Impact of Ambient Temperature on Mortality Burden and Spatial Heterogeneity in a Low Latitude Plateau Area: A Time-Series Study in 16 prefecture-level cities of Yunnan Province

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Abstract

Background: The relationship between climate change and human health has become one of the major worldwide public health issues.

Objective: This study evaluated the effect of ambient temperature on the mortality burden of non-accidental deaths in Yunnan Province and further explored its spatial heterogeneity among different regions.

Methods: We collected mortality and meteorological data from all 129 counties in Yunnan Province from 2014 to 2020, and 16 prefecture-level cities were analyzed as units. A distributed lagged nonlinear model was utilized to estimate the effect of temperature exposure on years of life lost (YLL) for non-accidental deaths in each prefecture-level city. The effect of ambient temperature on the total attributable fraction (AF) for death was calculated. A multivariate meta-analysis was applied to obtain an overall aggregated estimate of effects and spatial heterogeneity among 16 prefecture-level cities was evaluated by adjusting the city-specific geographical characteristics, demographic characteristics, economic factors, and health resources factors.

Results: The temperature-YLL association was nonlinear and followed slide-shaped curves in all regions. The cumulative extreme cold and mild cold effects along lag 0–21 days on YLL due to non-accidental deaths were 166.96 (95% empirical confidence interval [eCI] 45.76–288.17) and 47.57 (95% eCI 3.58–91.55), respectively. The AF for non-accidental deaths due to daily mean temperature was 5.99% (95% eCI 3.15–8.37). Cold temperature was responsible for most of the mortality burden (4.29% [95% eCI 2.78–5.67]), while the burden due to heat was low and non-significant. The vulnerable subpopulations include males, age <75, farmers, ethnic minorities, and patients with cardiovascular or respiratory diseases. Moreover, 48.2% heterogeneity in the effect of mean temperature on YLL was found after considering the inherent characteristics of the 16 prefecture-level cities.

Conclusions: This study suggests that the cold effect dominated the total effect of temperature on mortality burden, and its effect was heterogeneous among different regions, which provides a basis for spatial planning and health policy formulation for disease prevention.

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Impact of Ambient Temperature on Mortality Burden and Spatial Heterogeneity in a Low Latitude Plateau Area: A Time-Series Study in 16 prefecture-level cities of Yunnan Province

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Abstract

Background: The relation between climate change and human health has become one of the major worldwide public health issues. However, the evidence for low-latitude plateau regions is limited, where the climate is unique and diverse with a complex geography and topography.

Objectives: This study aimed to evaluate the effect of ambient temperature on the mortality burden of non-accidental deaths in Yunnan Province and further explored its spatial heterogeneity among different regions.

Methods: We collected mortality and meteorological data from all 129 counties in Yunnan Province from 2014 to 2020, and 16 prefecture-level cities were analyzed as units. A distributed lagged nonlinear model was used to estimate the effect of temperature exposure on years of life lost (YLL) for non-accidental deaths in each prefecture-level city. The attributable fraction (AF) of YLL due to ambient temperature was calculated. A multivariate meta-analysis was used to obtain an overall aggregated estimate of effects, and spatial heterogeneity among 16 prefecture-level cities was evaluated by adjusting the city-specific geographical characteristics, demographic characteristics, economic factors, and health resources factors.

Results: The temperature–YLL association was nonlinear and followed slide-shaped curves in all regions. The cumulative cold and heat effect estimates along lag 0–21 days on YLL for non-accidental deaths were 403.16 (95% empirical confidence interval [eCI] 148.14–615.18) and 247.83 (95% eCI 45.73–418.85), respectively. The attributable fraction for non-accidental mortality due to daily mean temperature was 7.45% (95% eCI 3.73–10.38%). Cold temperature was responsible for most of the mortality burden (4.61%, 95% eCI 1.70–7.04), whereas the burden due to heat was 2.84% (95% eCI 0.58–4.83). The vulnerable subpopulations include males, people aged <75 years, people with education below junior college level, farmers, non-married individuals, and ethnic minorities. In the cause-specific subgroup analysis, the total AF (%) for mean temperature was 13.97% (95% eCI 6.70–14.02), 11.12% (95% eCI 2.52–16.82), 10.85% (95% eCI 6.70–14.02), and 10.13% (95% eCI 6.03–13.18) for heart disease, respiratory disease, cardiovascular disease, and stroke, respectively. The attributable risk of cold effect was higher for cardiovascular than respiratory disease cause of death (9.71% vs. 4.54%). Furthermore, we found 48.2% heterogeneity in the effect of mean temperature on YLL after considering the inherent characteristics of the 16 prefecture-level cities, with urbanization rate accounting for the highest proportion of heterogeneity (15.7%) among urban characteristics.

Conclusions: This study suggests that the cold effect dominated the total effect of temperature on mortality burden in Yunnan Province, and its effect was heterogeneous among different regions, which provides a basis for spatial planning and health policy formulation for disease prevention.

Keywords: Mortality burden; Non-accidental deaths; Multivariate meta-analysis; Distributed lagged nonlinear mode; Attributable risk

Introduction

The association between global climate change and human health has become a profound global public health problem [1-3]. It is marked by rising average surface temperatures and heightened weather instability [4, 5]. Numerous epidemiological studies have shown that changes in ambient temperature are associated with increased risk of disease and mortality [6-10]. Both cold and heat exposure can have adverse effects on human health, including cause-specific mortality, emergency room visits, hospitalizations, and ambulance dispatch [11-15]. Specifically, temperature extremes are linked to an increased incidence of cardiovascular diseases, such as heart disease and stroke, as well as respiratory disease [16-18].

In recent years, numerous studies have investigated the impact of temperature on mortality, suggesting that non-optimal temperature may elevate the risk of chronic diseases and infectious disease transmission, thereby increasing the overall mortality burden [19-21]. For example, a prominent investigation in this field includes a worldwide study that assessed the relative risk associated with non-optimal temperatures on 176 specific causes of death [22]. The findings indicated distinct effects of heat and cold exposure on various causes of death. Additionally, a time-series analysis conducted in 272 major cities in China delved into the correlation between ambient temperature and YLL for non-accidental deaths, specifically focusing on cardiorespiratory disease [23]. The study identified an inverse J-shaped association between ambient temperature and the risk of mortality, highlighting the corresponding disease burden that is mainly attributable to moderate cold exposure in China. An association between ambient temperature and mortality risk has also been documented in India, the European Union, South Africa, and various other countries and regions [6, 24-26].

However, the assessment of temperature-related mortality burden in these studies primarily involved the number of deaths or mortality rate as the prevailing indicators, treating all deaths equally important [6, 7, 27]. As compared with the number of

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deaths or mortality, years of life lost (YLL) is more informative because it considers life expectancy and assigns a higher weight to deaths at younger ages [28]. Meanwhile, the attributable fraction (AF) can be combined with YLL to adequately reflect the effects of temperature exposure and ensure a comprehensive analysis. AF estimates the proportion of deaths that would not have occurred in the absence of an exposure, and it has important policy implications pointing to the potential impact of an intervention [29].

Despite numerous studies on the mortality burden of temperature, the results have been inconsistent due to global differences in environmental, geographical, economic, and demographic factors [8, 30]. In other words, spatial heterogeneity should be considered when comparing different regions. However, existing studies on the spatial heterogeneity of the effect of temperature on mortality burden are limited, with a few focusing on specific causes of death or only on heat effects [4, 17, 31]. Moreover, comprehensively analyzing spatial heterogeneity is difficult when study areas are restricted to individual cities or study areas with little variability in the geographic characteristics.

Yunnan Province is located on the Yunnan-Guizhou Plateau, with a particular geographical location, complex topography, and unique and diverse climatic environments. This situation results in a diversity of ethnic, economic, and health resource factors in Yunnan Province. Thus, the province is an ideal place to study the spatial heterogeneity of its different cities. Our previous studies examined the association between temperature exposure and YLL in several cities of Yunnan Province but did not investigate spatial heterogeneity because of lack of data from eastern, northern, and central cities [32, 33].

Therefore, this study used the entire Yunnan Province counties, representative of the low-latitude plateau region, as the study area to focus on assessing the mortality burden due to mean temperature, populations sensitive to environmental temperature exposure, and high-risk disease causes of death. Additionally, the study aimed to explore the spatial heterogeneity of the impact of mean temperature on mortality

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burden. The findings may contribute to the development of early warning strategies aimed at mitigating the risk of additional mortality due to ambient temperature in the region. Furthermore, they can inform measures to protect vulnerable populations and guide the allocation of resources and policy planning for interventions.

Methods

Ethical Considerations

The data used for this analysis were aggregated and had no identifiable information about the study subjects. Therefore, this study did not require research ethics committee approval.

Study site

This study selected all 129 county-level mortality monitoring sites in Yunnan Province, Southwest China, using 16 prefecture-level cities as units of analysis (Figure 1). Yunnan Province belongs to the subtropical plateau monsoon climate zone, with remarkable 3-D climate, various types, minor annual temperature differences, sizeable daily temperature differences, and distinct wet and dry seasons. Also, the temperature changes vertically with terrain height.

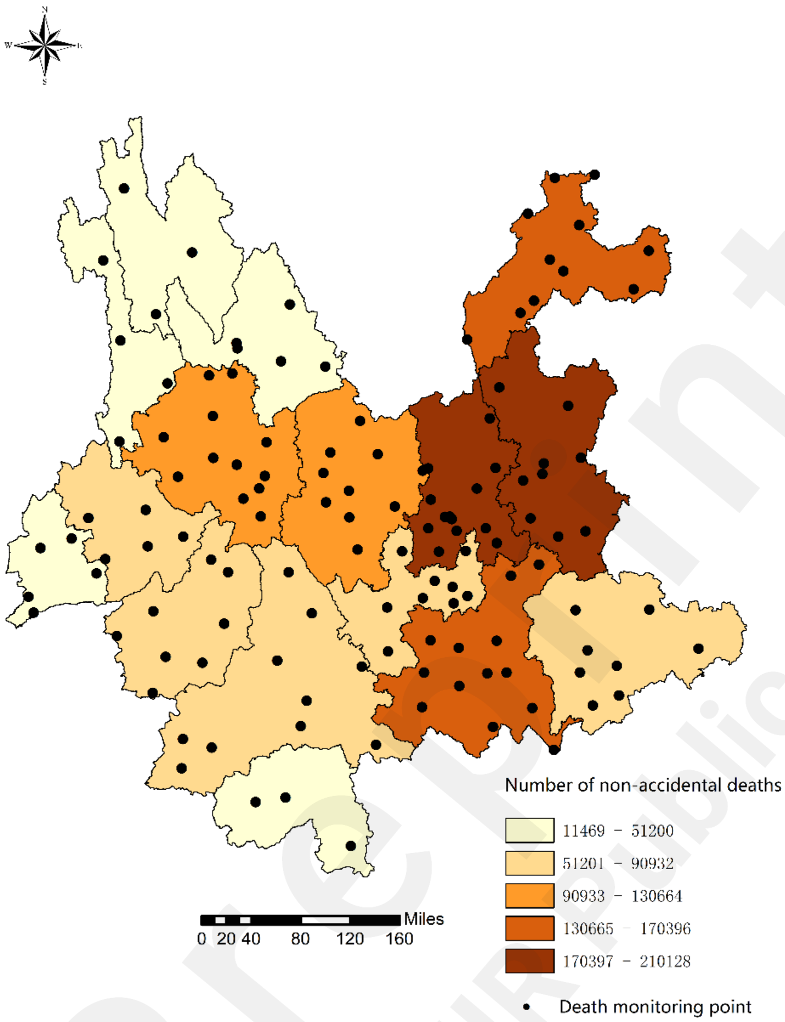

Figure 1. Spatial distribution of non-accidental mortality for the 16 cities and 129 death monitoring points in Yunnan Province in China, 2014–2020

Data collection

The study compiled all-cause mortality data for residents across all 129 counties in Yunnan Province from January 1, 2014, to December 31, 2020, using the Yunnan Centre for Disease Control and Prevention's death registration reporting system. To define the five causes of death [23, 34], we used codes from the International Classification of Diseases, 10th revision (ICD-10), namely total non-accidental deaths [A00–R99], cardiovascular disease [I00–I99], heart disease [I00–I51], stroke [I60–

I69], and respiratory disease [J00–J99]. Furthermore, total non-accidental deaths were classified according to age (< 75 or ≥ 75 years), sex (male or female), occupation (farmer, staff, or other), ethnicity (Han nationality or ethnic minorities), marital status (married or non-married), and education level (junior college and above or below junior college).

Daily meteorological data for the corresponding period were acquired from the China Meteorological Data Sharing System, encompassing parameters such as mean temperature, wind speed, atmospheric pressure, relative humidity, and sunshine duration. The geographical and social characteristics of the 16 prefecture-level administrative regions during the same period were extracted from the China Statistical Yearbook and the Yunnan Statistical Yearbook. These characteristics encompassed geographical indicators (latitude, longitude, altitude), demographic indicators (population density, natural population growth rate, urbanization rate), economic indicators (gross domestic product [GDP per capita, GDP growth rate, employment rate), and health resources (number of health technicians and hospital beds per 1,000 population).

The Chinese national life table (Multimedia Appendix 1), accessible from the World Health Organization's Global Health Observatory, offers age-specific life expectancy data for male and female nationwide from 2010 to 2019. Drawing on prior research [35, 36], life expectancy for the period 2014-2020 was estimated by averaging the values from 2010 and 2019. The calculation of YLL for each death involved aligning age and sex with the reference life table, followed by the summation of YLL for all deaths on a given day to derive the daily YLL.

Statistical analysis

A three-stage analysis method widely used in previous studies [37, 38] was used to estimate the association between mean temperature and YLL. The district map of Yunnan Province was drawn with ArcGIS. All analyses were performed with R

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v4.1.0, using the packages "dlnm" and "mvmeta". Two-sided P<.05 was considered statistically significant.

First stage: time series analysis

In the first stage of the analysis, because of the normal distribution of daily YLL, we used a general linear regression model with a link Gaussian function combined with a distributed lag nonlinear model (DLNM) to assess the nonlinear and delayed effects of mean temperature on YLL [34, 39, 40]. Regarding the lag effect, according to previous studies, the maximum lag days was set to 21 days [9, 38, 41, 42]. The general model is as follows:

$$YLL_t = \alpha + \beta Temp_{t,l} + NS(Time_t, df = 7 \times 7) + NS(RH_t, df = 3) + NS(SD_t, df = 3) + NS(WS_t, df = 3) + NS(AP_t$$

where YLL_t is the observed daily YLL at day t (t=1,2,3,...,2557), α is the intercept and β is the regression coefficient for mean temperature. $Temp_{t,l}$ is the cross-base matrix of mean temperature and lagged effects generated by the DLNM, with the two internal knots located at the 27.5th and 72.5th percentiles of the daily mean temperature distribution [43]; l is the maximum number of lagged days. NS() means a natural cubic spline; long-term trends and seasonality were controlled by a natural cubic B-spline with 7 degrees of freedom (*df*) per year. Relative humidity (RH), wind speed (WS), sunshine duration (SD), and air pressure (AP) were controlled by a natural cubic spline with 3 *df* [38, 44]. DOW_t and $Holiday_t$ are days of the week and public holidays in China, represented as categorical variables included in the model, and γ and δ are the regression coefficients for *DOW* and *Holiday*, respectively [38, 45].

In this study, YLL estimates and their 95% empirical confidence intervals (eCI) were calculated to assess the impact of temperature exposure on total non-accidental mortality and its subgroups under the cold and heat effects. Cold and heat were defined as temperatures above and below the temperature with lowest YLL.

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Second stage: multivariate meta-analysis

In the second stage, city-specific estimates of the associations between temperature exposure and YLL obtained from the first stage were pooled by multivariate meta-regression. The analysis also focused on the cumulative exposure response association by summing lagged effects to avoid excessive model parameters and to improve statistical power [46, 47].

A multivariate meta-regression was fitted using the intercept only to obtain an overall pooled estimate and to assess spatial heterogeneity. City-specific characteristics (longitude, latitude, altitude, population density, natural population growth rate, urbanization rate, GDP per capita, GDP growth rate, employment rate, and number of health technicians and hospital beds per 1,000 population) were separately included in the intercept-only models to determine whether specific meta-predictors could explain spatial heterogeneity. In addition, the Wald test was used to assess the significance of these individual meta-prediction models as compared with intercept-only models. All multivariate meta-regression models were estimated using maximum likelihood estimation, with residual heterogeneity tested by the Cochran Q test and the I^2 statistic, and the goodness of fit of the models was measured using the Akaike Information Criterion [48].

Third stage: disease burden attributable to ambient temperature

A univariate random-effects meta-analysis was used to pool the risk estimates for each city to construct an overall cumulative exposure–response curve for all cities and to obtain the best linear unbiased prediction (BLUP) for each city [48, 49]. The details of this method were previously described in previous studies [9, 48]. Subsequently, we used the natural cubic spline function of the quadratic B-spline function governing the temperature–mortality association. The temperature with lowest YLL of each city served as a reference point for calculating the estimated attributable risk for YLL.

Finally, the AF was computed for both high- and low-temperature groups with the formula AF = attributable YLL / total YLL [29, 50]. The 95% eCIs for AF were estimated by Monte Carlo simulation with 1000 resampling iterations [29]. The AF (%) with 95% eCIs was used to signify the impact of mean temperature on YLL.

Results

Data description

The basic characteristics of the daily number of non-accidental deaths in Yunnan Province from 2014 to 2020 are shown in Multimedia Appendix 2. The description results of daily YLL and weather conditions in Yunnan Province from 2014 to 2020 are shown in Table 1. The average daily YLL due to non-accidental deaths was 546.1 person-years: 322.7 person-years were for males and 223.4 for females. Within the specific cause of death subgroups, the average daily YLL for cardiovascular disease, respiratory disease, heart disease, and stroke were 196.3, 82.3, 87.7, and 98.6 person-years, respectively. The daily mean temperature was 17.4℃, ranging from -4.8℃ to 29.3℃. The mean values for air pressure, relative humidity, wind speed, and sunshine hours were 844.4 hPa, 71.6%, 1.8 m/s, and 5.7 h, respectively. The overall cumulative exposure-response curves (best linear unbiased prediction) for the 16 prefecture-level cities, as well as the distribution of temperatures, are shown in Multimedia Appendix 4.

Table 1. Descriptive statistics of daily years of life lost (YLL) and weather conditions in Yunnan Province, China, 2014–2020

	Mean (SD)	Median (Q1, Q3)	Min, Max
Total non-accidental mortality	**546.1 (391.65)**	**473.7 (232.1, 770.3)**	**0, 2969.3**
Cause-specific			
Cardiovascular disease	196.3 (139.0)	177.7 (83.2, 283.8)	0, 1081.7
Heart disease	87.7 (71.6)	73.6 (31.4, 128.4)	0, 604.9
Stroke	98.6 (77.6)	86.0 (36.2, 144.8)	0, 599.2
Respiratory disease	82.3 (89.0)	54.7 (14.8, 120.2)	0, 808.2

	Mean (SD)	Median (Q1, Q3)	Min, Max
Sex			
Male	322.7 (236.8)	275.9 (135.7, 460.6)	0, 1782.4
Female	223.4 (174.9)	186.4 (86.2, 320.2)	0, 1393.5
Age (years)			
¿75	436.5 (310.2)	376.9 (192.0, 619.1)	0, 2393.3
≥75	109.5 (93.7)	88.6 (33.9, 157.2)	0, 765.3
Ethnicity			
Han nationality	384.6 (372.0)	293.4 (100.4, 506.9)	0, 2884.9
Minorities	160.2 (137.6)	123.7 (57.9, 223.1)	0, 1079.7
Marital status			
Married	467.8 (338.4)	407.8 (193.8, 665.7)	0, 2747.0
Non-married	78.2 (87.7)	59.7 (0, 119.1)	0, 841.4
Occupation			
Farmer	416.3 (297.4)	380.9 (167.4, 588.6)	0, 2659.3
Staff	20.2 (83.8)	7.3 (0, 16.2)	0, 775.5
Other	109.5 (356.2)	64.6 (0, 147.7)	0, 1836.5
Education attainment			
Junior college and above	11.2 (24.1)	0 (0, 11.3)	0, 279.5
Below junior college	534.9 (382.5)	466.2 (227.4, 757.2)	0, 2889.1
Daily meteorological measures			
Mean temperature (°C)	17.4 (5.6)	18.4 (13.6, 22.0)	-4.8, 29.3
Air pressure (hPa)	844.4 (47.7)	850.5 (818.0, 878.1)	704.3, 915.5
Relative humidity (%)	71.6 (13.6)	74.0 (63.0, 82.0)	21.0, 99.0
Wind speed (m/s)	1.8 (0.8)	1.6 (1.2 ,2.2)	0.3, 5.5
Sunshine duration (h)	5.7 (3.3)	6.2 (2.9, 8.6)	0, 12.4

Figure 2 depicts the time series curves for the number of non-accidental deaths, YLL per day, and daily mean temperature for 2014-2020. Average daily non-accidental deaths and daily life expectancy loss show a gradual annual increase, with relatively high values in January and December. There was a clear seasonality in the daily mean temperature, with relatively constant peaks each year: low peaks in January and December and from June to August.

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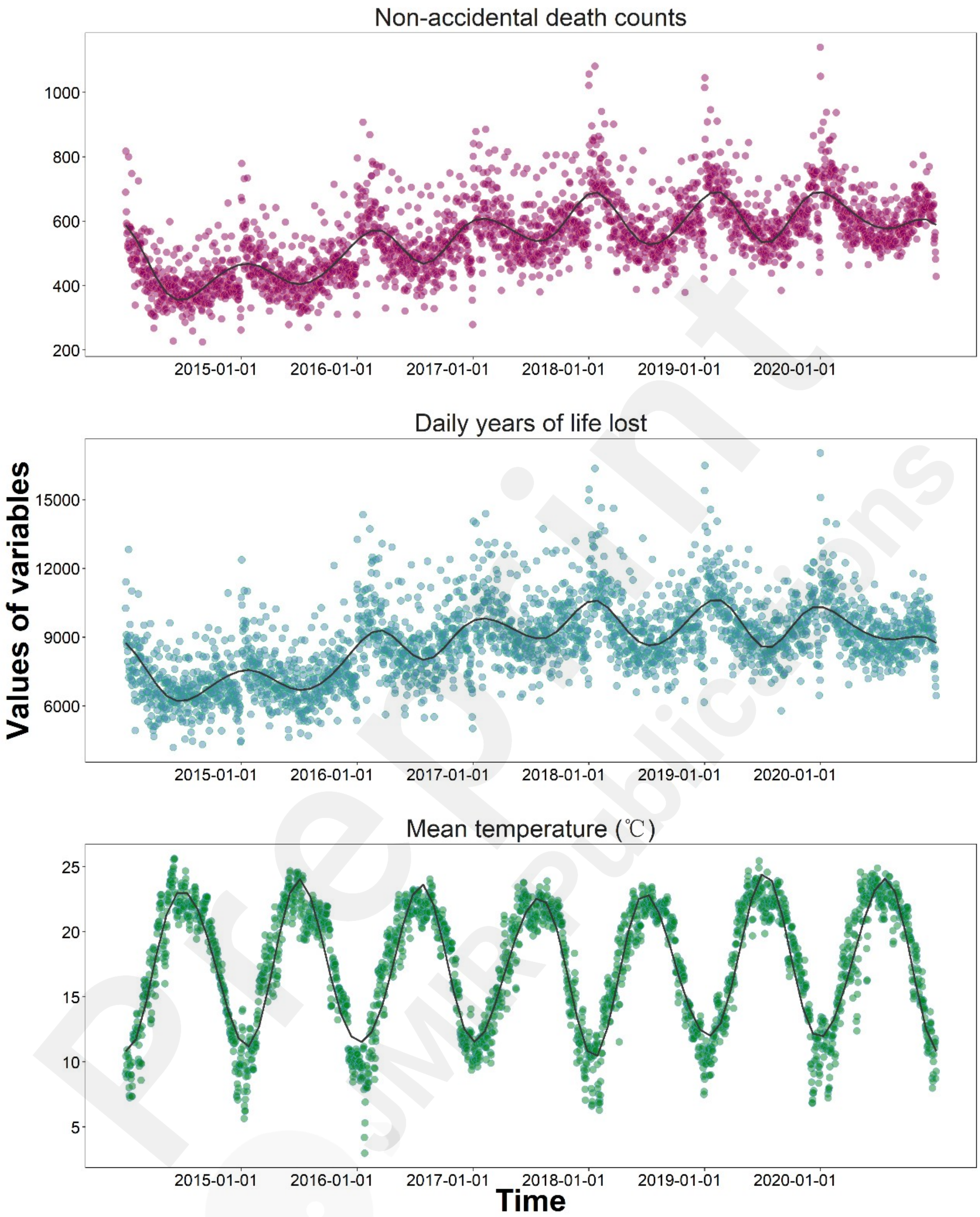

Figure 2. Time series of daily number of non-accidental deaths, daily years of life lost, and daily mean temperature, 2014-2020

Impact of daily mean temperature on YLL

Association between temperature and YLL

Figure 3 shows a plot of the overall cumulative effect of the daily mean temperature of YLL for non-accidental deaths for the 16 cities and a plot of the cumulative effect aggregated for Yunnan Province. The values marked by dotted lines in the graph are the 50th percentile of the daily mean temperature, and YLL values were calculated for different mean temperature levels relative to the 50th percentile. The association between daily mean temperature and YLL was nonlinear and had a “sliding scale” shape. Table 2 shows the YLL estimates for the effect of different temperature levels on non-accidental deaths and their subgroups. Overall, the effect of temperature exposure, especially cold, on the YLL for non-accidental deaths was significant, with effect estimates of YLL for non-accidental deaths of 650.99 (95% eCI 325.92–906.57) and 403.16 (95% eCI 148.14–615.18) for the 21-day lagged effects of overall and cold effects, respectively. The YLL values for the cardiovascular disease subgroup were significantly increased under cold conditions (304.90, 95% eCI 175.35–405.62), with no significant effect under heat conditions (35.90, 95% eCI -11.75–73.50). Among males, a noteworthy YLL estimate was observed under cold conditions (302.93, 95% eCI 187.41, 391.77) as compared with 167.64 (95% eCI -2.34–307.37) under heat conditions. In the age group < 75 years, under cold conditions, the YLL estimate was 403.63 (95% eCI 162.95–582.02), and for those aged ≥ 75 years, it was 65.81 (95% eCI 32.92–93.17). Additionally, for married individuals, under cold conditions, the YLL estimate was 313.41 (95% eCI 141.19–458.99) in contrast to 66.44 (95% eCI 1.66–107.83) for non-married individuals under the same conditions.

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Figure 3. The dose–response curves for mean temperature and years of life lost due to non-accidental mortality

Table 2. Estimated daily years of life lost for specific subgroups at different temperature levels

	Overall effect	Cold[a] effect	Heat[a] effect
Total non-accidental mortality	650.99 (325.92, 906.57)	403.16 (148.14, 615.18)	247.83 (45.73, 418.85)
Cause-specific			
Cardiovascular disease	340.80 (210.46, 440.16)	304.90 (175.35, 405.62)	35.90 (-11.75, 73.50)
Heart disease	195.99 (86.89, 274.14)	174.10 (75.55, 236.96)	21.89 (-13.86 ,46.53)
Stroke	159.79 (95.12, 207.88)	129.90 (77.08, 168.21)	29.90 (-0.37 ,56.13)
Respiratory disease	146.48 (33.14, 221.59)	59.85 (13.89, 95.40)	86.63 (-8.63, 149.76)
Sex			
Male	470.57 (255.36, 640.04)	302.93 (187.41, 391.77)	167.64 (-2.34, 307.37)
Female	258.98 (115.69, 368.94)	150.48 (34.81, 245.90)	108.50 (44.85, 164.79)
Age (years)			
¿75	635.36 (353.17, 874.06)	403.63 (162.95, 582.02)	231.73 (51.74, 377.31)
≥75	87.64 (37.64, 130.92)	65.81 (32.92, 93.17)	21.84 (-18.78, 57.09)
Ethnicity			
Han nationality	405.94 (96.07, 666.61)	200.02 (-22.52, 370.54)	205.92 (-32.86, 392.39)
Minorities	264.17 (145.78, 347.78)	214.21 (115.72, 294.22)	49.96 (-3.56, 95.14)
Marital status			
Married	549.74 (283.55, 762.00)	313.41 (141.19, 458.99)	236.33 (48.97, 398.86)
Non-married	140.07 (32.51, 205.71)	66.44 (1.66, 107.83)	73.63 (-8.52, 130.60)
Occupation			
Farmer	392.95 (169.37, 528.59)	200.60 (120.24, 258.14)	189.14 (3.10, 309.40)
Staff	72.48 (21.23, 92.07)	45.20 (6.57, 63.42)	27.77 (2.58, 38.85)
Other	228.57 (114.40, 284.49)	144.21 (66.05, 190.19)	86.10 (3.66, 124.02)
Education attainment			
Junior college and above	38.84 (-2.92, 52.17)	22.09 (3.92, 26.19)	16.75 (-17.78, 35.52)
Below junior college	635.13 (337.53, 885.24)	391.94 (145.06, 604.87)	243.19 (46.45, 403.71)

[a] Cold and heat were defined as those below and above the temperature with lowest YLL

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Spatial heterogeneity of the effect of mean temperature on YLL

The results of the meta-analysis (intercept only) and multivariate meta-regression (one meta-predictor) of mean temperature with YLL random effects are in Table 3. In the analysis of spatial heterogeneity in the effect of mean temperature on YLL, the heterogeneity across cities was statistically significant according to Cochran's Q test (Q=115.8, *P*<.001), with 48.2% of the heterogeneity due to actual differences between the 16 prefecture cities. Urban characteristics such as longitude, population density, urbanization rate, GDP per capita, and number of health technicians and hospital beds per 1,000 population could explain some of the spatial heterogeneity, with urbanization rate accounting for the highest proportion of heterogeneity (15.7%).

Table 3. Spatial heterogeneity of the effect of mean temperature on years of life lost

Predictors	Wald test			Model fit	Cochran Q test			I^2
	Stat	df[a]	*P*	AIC[b]	Stat	*df*	*P*	(%)
Reference model								
Intercept	-	-	-	792.0	115.8	60	<.001	48.2
Geographical indicators								
Longitude	21.9	4	<.001	755.4	87.6	56	.004	36.1
Latitude	2.9	4	.569	767.2	109.3	56	<.001	48.8
Altitude	4.4	4	.359	814.9	105.1	56	<.001	46.7
Demographic indicators								
Population density	19.6	4	<.001	790.5	90.0	56	.003	37.8
Natural population growth rate	2.8	4	.591	765.8	111.1	56	<.001	49.6
Urbanization rate	31.6	4	<.001	732.6	83.0	56	.011	32.5
Economic indicators								
GDP per capita	13.9	4	.007	826.9	100.5	56	<.001	44.3
GDP growth rate	4.4	4	.358	735.7	102.2	56	<.001	45.2
Employment rate	7.9	4	.100	733.5	108.2	56	<.001	48.3

Health resource indicators								
Number of health technicians per 1,000 population	11.1	4	.026	758.3	105.3	56	<.001	46.8
Number of hospital beds per 1,000 population	14.6	4	.005	755.6	93.3	56	.001	40.0

[a] *df*: Degrees of freedom.

[b] AIC: Akaike Information Criterion.

[c] GDP: gross domestic product

Attributable risk for the effect of mean temperature on YLL

The impact of mean temperature on the total AF for non-accidental deaths and their subgroups is presented in Table 4. Overall, the total proportion of deaths due to temperature was 7.45% (95% eCI 3.73–10.38). The cold effect explained most of the attributable risk (4.61%, 95% eCI 1.70–7.04) compared with heat effect (2.84%, 95% eCI 0.58–4.83). In the cause-specific subgroup analysis, the total AF (%) for mean temperature was 13.97% (95% eCI 6.70–14.02), 11.12% (95% eCI 2.52–16.82), 10.85% (95% eCI 6.70–14.02), and 10.13% (95% eCI 6.03–13.18) for heart disease, respiratory disease, cardiovascular disease, and stroke, respectively. The attributable risk of cold effect was higher for cardiovascular than respiratory disease cause of death (9.71% vs. 4.54%). In the subgroup analysis of individual characteristics, the total effect of daily mean temperature on mortality was 9.11% (95% eCI 4.95–12.40), 9.10% (95% eCI 5.06–12.51), 10.30% (95% eCI 5.69–13.57), 11.19% (95% eCI 2.60–16.44), 17.74% (95% eCI 7.64–23.86), and 7.42% (95% eCI 3.94–10.34) for males, people aged <75 years, minorities, non-married individuals, farmers and those with education below junior college level, respectively, higher than their corresponding counterparts. Except for Han ethnicity group, the cold effect was similar to the overall effect of temperature exposure, and the effects were higher for populations mentioned above than their corresponding counterparts.

Table 4. Attributable fraction (%) of years of life lost to total non-accidental mortality due to mean temperature and the specified subgroups

	Overall effect (%)	Cold[a] effect (%)	Heat[a] effect (%)
Total non-accidental mortality	7.45 (3.73, 10.38)	4.61 (1.70, 7.04)	2.84 (0.58, 4.83)
Cause-specific			
Cardiovascular disease	10.85 (6.70, 14.02)	9.71 (5.58, 12.92)	1.14 (-0.37, 2.34)
Heart disease	13.97 (6.19, 19.54)	12.41 (5.39, 16.89)	1.56 (-0.99, 3.32)
Stroke	10.13 (6.03, 13.18)	8.23 (4.89, 10.66)	1.90 (-0.02, 3.56)
Respiratory disease	11.12 (2.52, 16.82)	4.54 (1.05, 7.24)	6.58 (-0.66, 11.37)
Sex			
Male	9.11 (4.95, 12.40)	5.87 (3.63, 7.59)	3.25 (-0.05, 5.95)
Female	7.25 (3.24, 10.32)	4.21 (0.97, 6.88)	3.04 (1.25, 4.61)
Age (years)			
¿75	9.10 (5.06, 12.51)	5.78 (2.33, 8.33)	3.32 (0.74, 5.40)
≥75	5.00 (2.15, 7.47)	3.76 (1.88, 5.32)	1.25 (-1.07, 3.26)
Ethnicity			
Han nationality	6.60 (1.56, 10.83)	3.25 (-0.37, 6.02)	3.35 (-0.53, 6.38)
Minorities	10.30 (5.69, 13.57)	8.36 (4.51, 11.48)	1.95 (-0.14, 3.71)
Marital status			
Married	7.34 (3.79, 10.18)	4.19 (1.89, 6.13)	3.16 (0.65, 5.33)
Non-married	11.19 (2.60, 16.44)	5.31 (0.13, 8.62)	5.88 (-0.68, 10.43)
Occupation			
Farmer	17.74 (7.64, 23.86)	8.51 (5.10, 10.95)	9.53 (-0.79, 16.26)
Staff	12.34 (3.62, 15.68)	7.23 (1.05, 10.15)	5.11 (-5.80, 11.5)
Other	14.38 (7.20, 17.9)	8.52 (3.90, 11.24)	5.86 (-0.74, 9.29)
Education attainment			
Junior college and above	21.67 (-1.63, 29.11)	12.33 (2.19, 14.61)	9.35 (-9.92, 19.82)
Below junior college	7.42 (3.94, 10.34)	4.58 (1.70, 7.07)	2.84 (0.54, 4.72)

[a] Cold and heat were defined as those below and above the temperature with lowest YLL

Sensitivity analysis

We conducted sensitivity analyses to assess the robustness of the specified parameters in the model. Variations such as changing the maximum lag to 14 or 28 days and adjusting the degrees of freedom for the time variable to 6/year or 8/year as well as for the meteorological variable to 2 or 4 did not yield a significant difference in the AF related to YLL for non-accidental deaths concerning the temperature exposure indicator (Multimedia Appendix 3). Thus, the model demonstrated relative robustness.

Discussion

Using data from 16 prefecture-level cities of Yunnan Province, China, this province-wide research assessed the mortality burden attributable to temperature and further estimated its spatial heterogeneity. In general, the cumulative effects of ambient temperature on YLL for non-accidental deaths were nonlinear, with cold exposure contributing significantly to YLL. Moreover, geographic factors, socio-demographic information, economic status, and health resources were potential causes of spatial heterogeneity in the effect of ambient temperature on the mortality burden.

Our findings show that temperature was responsible for a significant proportion of YLL, corresponding to 7.45% of the mortality burden during the study period. As compared with high temperature, most of the mortality burden was due to exposure to low temperature (4.61% vs. 2.84%), consistent with findings from previous multicity mortality studies [9, 34, 36, 38]. Also, in the association between mean temperature and YLL, the effect estimates were higher for cold exposure than heat. The estimate of the YLL fraction attributable to ambient temperature was much lower than that reported in a previous study in Shenzhen (17.28%) [34]. This discrepancy may be explained by the special geographic location and climate of Yunnan province. Yunnan Province has a distinct subtropical plateau monsoon climate, displaying a low seasonal variation in temperature. Hence, temperature may have less effect on residents of Yunnan Province than those living in other areas. Hence, temperature may have less effect on residents of Yunnan Province than those living in other areas. Additionally, improving the health monitoring system to promptly observe temperature variations and monitor the population's health status is recommended.

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This facilitates early anomaly detection, enabling timely implementation of preventive and therapeutic interventions.

Several studies have investigated the mortality burden of temperature on different causes of death [22, 23, 51, 52]. By comparing the AF and YLL effect values of temperature on different causes of death, we found that the effects of temperature, especially cold, were more pronounced for cardiovascular than respiratory disease, which is consistent with previous studies [35, 53]. The effect of cold exposure on the cardiovascular system are usually due to potential complications associated with increased cardiovascular risk related to changes in the autonomic nervous system, blood pressure, inflammatory response, and oxidative stress [54, 55]. The effect of cold exposure temperature on the respiratory system might be due to increased respiratory infections in cold days [56]. In cardiovascular disease, the increase in mortality burden from heart disease and stroke was associated with ambient air temperature, and the attributable risk and YLL effect estimates for mean air temperature were higher for heart disease than stroke.

In comparison with prior studies conducted in Yunnan Province, our research revealed that cardiovascular disease is also affected by daily temperature changes [32]. This discovery contributes to a more nuanced understanding of the interplay between meteorological factors and cardiovascular as well as cerebrovascular disease, offering valuable insights for preventing and managing these health issues. Diverging from the findings of other investigations, we found that the influence of heat exposure on cardiovascular and respiratory disease lacked statistical significance. This discrepancy may be attributed to the distinctive temperature distribution in Yunnan, where the maximum temperature reached only 29.3 °C during the study period. In contrast, national and Shenzhen-based time-series studies, with maximum temperatures reaching 35.6 and 33 °C, respectively, confirm the significant impact of heat exposure on these diseases [57, 58]. Future research should consider a broader temperature gradient to ensure more comprehensive and comparable results. According to the study findings, it is advisable to disseminate information regarding the health effects of temperature fluctuations and educate the public on adopting suitable precautionary measures, particularly during extreme temperatures, to mitigate health risks. Moreover, improving the health monitoring system to promptly observe temperature variations and monitor the population's health status is recommended. This facilitates early anomaly detection, enabling timely implementation of preventive and therapeutic interventions.

Numerous studies have shown that demographic characteristics are an essential modifier of the association between mean temperature and health [59, 60]. In our study, we analyzed the modifying effects of potential confounders such as sex, age, ethnic group, and occupation on the effect of identifying susceptible populations to temperature. The mortality burden of temperature was greater for males, people <75 years of age, non-married individuals, farmers, and those with education below junior college level than for their corresponding counterparts. Previous research has substantiated that men are susceptible to the effects of cold [34]. This difference in the effect of temperature exposure on the mortality burden by sex may be due to biological differences and socio-economic factors. Consistent with our findings, numerous studies have identified a higher risk of mortality associated with cold exposure in younger versus older age groups [34, 60]. The observed outcome can be attributed to the prevalent practice among most older adults of staying indoors during the cold season to mitigate direct exposure to temperature extremes. Consequently, the difference in the extent and duration of exposure between younger and older age groups is the primary factor contributing to this divergence. We found that ethnic minorities, non-married individuals, and farmers were more sensitive to the effects of temperature exposure. Only a few previous studies have analyzed the modifying effects of ethnic group, marital status, and occupation on temperature effects [16, 61, 62]. Each ethnic group has its culture, food habits, and way of life, so ethnicity is also an essential factor. Compared to married, non-married individuals would be more socialization and take part in more outdoor sports. Compared to staff or others, the workplaces of farmers are mostly outdoors and are more exposed to ambient temperature, exhibit greater sensitivity to climate change than the non-farming population. Therefore, protective measures are needed to reduce the adverse effects for outdoor climate change. Additionally, education level is widely recognized as a key indicator of socioeconomic status. Individuals with lower levels of education often experience poorer living conditions and health statuses, engage in riskier behaviors, and have limited access to healthcare services [36].

This study considered geographical factors, socio-demographic information, economic status, and health resources as potential modifying factors and found spatial heterogeneity in the effect of temperature on the mortality burden across regions. The highest percentage of spatial heterogeneity was due to the urbanization rate. An early study in Zhejiang Province, China, found a rural mortality burden due to cold exposure of up to 16.4%, much higher than the urban estimate of 7.0% [63]. This finding may be due to the urban heat island effect, with urban temperatures noticeably higher than rural temperatures. GDP per capita was this study's most crucial correction factor. A study of 272 major cities in China found that GDP per capita and urbanization rates can alter the temperature–YLL association and its lag structure [23]. Another study showed a robust adverse effect of temperature on mortality in Asian cities with low GDP, with no significant association observed in cities with higher GDP [64]. We found that health resources (health technicians per 1,000 population and hospital beds per 1,000 population) similarly explained some of the heterogeneity in the temperature–YLL association. Areas with adequate health resources have better access to health care for their residents. Differences due to such health resource effects are more difficult to explain because evidence from relevant studies is sparse worldwide. Further epidemiological investigation is needed to elucidate whether and how health resources moderate or change the attributable risk of temperature on mortality.

A significant proportion of the spatial heterogeneity in the effect of mean temperature on YLL could also be attributed to longitude and population density. Available epidemiological evidence suggests that latitude and longitude may modify the association between temperature and mortality [65]. Because geographical coordinates such as longitude are usually highly correlated with local climatic characteristics (especially temperature distribution), the modification effect of geographical characteristics can be considered an indirect contribution to climate adaptation [66]. The sensitivity to temperature varies among individuals residing at different latitudes and longitudes. Areas with high population density primarily consist of economically developed cities, urban regions with industrial activities and vehicular emissions contributing to heat exposure, with the combined impact of heat island effects resulting from residential energy consumption and urban building structures. These factors, along with influences on health resources, environmental conditions, and others, can affect the association between temperature and population health [67].

There are some strengths and weaknesses to our study. The strengths include the fact that it was a comprehensive and systematic multi-city study that quantified the impact of temperature exposure on the burden of mortality in Yunnan Province, southwestern China. In addition, it was the first study in Yunnan Province to explore the causes of potential heterogeneity from multiple perspectives, including geography, socio-economic status, and health sources. However, the study had some limitations. First, the results apply only to Yunnan Province, so caution should be exercised when generalizing its findings to other, particularly non-highland, geographical areas. Second, the study assumed that everyone was exposed to the same mean temperature simultaneously, so there may be some exposure measurement bias. Third, a proportion of the heterogeneity in the results remains unexplained. Because of lack of available data, there may be essential correction factors that we failed to consider, such as vegetation cover, soil characteristics, and public health interventions.

Conclusions

In summary, temperature exposure seems to exert a substantial impact on population health across the 16 prefecture-level administrative regions in Yunnan, particularly affecting individuals with cardiovascular and respiratory diseases. The cumulative effects of ambient temperature on YLL for non-accidental deaths showed a nonlinear pattern, with cold exposure contributing more significantly than heat exposure to this effect. Specifically, under cold conditions, males, non-married individuals, ethnic minorities, and farmers were susceptible. In addition, after considering the effects of geographic characteristics, socio-demographic information, economic status, and health resources, we observed moderate spatial heterogeneity among the 16 prefecture-level cities in Yunnan Province. The implications of our study extend to both the research domain and the public health policy arena. The insights gained may assist policymakers in formulating effective intervention strategies, fortifying protection measures for vulnerable populations, and forecasting the potential impacts of climate change in this specific region.

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Data availability

The data sets analyzed for this study will be available from the corresponding author upon reasonable request.

Disclosure of AI Use

The generative artificial intelligence was not used in any portion of the manuscript writing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal

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relationships that could have appeared to influence the work reported in this paper.

Abbreviations

AF: attributable fraction

AIC : Akaike Information Criterion

AP: air pressure

BLUP: best linear unbiased prediction

df: degrees of freedom

DLNM: distributed lag nonlinear model

eCI: empirical confidence interval

GDP: gross domestic product

ICD-10: International Classification of Disease, 10^{th} revision

NS: natural cubic spline

RH: relative humidity

RR: relative risk

SD: sunshine duration

WS: wind speed

YLL: years of life lost

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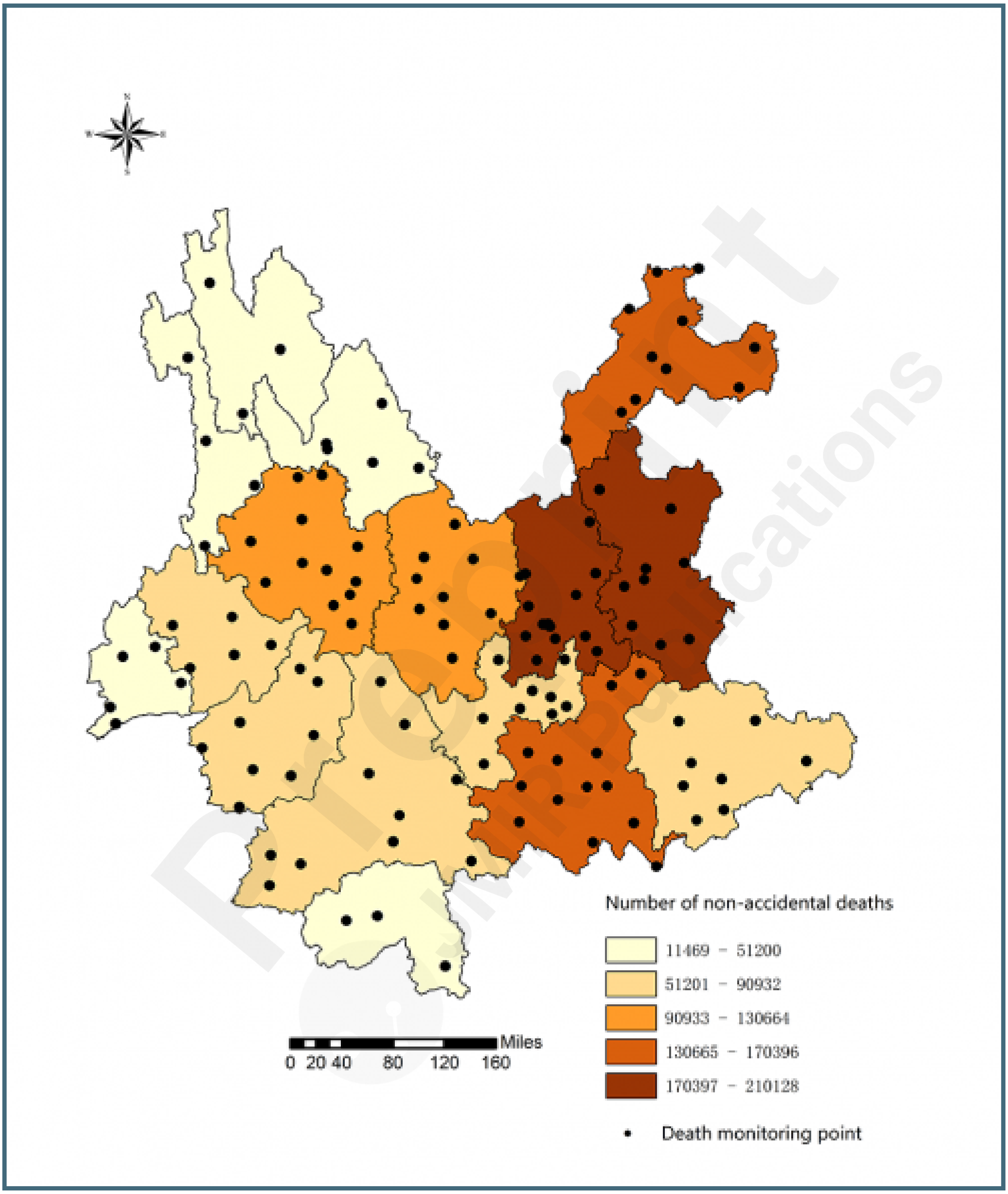
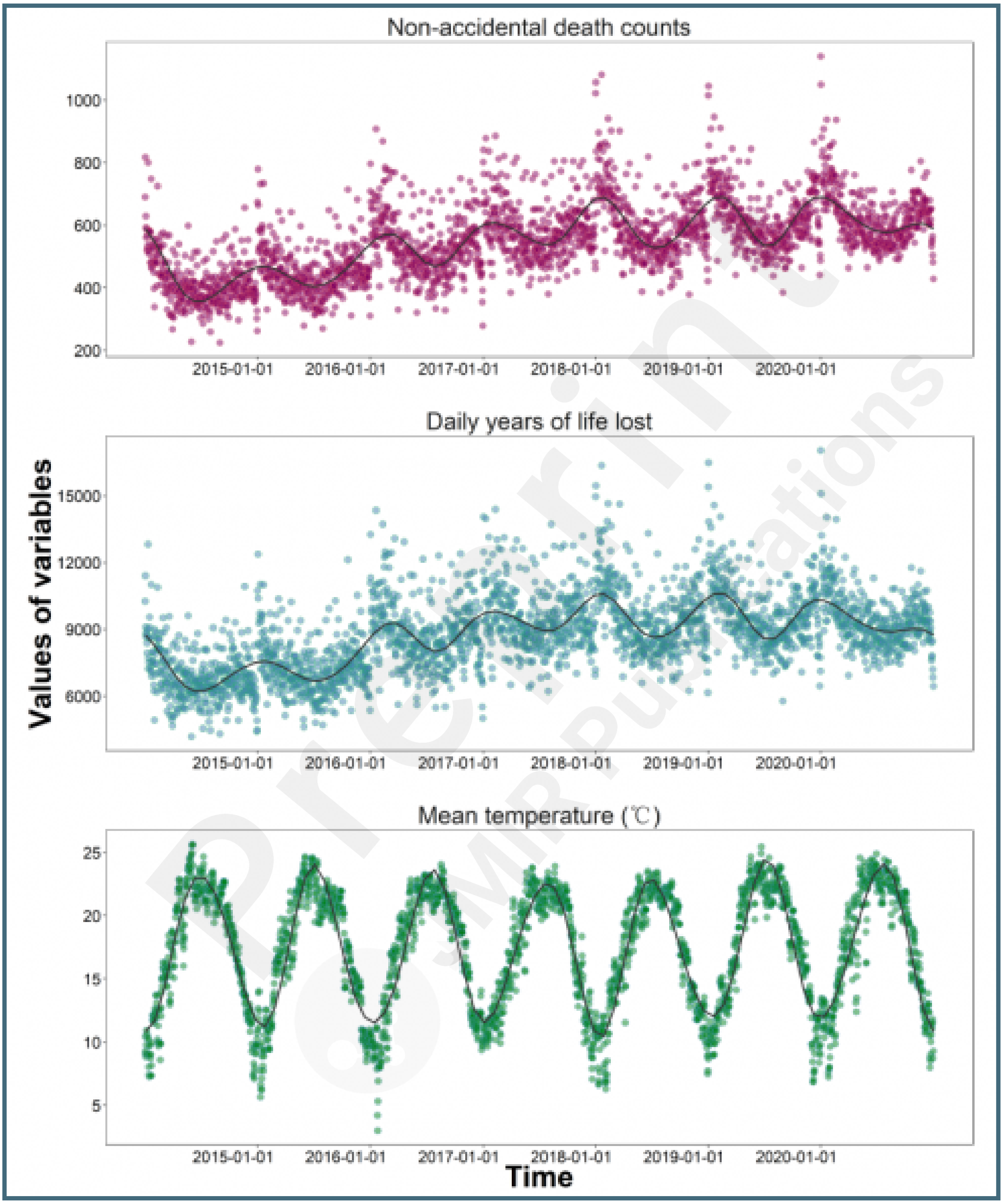
Figures

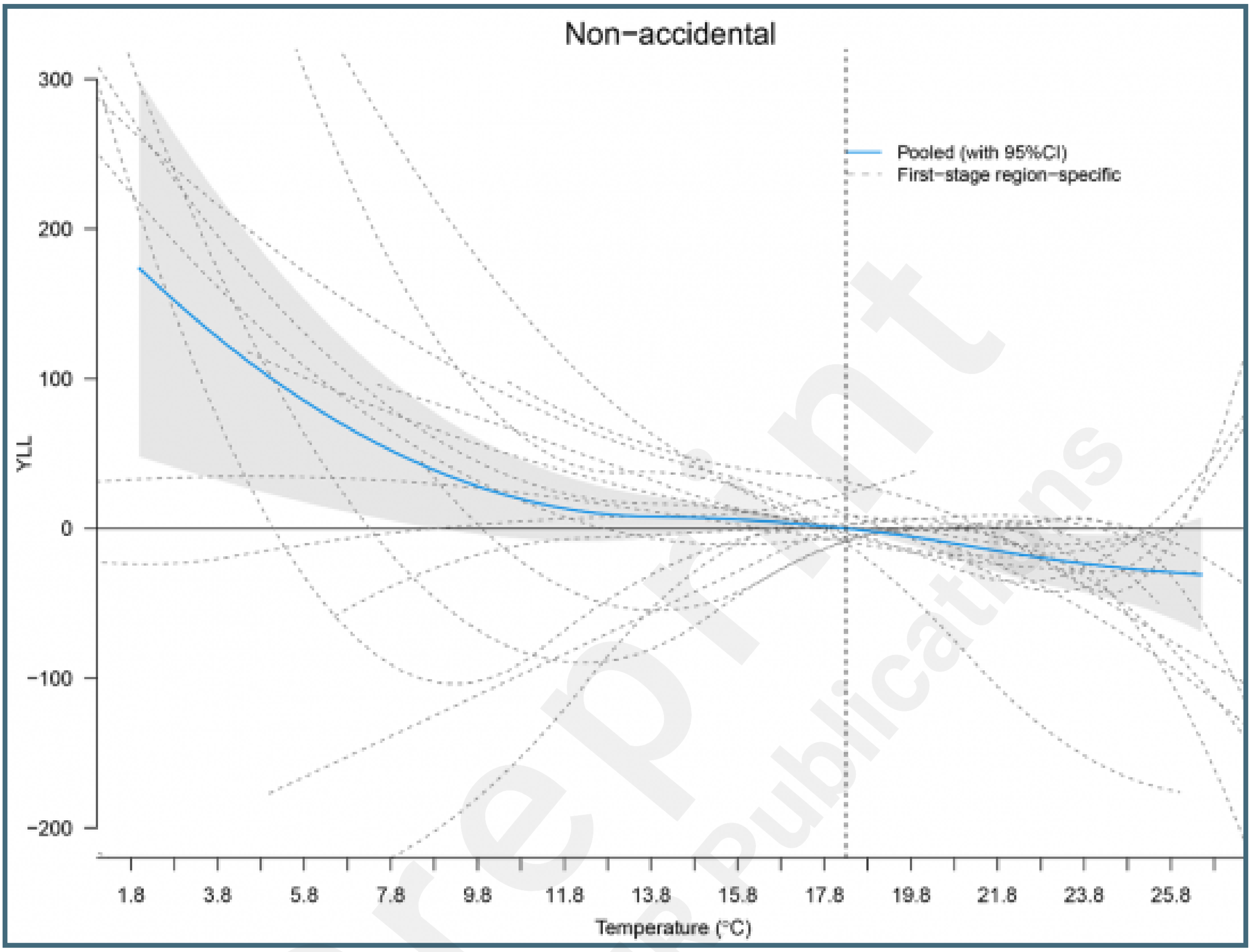
Spatial distribution of non-accidental mortality for the 16 cities and 129 death monitoring points of Yunnan Province in China, 2014–2020.



Time series of daily number of non-accidental deaths, daily years of life lost, and daily mean temperature, 2014-2020.



The dose-response curves of mean temperature and YLL due to non-accidental mortality.



Multimedia Appendixes

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Life expectancy table for Chinese population.
URL: http://asset.jmir.pub/assets/28e83db230568d6a19cbc75ac84bf910.docx

Summary statistics table for daily non-accidental mortality, by mortality causes and individual characteristics, in Yunnan Province, China, 2014–2020.
URL: http://asset.jmir.pub/assets/b7bda1e7ea37dc974a68814430c444e0.docx

Sensitivity analysis.
URL: http://asset.jmir.pub/assets/a471858181d831946ca43c4070fa034f.docx

Cumulative effect of temperature on non-accidental deaths and its temperature distribution in 16 prefecture-level cities.
URL: http://asset.jmir.pub/assets/96e1ba739ccfaff18728ade2248eda35.png

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