSA period is greater than that of the HSA period in the overall area in each season, which confirm that the solar activity effect is essential to the occurrence of epidemics.

Epidemics and disasters owing to temperature and precipitation

There are, in total, 242 anomalous temperature disaster years, 419 irregular precipitation disaster years, and 282 epidemics event years during 1–1911 CE. Tables 3 and 4 are the contingency tables for illustrating the occurrence with zero time lag of epidemics and natural disasters owing to anomalous temperatures and irregular precipitations, respectively. In Table 3, there are 56 (1443) years in which epidemics and anomalous temperature disasters (not) occurred simultaneously in the same year; 226 years of epidemics without anomalous temperature disasters; and 186 years of anomalous temperature disasters without epidemics. Similarly, in Table 4, there are 89 (1299) years in which epidemics and irregular precipitation

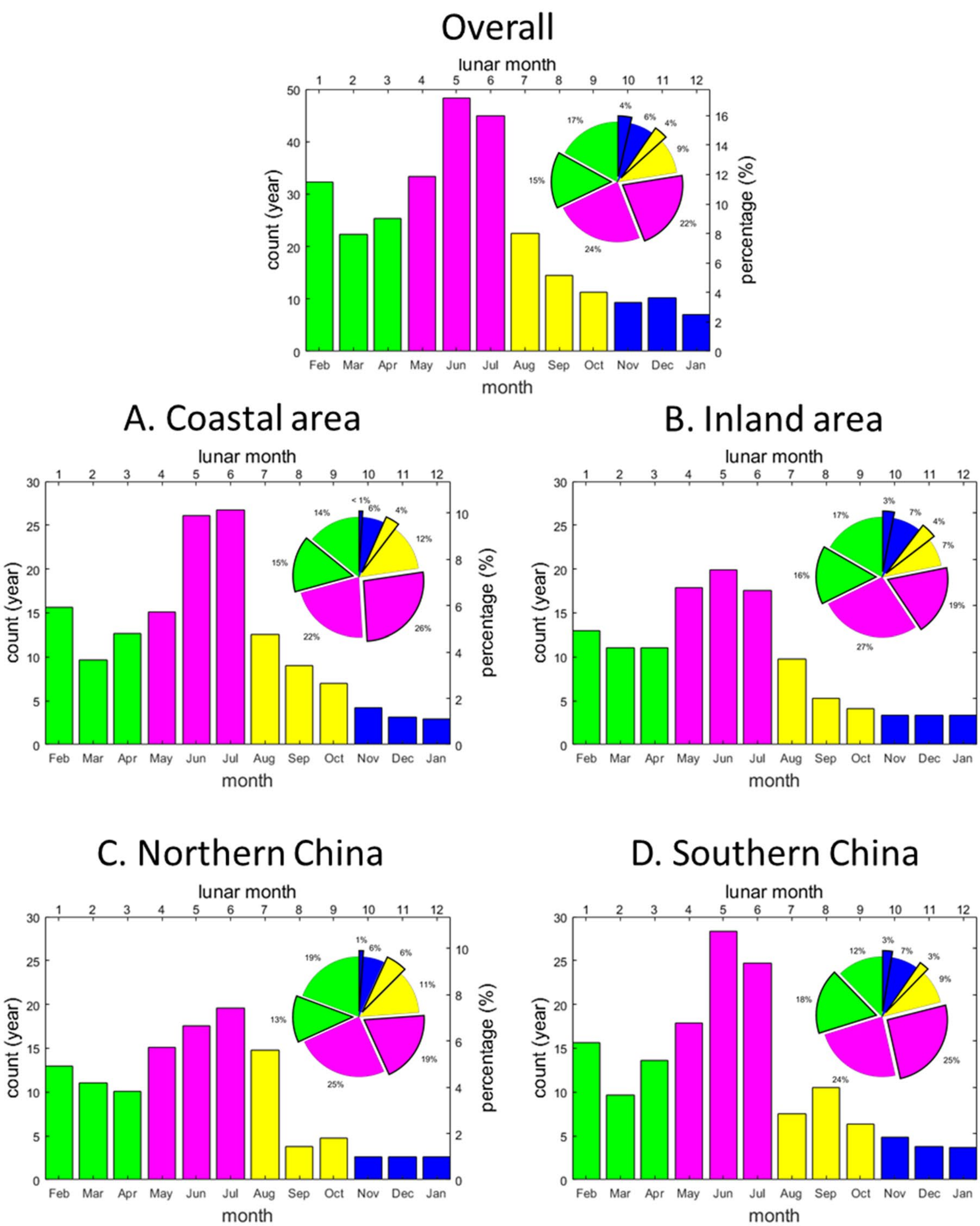

Fig. 4 Epidemic occurrence percentages of months and seasons in the overall, costal, inland, Northern and Southern areas. The lunar month of 1–12; solar month of January–December; and seasons of spring (greed bars), summer (pink bars), autumn (yellow bars), and winter (blue bars) are presented

disasters (not) occurred simultaneously in the same year; 193 years of epidemics without anomalous temperature disasters; and 330 years of irregular precipitation disasters without epidemics. The Chi-square statistics for testing of independence are further computed as $\chi^2 = 15.48$ and 17.94 for Tables 3 and 4, respectively.

Table 3 Epidemic vs disasters of anomalous temperature

	Number of years with anomalous temperature	Number of years without anomalous temperature	Total
Number of years with epidemic	56	226	282
Number of years without epidemic	186	1443	1629
Total	242	1669	1911

Table 4 Epidemic vs disasters of irregular precipitation

	Number of years with irregular precipitation	Number of years without irregular precipitation	Total
Number of years with epidemic	89	193	282
Number of years without epidemic	330	1299	1629
Total	419	1492	1911

Since both the Chi-square statistics are greater than $\chi^2_{1,0.001} = 10.89$, the association between the simultaneous occurrences of epidemics and any natural disaster under study is significant under level 0.001. The results suggest the co-occurrence of epidemics and the disaster of anomalous temperatures or irregular precipitations. Note that there are, on the average, about one epidemic year in 7 years ($=1191/282 \approx 6.8$). To see if there is any time lag between the occurrences of epidemics and disasters, we then conduct the Chi-square independence test for the disasters owing to anomalous temperature or irregular precipitation occurred one to three years before or after each epidemic year. The significant Chi-square values in Fig. 5 indicate that the irregular precipitation and anomalous temperature preceded the epidemics by one and two years, respectively. Since Liu et al. (2022) show that natural disasters owing to temperature anomalies and precipitation irregularities occur preferentially in China during low solar activity periods. The results in Fig. 5 strongly suggest that the disasters of anomalous

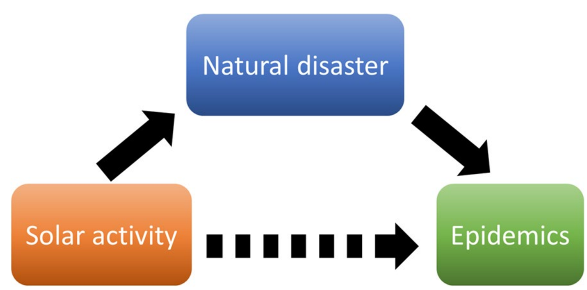

Fig. 6 Simple mediation model

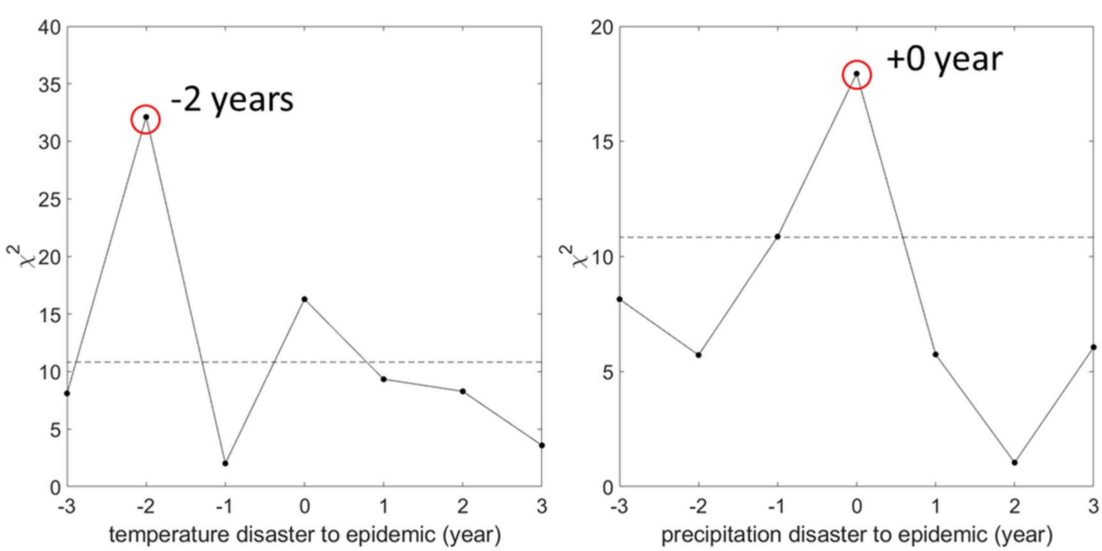

Fig. 5 Chi-square statistic for the occurrences of epidemics and disaster years of anomalous temperatures or irregular precipitations at some time lags

temperature and irregular precipitation are the mediators that link the solar activity and epidemics (Fig. 6).

Discussion

Epidemics could be related to geographical environment, solar radiations, seasons, and natural disasters due to severe weather. We examine occurrences of 224 epidemic years at inland/costal or northern/southern areas in various seasons and solar activities as well as natural disasters owing to anomalous temperatures of severe cold and extremely hot and irregular precipitations of heavy wet and severe dry in China during 1–1911 CE.

Morabia (2009) examined major epidemic outbreaks across time and place between 300 BC (before Christ) and 1911 CE in China and found the epidemiological evolution, closely matching the demographic growth, was similar in the north and south of China. Figure 1 shows that the epidemics frequently occur along the climate boundary of Qinling–Huaihe Line at about 33° N. The top four provinces of Shandong, Zhejiang, Henan, and Hubei indicates that the epidemics frequently occur around major harbors, estuaries, metropolitans or transportation hubs. As the geographic center of China, Wuhan City in the Hubei Province has been the largest land and water transportation hub in China and provided a shipping center in the middle reaches of the Yangtze River in last thousands of years. In fact, Wuhan City has been acting as Rome in China that "All roads lead to Rome." Wuhan, the capital of Hubei Province, is the largest city in central China and one of the most important industrial bases and transportation hubs of the country; it is famous for its "major juncture of nine provinces" (Jiang et al. 2021). On the other hand, the epidemic occurrences in Shandong and Zhejiang are about 5 times more likely than the average, which might be due to the fact that the former is nearby the Yellow River estuary and the latter is within the Yangtze River alluvial fan. Note that Yellow River and Yangtze River are the two largest rivers, where have been highly populated, and been called mother rivers in China. Therefore, heavy transportations and high populations are considered to contribute to epidemics.

Lee et al. (2017) examining 5961 epidemic incidents in China during 1370–1909 CE found that the overall country-wide temperature–epidemics relationship is primarily attributable to the temperature–epidemics association in northern China and central China. Table 2 shows that the epidemics in the inland or northern area occur significantly in the LSA period, and the Shandong and Zhejiang provinces, where are in central China, yield the top 2 occurrences of epidemics among the 22 provinces. The agreements between Table 2 and Lee et al. (2017) indicate the climate boundary of the Qinling–Huaihe Line being essential.

Lee et al. (2017) investigated the 5961 epidemic events in China during 1370–1909 CE and found that temperature is negatively correlated with the epidemics. Pei et al. (2015) investigating the climate–economy–epidemics mechanism in the Ming and Qing Dynasties in China during 1368–1901 CE found the negative correlation between epidemics and temperature and suggested that the warm climate could have decreased the occurrence of infectious disease in the past. Gong et al. (2020) found that on the millennial scale, the frequency of epidemics is significantly negatively correlated with temperature during the past 2200 years, which indicates that epidemics were relatively frequent in cold periods. Meanwhile, scientists find that during the LSA period, decreases of solar irradiances could lower global temperature (Eddy 1976; Reid 1987; Friis-Christensen and Lassen 1991; Lean et al. 1995; Tinsley 1996; Mann et al. 1998; Rind 2002) and affect precipitation (Verschuren et al. 2000; Kniveton and Todd 2001). The overall proportions of $P_L = 0.1406$ and $P_H = 0.1254$ show that the epidemics tend to occur during the LSA periods, which agrees well with that on the millennial scale, the frequency of epidemics is significantly negatively correlated with temperature reached by the previous studies (Pei et al. 2015; Lee et al. 2017; Gong et al. 2020).

By contrast, Fig. 4 shows that the peak (trough) of the epidemics is in summer of May–July (winter of November–January), which suggest that the frequency of epidemics is proportional to temperature. However, in each season, the epidemic occurrence percentage of the LSA period is greater than that of the HSA period in the overall area, which again show that on the millennial scale, the frequency of epidemics is significantly negatively correlated with temperature. Thus, the millennial scale yields a negative correlation, while the yearly scale reveals a positive correlation. The discrepancy might be resolved by the solar UV irradiation. Note that the solar UV irradiation in summer is about 3–4 times stronger than that in winter in each year (Sahan 2019), while the solar UV irradiation during the HSA period is about 0.3–3 times greater than that during the LSA period, with each period of about a hundred years (see Table 1). It might be due to less intense of the solar UV irradiation with a rather long-term duration (i.e., the millennial scale), the epidemics frequently occur during the LSA period (Benevolenskaya and Kostuchenko 2013). Meanwhile, Chen et al. (2023) examined the correlation between the occurrence of epidemic in ancient China and solar activity, found that there are similar periodic changes between the epidemic index and sunspot number, and concluded that the factors affecting epidemics are still unknown. However, the Chi-square statistic strongly shows that the disaster of irregular precipitations is the mediator, while the disaster of anomalous temperatures and epidemics are simultaneously modulated by solar activities. Note that severe weather disasters might not be the only cause of epidemics and the link between solar activities as well as epidemics needs further exploration (dashed line in Fig. 6).

In conclusion, in ancient China, the epidemics frequently occur and fast spread in the regions where are densely populated and/or heavy traffic. The epidemic significantly occurs in the northern or inland areas and the Shandong province during the LSA period, as well as the Zhejiang province during the HSA period, which indicate the geographic climate of the climate boundary of the Qinling–Huaihe Line and inland/coastal effects are important. In general, the epidemics tend to occur during low solar activity periods. Natural disasters due to anomalous temperature and irregular precipitation can act as mediators which significantly cause epidemics.

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All authors read and approved the final manuscript.

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Availability of data and materials
All the digitized data of epidemic, temperature anomaly, and precipitation irregularity disaster years are available from gitlab of Ionospheric Radio Science Laboratory (IRSL), Graduate Institute of Space Science, National Central University (NCU) (http://tiger.ss.ncu.edu.tw:8038/michael60109/GOSL_epidemics.git).

Declarations

Competing interests
The authors declare that they have no competing interests.

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