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Relationship between meteorological factors and mortality in patients with coronavirus disease 2019: A cross-sectional study

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ABSTRACT

Background: Recent studies on COVID-19 have demonstrated that poverty, comorbidities, race/ethnicity, population density, mobility, hygiene and use of masks are some of the important correlates of COVID-19 outcomes. In fact, weather conditions also play an important role in enhancing or eradicating health issues. Based on Chinese experience, the development of SARS and COVID-19 is partially associated with alterations in climate that align with the seasonal shifts of the "24 solar terms." However, the applicability of this pattern to other countries, particularly the United States, which has the highest global incidence and mortality rates, remains subject to ongoing investigation. We need to find more evidence to in the U.S. states verify the relationship between meteorological factors and COVID-19 outcomes to provide epidemiological and environmental support for the COVID-19 pandemic prevention and resource preservation.

Objective: To evaluate the relationship between meteorological factors and Coronavirus Disease 2019 (COVID-19) mortality.

Methods: We conducted an ecological cross-sectional study to evaluate the relationship between meteorological factors (maximum temperature, minimum temperature, humidity, wind speed, precipitation, atmospheric pressure) and COVID-19 mortality. This retrospective observational study examines mortality rates among COVID-19 patients in the three US states, California, Texas, and New York, with the highest fatality numbers, between March 7, 2020 and March 7, 2021. The study draws upon data sourced from the publicly accessible Dryad database. The daily corresponding meteorological conditions were retrieved from the National Oceanic and Atmospheric Administration Global Meteorological website (https://www.ncei.noaa.gov/maps/hourly/). This study employed multivariate linear regression analysis to assess the correlation between six meteorological factors and COVID-19 mortality. Gaussian distribution models were utilized to generate smooth curves for examining the linear association between maximum or minimum

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temperature and mortality. Additionally, breakpoint analysis was conducted to evaluate the threshold effect of temperature.

Results: We found that the death toll of patients with COVID-19 decreased with an increase in the highest and lowest ambient temperatures ($p < 0.001$). In our study, we observed a seasonal difference in mortality rates, with a higher number of deaths occurring during winter months, particularly in January and February. However, mortality rates decreased significantly in March. Notably, we found no statistically significant correlation between relative humidity, average precipitation, and average wind speed with COVID-19 mortality (all $p > 0.05$). Daily COVID-19 death was negatively correlated with the maximum temperature ($\beta = -22$, 95% CI, -26.2 to -17.79 –, $p < 0.01$), while the maximum temperature was below 30 °C. Similarly, the number of deaths was negatively correlated with the minimum temperature ($\beta = -27.46$, 95% CI, -31.48 to -23.45, $p < 0.01$), when the minimum temperature was below 8 °C. Our study found a significant association between temperature and COVID-19 mortality, with every 1 °C increase in maximum or minimum temperature resulting in a decrease of 22 and 27 deceased cases, respectively. The relationship between atmospheric pressure and COVID-19 mortality was not fully elucidated due to its complex interaction with maximum temperature.

Conclusions: This empirical study adds to the existing body of research on the impact of climate factors on COVID-19 prevention and resource allocation. Policymakers and health scientists may find these findings useful in conjunction with other social factors when making decisions related to COVID-19 prevention and resource allocation.

1. Introduction

Since late 2019, coronavirus disease 2019 (COVID-19), caused by the novel severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), has rapidly spread worldwide [1]. Based on the data from August 2021, there were over 202 million global COVID-19 cases, with over four million deaths globally. The highest percentage of cumulative cases correlated with the COVID-19 burden and was concentrated in America, Europe, and Asia [2].

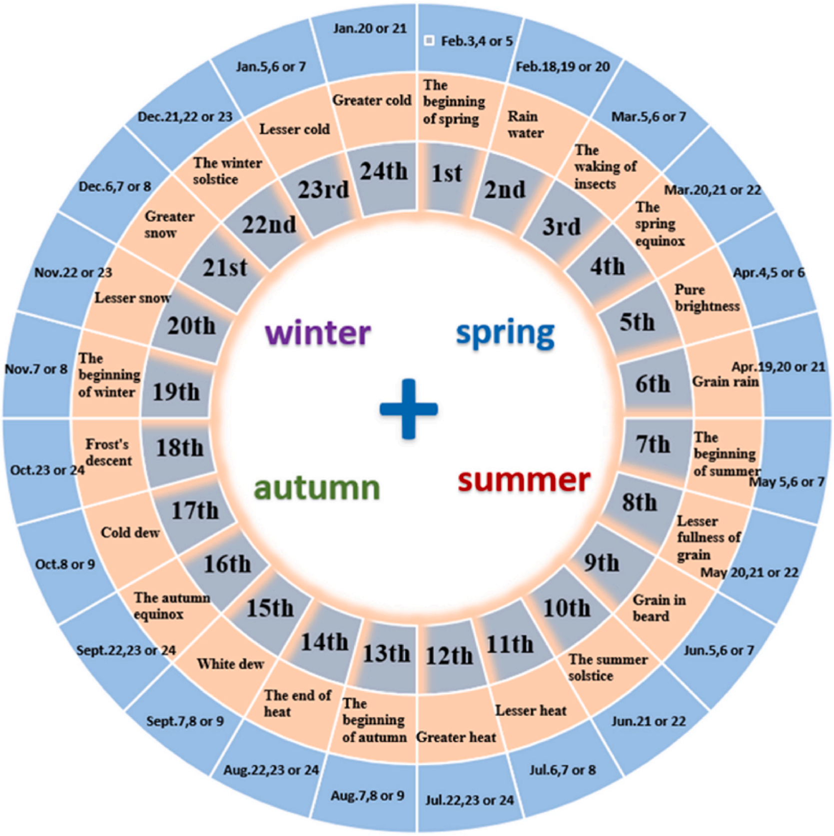

Fig. 1. The names and time divisions of Chinese "24 solar terms".

The transmission of COVID-19 infections and the resulting mortality rates are influenced by a multitude of factors. Some studies focusing on neighborhood social contexts have demonstrated that poverty, comorbidities, and race/ethnicity are some of the important correlates of COVID-19 outcomes [3]. Previous studies have suggested that patient outcomes may be impacted by a range of environmental, socioeconomic, and politico-cultural factors, including but not limited to population density, population mobility, lockdown policies, use of masks, air pollution, and access to quality medical care [4–6]. In addition, weather conditions also play an important role in enhancing or eradicating health issues.

During the Han Dynasty over two thousand years ago, Chinese ancestors established a connection between the position of the sun on the ecliptic throughout the year and the evolution of climate. This linkage was reflected in the annual movement of the sun and became known as “the 24 solar terms” theory. The year was divided into 24 equal parts based on different seasons and climatic conditions, each lasting approximately 14 days (Fig. 1). There was a proverb that summarizes the laws of pandemic development, indicating that pandemics often begin during “Greater snow,” start at “The winter solstice,” are born at “Lesser cold,” grow during “Great cold,” flourish at “The beginning of spring,” weaken at “Rain water,” decline during “The waking of insects,” end at the “Spring equinox,” and are extinguished at “Pure brightness.” Different solar terms are distinguished by various climatic characteristics, such as temperature, humidity, precipitation, wind speed, atmospheric pressure, and other parameters. The Severe Acute Respiratory Syndrome (SARS) outbreak in China in 2003 followed this law of development, with the earliest cases occurring in Guangdong in December around the time of “Greater snow,” peaking during “Great cold,” and gradually decreasing after “Rain water.” Some clinical examinations suggested that COVID-19 patients are similar to those of SARS [7]. Reviewing the epidemic trend of COVID-19 from the end of 2019, it somewhat followed the same pattern of fluctuations with climate change [8]. In 2021, a new variant strain of COVID-19, Omicron, emerged in South Africa during the winter season, as well.

What is the relationship between climate factors and COVID-19 incidence and mortality? Numerous studies have examined the impact of temperature, humidity, wind speed, and other meteorological factors on the rates of pneumonia [9], SARS [10], and COVID-19 [11–13]. While most studies have found that high temperature and high humidity can partially reduce the reproduction and mortality rates of COVID-19, some have failed to identify a significant association. The discrepant results may be attributed to regional differences, inconsistent climate parameters, exposure assessments, policy interventions, socioeconomic status, and public health services [14,15].

To mitigate the influence of geographic, economic, and policy disparities across various nations on COVID-19 mortality, this investigation solely concentrates on patients within the United States, one of the countries that experienced a high fatality rate due to COVID-19. A retrospective analysis of data was carried out to examine the correlation between meteorological parameters and COVID-19 mortality. Additionally, the study aimed to confirm the applicability of the epidemiological laws of the 24 solar terms in China to the United States.

To the best of our knowledge, most studies have examined the relationship between climatic factors, especially temperature, and the incidence, not mortality of COVID-19 in the United States, with time span usually less than six months [16–18]. Carson R.T. et al. [19] concluded that COVID-19 death counts are strongly influenced by changes in maximum daily temperature. However, Karimi S.M [20] collected weather data of 3141 US counties, including minimum and maximum daily temperature, precipitation, ozone

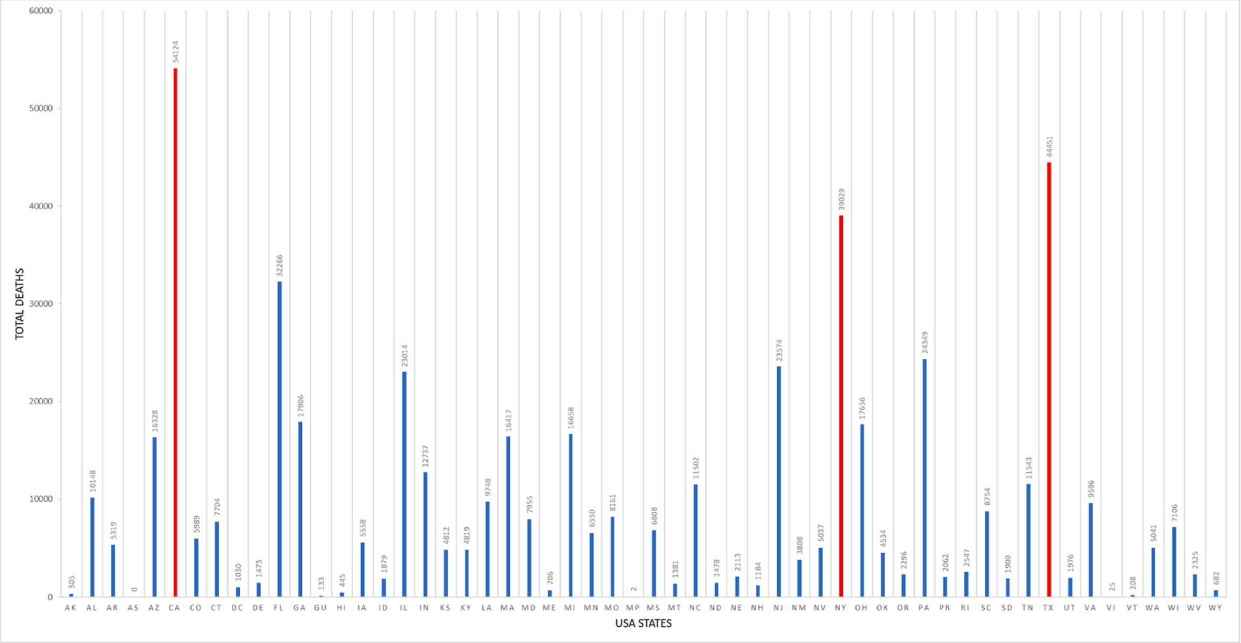

Fig. 2. Comparative histogram of COVID-19 deaths in states of America from March 7, 2020 to March 7, 2021.

concentration, PM2.5 concentrations, and U.V. light index, and found the association between weather changes and US COVID-19 fatality rates only appeared to be associated with minimum temperature and ozone levels. Some studies discussed about the relationship between one or more weather parameters comprising of humidity [21,22], wind speed [23], precipitation and air pressure [24] with the COVID-19 death rate. However, the specific effect of each meteorological parameter on COVID-19 incidence and mortality remains unclear and may vary across different regions. Commonly used statistical methods include Spearman's rank correlation, descriptive statistics, and generalized additive models, with only a few studies using linear regression analysis to analyze continuous meteorological data and COVID-19 mortality [25].

The highlight of this study is the selection of one-year-long meteorological data (maximum temperature, minimum temperature, humidity, wind speed, precipitation and air pressure) and the top-three-state (California, Texas, and New York) death toll data in the United States (Fig. 2). Multiple regression models were employed to investigate the potential threshold effect between maximum and minimum temperature and COVID-19 mortality. The study's findings may contribute to the development of more effective strategies for COVID-19 prevention and resource management from an epidemiological and environmental perspective [26].

2. Methods

2.1. COVID-19 deaths data

We conducted a retrospective observational study of mortality in patients with COVID-19 in the United States from March 7, 2020, to March 7, 2021, through the Dryad public database. This database contains the daily number of positive nucleic acid detection tests, hospitalizations, and COVID-19 deaths in each state of the USA.

2.2. Meteorological materials

The corresponding daily meteorological conditions were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Global Meteorological website(https://www.ncei.noaa.gov/maps/hourly/). Three states, including California, Texas, and New York, were chosen as the study objects because of the highest death toll, representative weather conditions, and complete meteorological data. For our analysis, we utilized data from the ten nearest weather stations to each state and selected the records that were most comprehensive. Occasionally, missing values are replaced by the average of the two days before and after. Since the number of deaths in Texas had not been recorded until March 17, 2020, we summarized meteorological data from March 17, 2020, to March 7, 2021. The indicators include maximum temperature, minimum temperature, relative humidity, air pressure, precipitation, and wind speed. We collected meteorological parameters every morning at 07:59:00 a.m. for each state. For analysis, we utilized the highest and lowest values of maximum and minimum temperatures observed in the three states on the same day, while average values were employed for relative humidity, atmospheric pressure, precipitation, and wind speed at the same time point. Daily death tolls were calculated by summing the numbers from the aforementioned states.

2.3. Statistical methods

All analyses were performed using the statistical software packages R (http://www.R-project.org, The R Foundation) and Free Statistics Version 1.7 (Beijing, China). The normality of the data was assessed. Means (standard deviation [SD]) or medians (25th

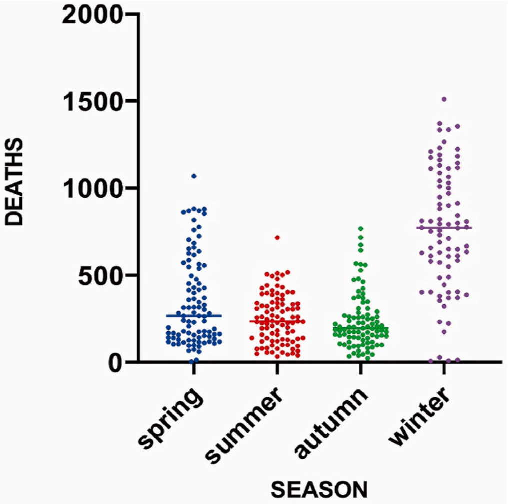

Fig. 3. Scatter chart of the number of deaths in California, Texas, and New York at one year.

percentile, 75th percentile) and proportions were calculated for the baseline characteristics. Normally distributed variables are presented as mean (SD), while skewed variables are presented as medians (interquartile range, 25%–75%). A one-way analysis of variance for continuous variables with normality was applied to compare the characteristics of COVID-19 deaths among the four seasons of the year. Tukey's method was used for multiple comparisons. Multivariate linear regression analysis was used to evaluate the relationship between climatic factors and COVID-19 mortality. To assess confounding, we entered covariance into a regression model in the basic model one by one and compared the regression coefficients. We conducted a Gaussian distribution model to develop smooth curves with maximum and minimum temperatures as independent variables, respectively, and the number of deaths as dependent variable. Meanwhile, the breakpoints were tested by segmentation function to determine the threshold effects of temperatures, adjusted by other parameters as relative humidity, daily precipitation, and wind speed. Statistical significance was set at $P < 0.05$.

3. Results

According to the records, from March 7, 2020, to March 7, 2021, 515 151 individuals died of COVID-19 in 56 states of the U.S. As can be seen in Fig. 2, California, Texas, and New York have the largest number of deaths. In California, for example, 54 124 individuals died in one year, with an average daily death toll of nearly 148. To explore the seasonal distribution of deaths, we divided the number of deaths by season: March 21 to June 21 as spring; June 22 to September 22 as summer; September 23 to December 21 as autumn; and December 22 to March 20 as winter. Figs. 3 and 4 demonstrate that COVID-19 mortality rates followed a similar pattern to "the 24 solar terms" observed in China. Specifically, the mortality rates increased during the "Great Cold" period in January and subsequently declined around the time of "The Waking of Insects" and "The Spring Equinox" in March. We further compared the independent death tolls of the three states as shown in Fig. 5. According to the line chart, the death toll in each state was still the highest in January and February and gradually decreased after April and May, except that New York State had an unexpectedly small peak in April. We also saw the August short peaks of death in California and Texas. In winter, the death tolls in December rose again.

Table 1 displays the monthly COVID-19 death tolls and corresponding meteorological parameters. Data from March 7, 2020, to March 16, 2020, were not included because of missing death data in the Dryad database. Based on the two public database sources, the relationship between meteorological factors and COVID-19 mortality was further studied using univariate Gaussian regression (Table 2). The death toll of COVID-19 was closely related to the daily maximum temperature, minimum temperature, and average atmospheric pressure (all $p < 0.01$). There was no significant correlation between relative humidity, average precipitation, and average wind speed (all $p > 0.05$). Next, we conducted a multiple regression analysis of maximum, minimum temperature, and atmospheric pressure with the death toll. With adjustment for other climate factors, the relationship remained significant between daily maximum temperature ($\beta = -22$, 95% CI -26.2 to -17.79, $p < 0.01$), minimum temperature ($\beta = -27.46$, 95% CI -31.48 to -23.45, $p < 0.01$), and COVID-19 death (Table 3). For every 1 °C increase in maximum or minimum temperature, the number of deceased cases decreased by 22 and 27 individuals, respectively. However, the relationship between atmospheric pressure and COVID-19 mortality was no longer stable after adjusting for the maximum temperature parameter, which may indicate an interaction between atmospheric

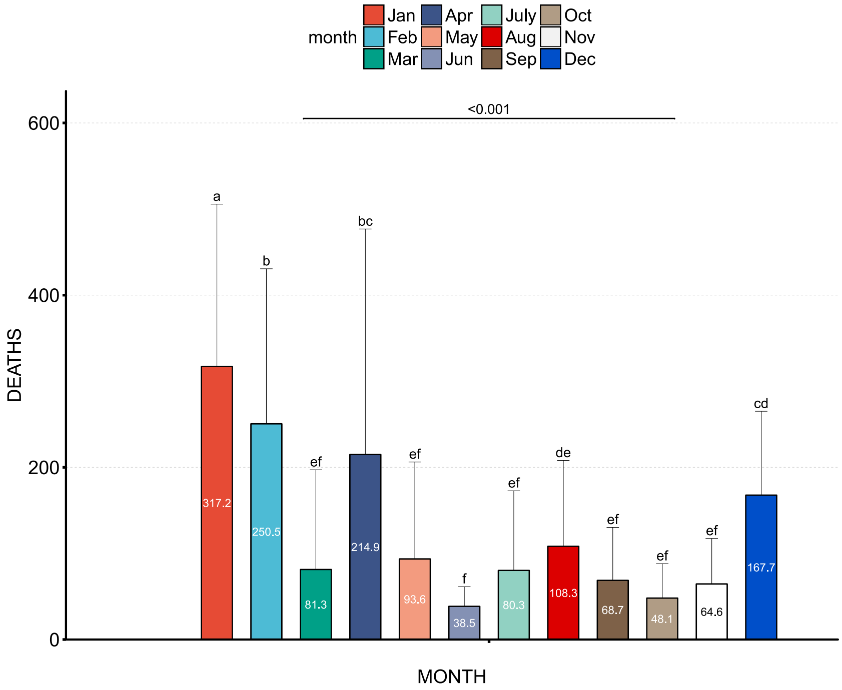

Fig. 4. COVID-19 monthly distribution histogram of total death tolls in California,Texas,and New York.

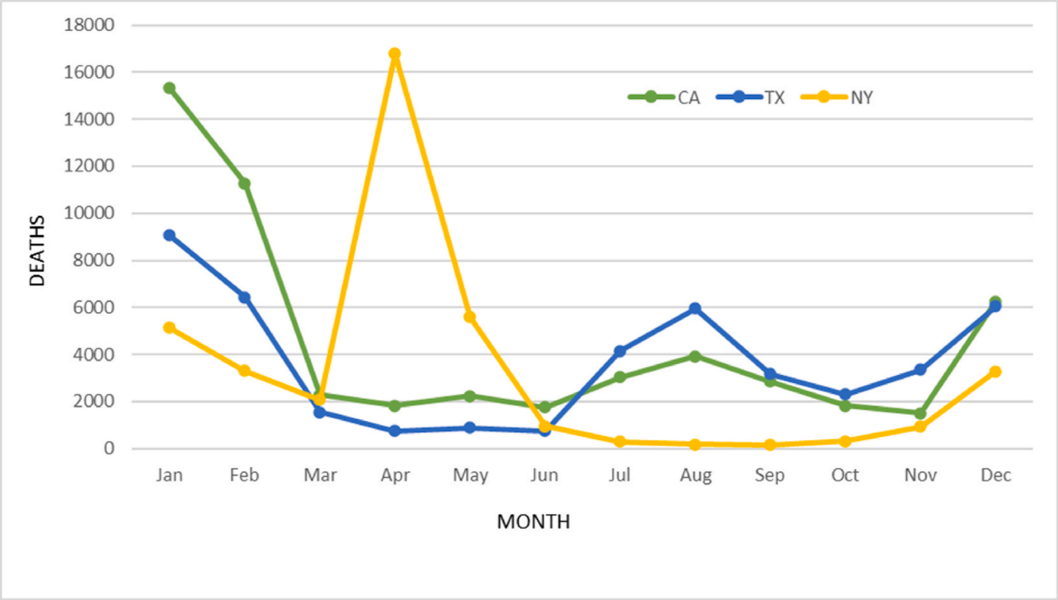

Fig. 5. Death tolls comparison between the three states: California (CA), Texas (TX), and New York (NY).

Table 1
Meteorological characteristics and daily deaths from March 17, 2020, to March 7, 2021.

Months	Daily deaths, Median (IQR)	MaxT, Mean ± SD (°C)	MinT, Mean ± SD (°C)	RH, Mean ± SD (%)	AP, Mean ± SD (hPa)	DP, Median (IQR) (mm)	WS, Mean ± SD (m/s)
Total (356 days)	281.0 (156.0, 550.8)	28.1 ± 7.0	4.1 ± 6.7	82.2 ± 6.2	1016.2 ± 3.9	1.7 (0.0, 16.2)	3.5 ± 0.9
Jan (n = 31)	1030.0 (783.0, 1186.0)	20.4 ± 3.0	−4.3 ± 3.8	83.2 ± 5.1	1018.5 ± 4.3	6.7 (1.0, 32.6)	3.4 ± 0.7
Feb (n = 28)	734.0 (533.0, 979.8)	20.9 ± 4.2	−5.1 ± 3.9	80.8 ± 4.7	1019.1 ± 4.2	2.2 (0.0, 6.3)	3.1 ± 1.4
Mar (n = 22)	194.0 (38.5, 390.5)	24.0 ± 3.8	−0.6 ± 4.9	83.3 ± 6.8	1018.2 ± 3.5	14.5 (1.0, 27.2)	3.6 ± 0.8
Apr (n = 30)	630.5 (540.2, 772.0)	25.9 ± 5.9	2.5 ± 3.0	84.7 ± 5.9	1014.0 ± 2.8	5.2 (1.2, 20.0)	4.0 ± 1.1
May (n = 31)	266.0 (176.5, 315.0)	32.1 ± 4.0	7.8 ± 4.6	81.3 ± 5.6	1014.8 ± 1.9	2.7 (0.4, 25.9)	3.9 ± 1.0
Jun (n = 30)	118.5 (97.2, 139.2)	33.5 ± 1.7	10.7 ± 2.2	80.3 ± 8.1	1014.0 ± 4.1	0.0 (0.0, 7.8)	3.9 ± 0.7
Jul (n = 31)	235.0 (157.5, 302.5)	37.3 ± 2.3	11.4 ± 1.1	83.0 ± 4.7	1012.8 ± 1.5	0.7 (0.0, 14.2)	3.7 ± 0.6
Aug (n = 31)	361.0 (226.5, 427.5)	37.6 ± 2.3	10.3 ± 2.1	80.9 ± 4.5	1012.9 ± 2.4	0.0 (0.0, 5.3)	3.4 ± 0.5
Sep (n = 30)	224.5 (124.2, 271.8)	29.9 ± 3.9	8.9 ± 3.2	87.3 ± 4.2	1016.2 ± 3.6	0.0 (0.0, 4.6)	2.9 ± 0.9
Oct (n = 31)	157.0 (97.0, 178.0)	26.0 ± 6.6	5.5 ± 4.6	83.7 ± 4.8	1016.8 ± 2.5	1.7 (0.0, 26.6)	3.2 ± 0.8
Nov (n = 30)	202.0 (129.0, 249.0)	24.7 ± 2.3	2.8 ± 3.7	81.0 ± 6.8	1019.5 ± 2.6	1.0 (0.0, 13.4)	3.6 ± 0.8
Dec (n = 31)	479.0 (355.5, 638.0)	22.5 ± 2.6	−2.4 ± 3.7	77.6 ± 7.0	1018.7 ± 3.1	3.3 (0.0, 14.8)	3.6 ± 1.0
P value	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	<0.001

Meteorological factors in this table refer to: MaxT = Maximum temperature, MinT = Minimum temperature, RH = relative humidity, AP = atmospheric pressure, DP = daily precipitation, WS = wind speed. Rendered data are the mean values of three cities: California, Texas, and New York, except MaxT and MinT. The meteorological data come from different stations in each state, with a little difference in longitude and latitude. The data on March are from March 17 to March 31, 2020, and March 1 to March 7, 2021, less than one year, due to the lack of details on COVID-19 deaths in the original Dryad database.

pressure and temperature. The adjusted parameters are provided as explanatory notes below the table.

Based on the multivariable adjusted restricted cubic splines presented in Fig. 6a and b, along with the breakpoints estimated in Table 4, our study identified threshold effects of temperature after adjusting for relative humidity, daily precipitation, and wind speed. These results suggest that mortality rates gradually decreased as maximum temperatures increased; however, this correlation was no longer significant once the temperature exceeded 30 °C. In addition, we observed a significant negative correlation between minimum

Table 2
Association between meteorological factors and COVID-19 deaths by univariate regression analysis.

Item	β (95% CI)	P
MaxT, °C	−20.94 (−25.12, −16.76)	<0.001
MinT, °C	−27.12 (−31.11, −23.12)	<0.001
RH, %	−2.56 (−7.88, 2.76)	0.344
AP, hPa	14.79 (6.54, 23.05)	<0.001
DP, mm	0.42 (−0.7, 1.54)	0.464
WS, m/s	15.54 (−20.05, 51.13)	0.391

Table 3
Association between meteorological factors and COVID-19 deaths in multiple regression model.

Variable	Model 1 (unadjusted)			Model 2 (adjusted)		Model 3 (adjusted)	
	N	β (95% CI)	*P*-value	β (95% CI)	*P*-value	β (95% CI)	*P*-value
MaxT, °C	356	−20.94 (−25.11 to −16.77)	<0.001	−22.75 (−27.58 to −17.93)	<0.001	−22 (−26.2 to -17.79)	<0.001
MinT, °C	356	−27.12 (−31.1 to −23.14)	<0.001	−30.81 (−35.49 to −26.13)	<0.001	−27.46 (−31.48 to -23.45)	<0.001
AP, hPa	356	14.79 (6.57 to 23.02)	<0.001	−2.89 (−11.86 to −6.08)	0.528	−11.5 (−19.95 to -3.04)	0.008

Model 1: unadjusted.
Model 2: MaxT adjust for relative humidity, atmospheric pressure, daily precipitation, and wind speed; MinT adjust for relative humidity, atmospheric pressure, daily precipitation, and wind speed; AP adjusts for Max temperature, relative humidity, daily precipitation, and wind speed.
Model 3: MaxT adjust for relative humidity, daily precipitation, and wind speed; MinT adjust for relative humidity, daily precipitation, and wind speed; AP adjusts for Min temperature, relative humidity, daily precipitation, and wind speed.

temperatures and mortality rates, particularly when temperatures fell below 8 °C.

4. Discussion

As early as 2000 years ago, it was recorded in the Inner Canon of the Yellow Emperor, the earliest medical classic in ancient China, that the health of humankind was adapted to the four seasons of the earth. It is believed that periodic rhythmic changes in nature directly or indirectly affect the human body, and the human body forms many life activity rhythms in the process of adapting to nature. These periodic changes are reflected in human physiology and pathology, which can be roughly divided into four categories: circadian rhythm, monthly rhythm, annual rhythm, and super annual rhythm. The annual rhythm includes the rise and fall rhythm of Yin and Yang, death rhythm, and onset rhythm in the four seasons [27]. Since the 1980s, research on time medicine has been conducted worldwide [28,29]. Many studies have shown that death due to respiratory diseases, such as lung cancer and spontaneous pneumothorax, is related to Chinese solar terms, which divide one year into 24 time periods by meteorological factors [30,31]. The World

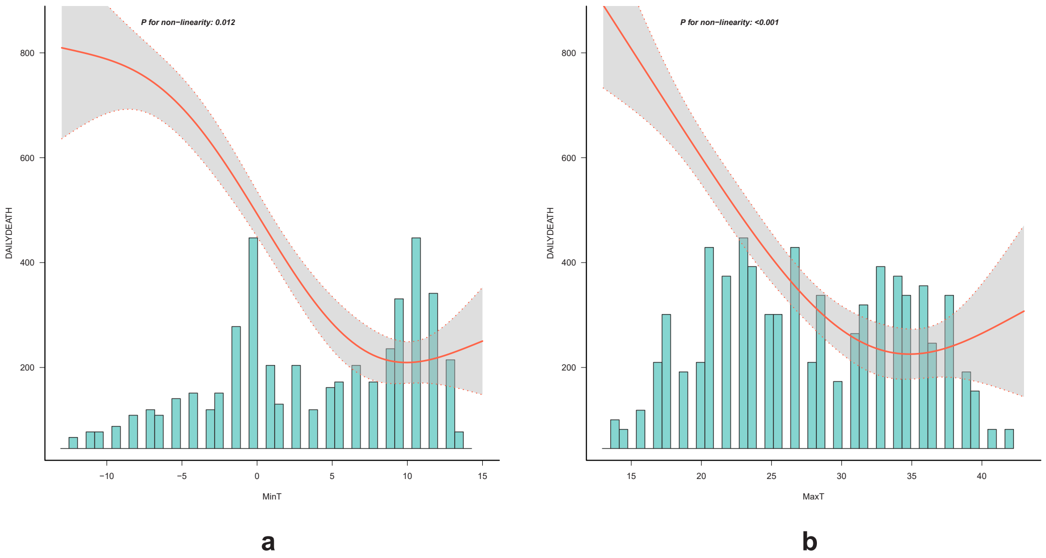

Fig. 6. Linear relationships between COVID-19 death tolls and temperature values.

Table 4

Threshold effect analysis of association between COVID-19 deaths and temperature level.

Item	β	Lower 95% CI	Upper 95% CI	P-value
MaxT[a]				
Estimated Breakpoint	30.486	30.191	30.781	
Slope 1	−37.084	−48.032	−26.136	<0.001
Slope 2	2.377	−7.172	11.925	0.623
Non-linear Test	–	–	–	<0.001
MinT[a]				
Estimated Breakpoint 1	8.624	7.809	9.439	
Slope 1	−35.387	−43.542	−27.232	<0.001
Slope 2	−5.263	−21.727	11.201	0.528
Non-linear Test	–	–	–	0.012

[a] MaxT and MinT are measured in °C, adjusted for relative humidity, daily precipitation, and wind speed, respectively.

Health Organization estimates that between 2030 and 2050, there will be approximately 250 000 deaths caused by climate change worldwide every year [32].

Excluding the influence of other social factors, meteorological factors may also have some degree of correlation with COVID-19 outcomes [33,34]. In Bangladesh, analyses showed that with a decrease in temperature and increase in wind speed, the infection rate and death increased significantly [35]. Some studies revealed negative correlation between the number of daily COVID-19 deaths and humidity in Oman, Kuwait, Qatar, Bahrain, the United Arab Emirates, Saudi Arabia, China and India [28,36–38], while few studies showed positive association [16]. A study in China found that higher average temperatures and more precipitation were beneficial for the recovery rate of COVID-19 but not correlated with wind speed and relative humidity [39]. In contrast, some studies have reported that no climate factors correlated with daily COVID-19 deaths [21,40]. A bidirectional causality between COVID-19 cases and meteorological factors, such as air pressure, humidity, and temperature, has been confirmed in other studies [41]. In our study, the death toll in winter was higher than that in summer, especially in January and February, with a small peak of death from August to September. This conclusion was confirmed in another study on respiratory diseases [42]. The above tables show that temperatures are correlated with COVID-19 death ($p < 0.01$). The study identified a negative correlation between temperature and daily COVID-19 deaths. However, the investigation also revealed the presence of threshold effects associated with maximum or minimum temperature. We did not find a correlation between relative humidity, precipitation, wind speed, and death, which may be related to the lack of significant changes in these indicators in the three states. This conclusion is slightly different from that of a previous study [28]. After adjusting for other meteorological factors, the correlation between maximum temperature, minimum temperature, and mortality was still stable, while the influence of atmospheric pressure was no longer significant. This may be related to the significant influence of air temperature and the interaction between the two factors.

Among those meteorological factors, the temperature has the greatest impact on COVID-19 death, which is consistent with previous research conclusions [4,16,37,43]. At present, the curves that study the relationship between daily temperature and the number of COVID-19 deaths generally show a U-shape, V-shape, or J-shape [44,45], and few studies have shown linear relationships between air quality indicators and COVID-19 death [46]. In our analysis, the smooth curve between the maximum temperature and COVID-19 death tolls has a breakpoint temperature of 30 °C, showing a J-shape. Meanwhile, the breakpoint of the minimum temperature curve was 8 °C. Some previous conclusions are similar to our results. For example, a significant negative correlation between temperature and death was found in New York City [18], Organization for Economic Co-operation and Development countries, Paris, and Iran [47–49]. Another study, conducted in 25 areas of Europe and the US, found that the relationship between the number of deaths/1 million people and the average monthly high temperatures was not steady in March and April [50]. The optimum temperature for diseases may be related to disease type and geographical location. Yang [51] found that the most suitable temperatures for patients with cardiovascular disease in Harbin, Shenyang, Changsha, and Guangzhou are different, which shows that the most suitable temperature in the high-temperature southern region is higher than that in the cold northern region. According to the quantile analysis conducted in Istanbul, temperature exerts a significant and positive impact on COVID-19 at higher quantiles (0.8–0.9), while its effects at initial and middle-level quantiles were deemed insignificant [4]. Another study [52] analyzed the effect of temperature on respiratory mortality in Mashhad, Iran. It was found that the risk of death increased by 1.36% for every 10 °C reduction. For the COVID-19 study in 138 countries, every 1 °C increase in average temperature, the number of confirmed and deceased cases decreased by 2047 ($p = 0.03$) and 157 ($p = 0.016$) individuals, respectively [53]. This could be because, in winter, a slight reduction in temperature can prolong the survival time of the virus in the atmosphere; thus, facilitating virus transmission. However, as high temperatures inactivate viruses by denaturing the capsid protein and glycoprotein spike, the increase in maximum temperature would prevent the virus from attaching to the host cells in summer [54]. In addition, our study shows that extraordinarily high temperatures, higher than 30 °C, are not beneficial to the prognosis of the disease. Excessively high temperature increases human perspiration, with excessive salt loss, resulting in cell electrolyte disorder and acid-base imbalance. This series of physiological reactions will lead to changes in physiological homeostasis, making the human body more vulnerable to the invasion of toxic substances. Another plausible explanation for the temperature effect may pertain to the immune system of local inhabitants, which has a correlation with weather, dietary habits, and daily routines. Specifically, low temperatures can impede blood supply, thereby hindering the delivery of immune cells to the nasal mucosa. This phenomenon can be exacerbated by indoor crowding and inadequate ventilation.

Limitations of our study include incomplete information retrieved from public databases due to data availability constraints. The meteorological data used in this study were obtained from multiple stations near the states, and the average concentration may not represent real-time exposure levels. Moreover, it is difficult to unify the season, distinguishing all the states because of the longitude and latitude differences. We attempted to verify this conclusion by comparing three typical states. In addition, other factors, such as ultraviolet radiation, air pollution, demographic data, state economic conditions, and utilization rate of medical resources, were not included in our analysis. However, through the monthly longitudinal comparison of the same state, the bias in the results caused by different macro conditions can be offset to a certain extent.

5. Conclusion

This study expands on previous investigations by examining the association between weather parameters and daily COVID-19 deaths at the regional level across three American states. Our findings demonstrate that the “24 solar terms” pattern of pandemic progression observed in China also applies to the US population. Moreover, we discovered a consistent relationship between temperature and COVID-19 mortality, including threshold effects for maximum and minimum temperatures. The results can be useful to policymakers in the government and health organizations to make decisions before the possible surge of COVID-19 cases depending on the weather forecasting mechanism and provide personnel, medical supply reservation and early warning information for the surge of death cases before winter.

Despite over a century passing since the Spanish influenza pandemic, the factors driving the seasonal recurrence of viruses remain incompletely understood. Given the unpredictable nature of SARS-CoV-2, it may take some time to establish a coherent pattern. Future analyses should focus on additional factors that impact COVID-19 transmission and mortality, such as virus resistance, population density, urbanization, mobility, hygiene, and the use of masks and sanitizers.

Author contribution statement

Shanshan Xu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Haibo Li: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Zhengxiang Dai: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data. Lin Lu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Juan Wang: Conceived and designed the experiments.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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