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Temperature and mortality on the roof of the world: A time-series analysis in three Tibetan counties, China

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HIGHLIGHTS

- Due to the rapid warming and unique high-altitude ecosystem, Tibet is considered to be highly vulnerable to global warming.
- The effect of cold was stronger and lasted longer than the heat effect.
- Vulnerable subpopulations include males, the elderly and illiterate people.
- The effect of heat was more marked for cardiovascular deaths than total non-accidental deaths.

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ABSTRACT

Background: Tibet, with an average altitude of more than 4,000 meters, is warming faster than anywhere else in China. However, there have been no studies in Tibet of the relation between ambient temperature and mortality.
Methods: We examined mean temperature and daily mortality in three Tibetan counties (Chengguan, Jiangzi and Naidong) using a distributed lag non-linear model (DLNM) based on 5,610 deaths that occurred in 2008–2012. We separately investigated hot and cold effects on non-accidental deaths, cardiovascular deaths, out-of-hospital deaths and vulnerability factors including age, sex and education.
Results: In all three counties, the effect of heat tended to be immediate, while the impact of cold lasted longer. The effects were consistent but modest in size and not statistically significant except for cumulative cold effects in Jiangzi (lag = 0–14, RR = 2.251, 95% CI = 1.054–4.849). Those who were more vulnerable to temperature extremes tended to be men, the elderly (over 65 years) and illiterate persons. We found stronger temperature effects on cardiovascular deaths than on all-cause mortality, and we also observed an increase in out-of-hospital mortality in one county.
Conclusions: This is the first study to investigate the temperature–mortality relationship in Tibet, and the findings may guide public health programs and other interventions to protect the population against extreme temperatures in a developing Tibet.

1. Introduction

The adverse impacts of both hot and cold temperatures on daily mortality have been reported worldwide (Basu and Ostro, 2008; Chung et al., 2009; Guo et al., 2012; McMichael et al., 2008). Susceptibility to temperature extremes tends to vary by cause of death, place where the death occurs, demographic and socioeconomic circumstances (Díaz et al., 2002; Martiello and Giacchi, 2010; O'Neill et al., 2003; Schwartz, 2005). Cardiovascular diseases are the number one cause of death globally and also in China. Evidence is mounting weather changes (e.g., variations in temperature) influence cardiovascular mortality and morbidity (Atsumi et al., 2013; Khanjani and Bahrampour, 2013; Madrigano et al., 2013; Wichmann et al., 2013; Zeng et al., 2012). Some studies found that those dying outside a hospital were more vulnerable to extreme cold (O'Neill et al., 2003) and heat (Medina-Ramón

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et al., 2006) than individuals who died in-hospital. It is clearly important to identify those who are most seriously affected by variations in temperature in order to efficiently target interventions and develop location-specific public health programs.

To date, most studies in the field have been conducted in developed countries, and there is less information about health effects of temperatures available from developing countries though these are considered to be most vulnerable to climate change and climate variability. Tibet of China lies at an average altitude of more than 4000 meters. This region accounts for one eighth of China's total land mass and is often called “the third pole of the world” due to extensive glaciation and the enormous volume of water held in ice sheets and snowfields. Tibet has experienced noticeable changes in climate over the past 50 years (Du et al., 2011; Liu and Chen, 2000). The temperatures in Tibet have been rising by 0.16 °C for the annual mean and 0.32 °C for the winter mean every decade since the 1960s. The rates of warming are higher than those for the Northern Hemisphere and the same latitudinal zone in the same period (Liu and Chen, 2000). A recent study claimed that winter temperatures in Tibet have been increasing at a faster rate than any other inland area of China, between 0.29 °C 1.04 °C every decade, although Tibetans still experience periods of extreme cold (Du et al., 2011). Tibetans normally rely on subsistence farming, most commonly raising yaks, and the viability of this industry is threatened by extreme weather and climate change. These peculiarities of Tibet indicate that it is important to explore effects of temperature on health in this setting and, where possible, to identify vulnerable subgroups.

The aim of this study was therefore to examine the relationship between temperature and all-cause mortality (excluding accidental deaths) in three counties in Tibet. We also aimed to identify factors that increase susceptibility to hot and cold effects. Separately, we investigated the influence of temperatures on cardiovascular deaths and deaths occurring out-of-hospital.

2. Methods

2.1. Study population and data collection

We conducted a time-series analysis using temperature and mortality data from three Tibetan counties (Chengguan, Lhasa; Jiangzi, Rikaze; and Naidong, Shannan) during the period 2008–2012 (Fig. 1). Chengguan is the urban district of Lhasa (the capital city of Tibet), while Naidong and Jiangzi are predominantly rural. These are three of the five counties that have been randomly selected by the Chinese Center for Disease Control and Prevention to carry out death surveillance in Tibet since 2008. We excluded data from the other two counties because of small numbers of deaths. The study was approved by the Ethical Review Committee of Chinese Center for Disease Control and Prevention (No. 201214).

We obtained daily mortality data for each county during 2008–2012 from the Tibetan Center for Disease Control and Prevention. Death certificates include date, place and cause of death and personal characteristics such as age, sex, occupation, ethnic group and educational attainment. Based on the *International Classification of Disease, 10th Revision, Clinical Modification* (ICD-10), we classified the data into non-accidental deaths (A00-R99) and cardiovascular deaths (I00-99). Meteorological data on daily temperature and humidity are provided by the National Climate Center. There are no data from Naidong, so we used temperature records from the nearest county with similar latitude and altitude.

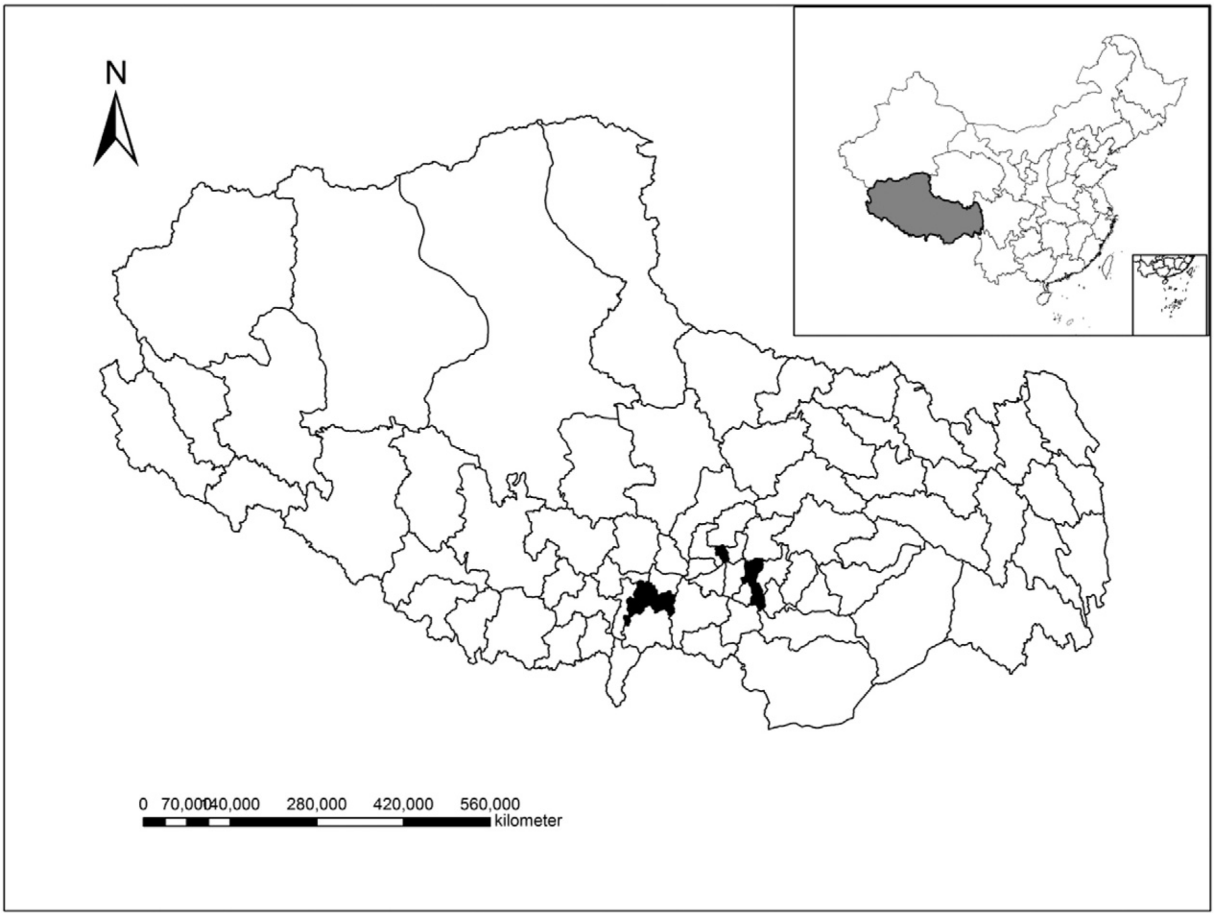

Fig. 1. The three counties (in black) into this research.

2.2. Data analysis

Previous studies showed that the effects of temperature on mortality and morbidity may be delayed in time. Accordingly, we used a distributed lag non-linear model (DLNM) to examine the relationship between temperature and daily deaths in three counties in Tibet. DLNM has recently been applied in studies to qualify effects of temperature (Guo et al., 2011; Kim et al., 2012; Lin et al., 2013; Wu et al., 2013) and air pollution (Goldberg et al., 2013) on mortality. The major advantage of this method is that it is flexible enough to simultaneously describe a non-linear exposure-response association and delayed effects or harvesting (Gasparrini, 2011; Gasparrini et al., 2010).

We controlled for seasonality and long-term trend using a natural cubic spline with 7 *df* per year for time. To control any confounding by weekly pattern, day of week was also included as an indicator in our analysis. Public holiday was controlled as a binary variable. We did not control relative humidity, as levels of water vapor in the air in Tibet vary little across the year. We evaluated the model fit using Akaike's information criterion for quasi-Poisson (Q-AIC). The results showed that models with humidity had higher Q-AIC values, indicating models excluding humidity are better fit (results not shown). Mean daily temperature was used as the primary measure of temperature in this analysis. We found it to be a better predictor (having the lowest Q-AIC values) than maximum and minimum temperatures, which is consistent with previous studies (Guo et al., 2011; Wu et al., 2013).

We used a DLNM with 4 degrees of freedom natural cubic for temperature (knots at equally spaced percentiles by default) and with 5 degrees of freedom natural cubic for lags (knots at equally spaced values in the log scale of lags by default) (Wu et al., 2013). The median values of mean temperature were used as the reference values to calculate the relative risks associated with heat and cold (Chengguan: 10.2 °C, Naidong: 10.3 °C, Jiangzi: 6.7 °C). A maximum lag of 14 days was used to completely capture the overall temperature effect in each county and adjust for possible harvesting effects (Guo et al., 2011). We examined and plotted cumulative effects on total non-accidental deaths for each county for lags 0, 0–2, 0–7 and 0–14.

Table 1
Summary statistics of temperatures and study population in three Tibetan counties during 2008 to 2012.

	Chengguan	Naidong	Jiangzi
Meteorological data			
Mean temperature (°C)			
Mean (SD*)	9.7 (6.7)	9.2 (6.8)	5.8 (6.5)
Min	−7.3	−8.1	−12.2
1st	−3.4	−4.4	−7.2
25th	3.8	3.4	0.2
Median	10.2	10.3	6.7
75th	15.5	15.3	11.8
99th	21.7	20.2	15.8
Max	22.6	21.2	16.4
Mean relative humidity (%)	32.3	42.5	35.0
Population under study (%)			
Sex			
Male	60.3	57.1	50.9
Female	39.7	42.9	49.1
Age			
0–64	59.5	50.4	45.5
≥65	40.5	49.6	54.5
Education**			
Illiterate	32.2	50.5	63.6
Literate***	61.0	45.7	32.2
Unknown	6.8	3.8	4.2
Cardiovascular deaths	39.6	52.5	34.3
Out-of-hospital deaths	51.4	75.7	90.3
Total no. of non-accidental deaths	2524	1722	1364

* Standard deviation.
** For those older than 21 years.
*** Primary school graduate or more.

Hot and cold effects were then separately examined for total non-accidental deaths, cardiovascular deaths and death occurring outside of a hospital. To understand whether the effects of hot and cold on mortality differed by age, sex and education, we fitted models for males, females, those aged 0–64 years, older than 65 year, illiterate and non-illiterate people for each county. For hot effects, we calculated relative risks associated with the 99th percentile of temperature (high temperature) relative to the 75th percentile of temperature. For cold effects, we calculated relative risks associated with first percentile of temperature (cold temperature) relative to the 25th percentile of temperature (Guo et al., 2012). The cumulative effects of hot and cold temperature along the lags were then estimated separately for different study groups in three counties.

Sensitivity analysis were conducted by varying the *df* for time from 5 to 12 per year, the maximum lag days from 7 to 20 days and the *df* for temperature and lags from 3 to 6. All statistical tests and modeling were performed using the R software (version 3.0.1). Distributed lag non-linear models were fitted through “dlnm” package (Gasparrini, 2011).

3. Results

Table 1 summarizes temperature and mortality statistics by county. A total of 5,610 deaths were included. Temperatures in Chengguan are slightly higher than those in Naidong and Jiangzi. The maximum temperature in Chengguan reached 30.4 °C on the hottest summer day in 2009, the highest recorded in the three counties during the study period. The counties differ in sex distribution at deaths, with a higher proportion of male deaths in Chengguan. Lower educational attainment and a higher proportion of out-of-hospital deaths are observed in Jiangzi and Naidong. In all counties, cardiovascular diseases are the most common cause of death.

Fig. 2 shows county-specific temperature effects on non-accidental mortality at lags 0, 0–2, 0–7 and 0–14. Non-linear dose–response relationships were apparent for three counties, with higher relative risks at extreme temperatures except for cumulative risk at lags 0–7 and 0–14 in Naidong. In all the three counties, the effect of high temperature was more immediate, as an increase in deaths was observed within a short interval. However, the effect of cold lasted longer, and this was most marked in Jiangzi.

Tables 2–4 show the cumulative temperature effects along the lags on total non-accidental deaths, cardiovascular deaths, out-of-hospital deaths and demographic-specific non-accidental deaths in Chengguan, Naidong and Jiangzi, respectively. In Chengguan, there were no effects of heat or cold on non-accidental mortality that were statistically significant ($p < 0.05$). However, some subpopulations were clearly more sensitive to temperature. Those older than 65 years tended to be at higher risk of dying on very hot days, but it was those younger than 65 years who tended to show stronger effects of cold. Illiterate people tended to be more affected by heat than those who were literate; there was no clear pattern for cold.

In Naidong, there were small effects of heat and cold on non-accidental deaths, but in every case, the 95% confidence interval included 1.0. The cumulative effects of cold on cardiovascular deaths were larger and were statistically significant. The effect of heat on non-accidental mortality was stronger among men than women, and among those over 65 compared with persons under 65 years of age.

Compared to Chengguan and Naidong, Jiangzi has lower temperatures, but the population was generally more susceptible to cold. Cumulative cold risks at lags 0–14 were generally higher than those recorded with lags 0, 0–2 and 0–7. Cold effects within 2 weeks were positively and strongly associated with total non-accidental deaths (RR = 2.251, 95% CI = 1.054–4.849) and out-of-hospital deaths (RR = 2.274, 95% CI = 1.127–5.015). Heat-related mortality risk was observed at shorter lags (0 and 0–2 days).

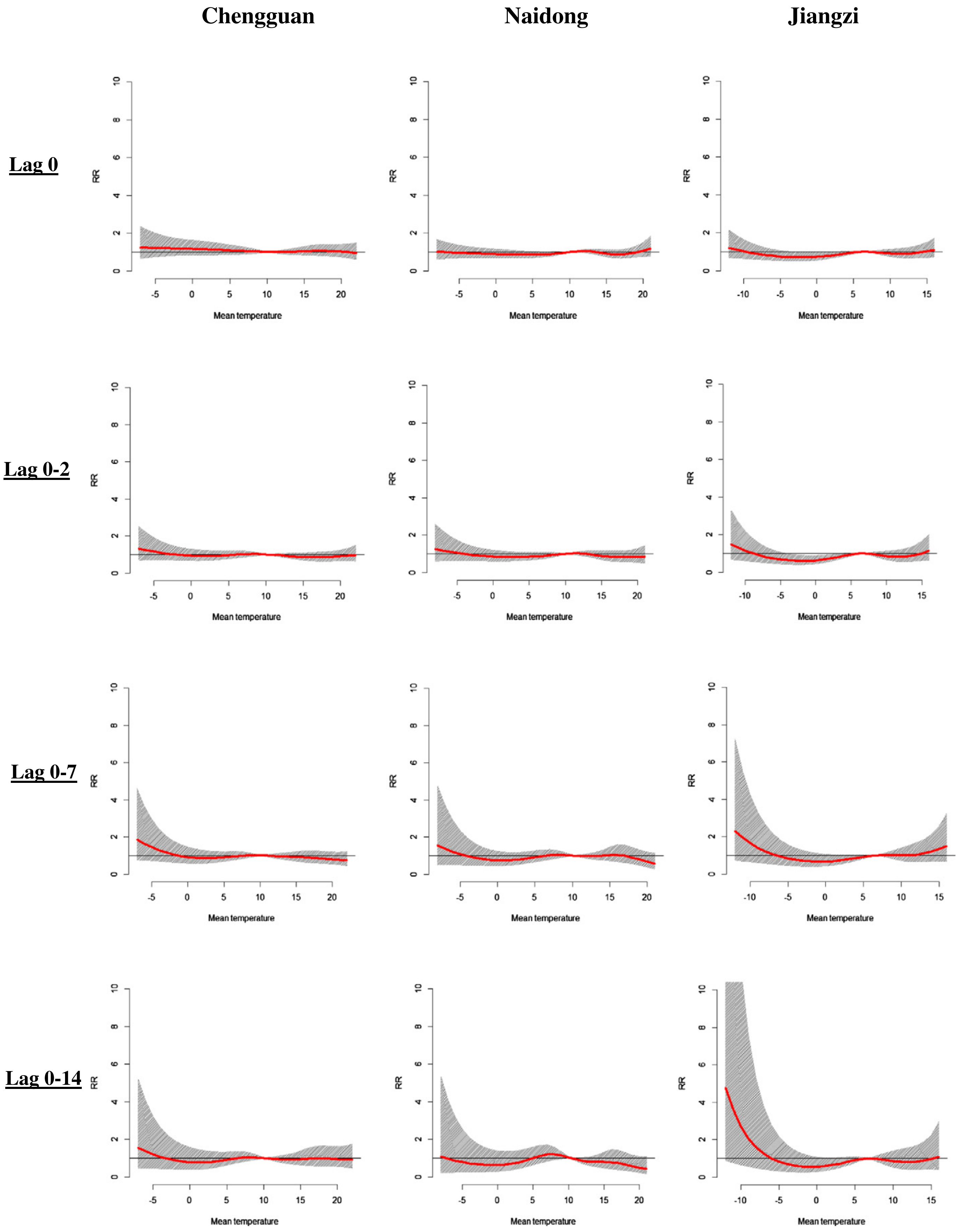

Fig. 2. Dose–response curves of non-accidental mortality in Chengguan (left), Naidong (middle) and Jiangzi (right) along lags.

Table 2
The cumulative relative risks of cold and hot effects* on non-accidental deaths, cardiovascular deaths and out-of-hospital deaths in Chengguan. Also shown are relative risks for non-accidental deaths stratified by demographic variables.

	Lag 0	Lags 0–2	Lags 0–7	Lags 0–14
Cold effect				
Non-accidental	1.017 (0.824–1.257)	1.167 (0.880–1.548)	1.395 (0.962–2.023)	1.380 (0.842–2.262)
Cardiovascular	1.105 (0.787–1.553)	1.358 (0.865–2.133)	1.449 (0.802–2.616)	1.617 (0.737–3.548)
Out-of-hospital	1.108 (0.837–1.466)	1.201 (0.828–1.742)	1.144 (0.697–1.876)	1.198 (0.622–2.308)
Male	1.018 (0.778–1.331)	1.211 (0.854–1.718)	1.456 (0.937–2.262)	1.441 (0.813–3.022)
Female	0.995 (0.718–1.379)	1.100 (0.708–1.708)	1.372 (0.764–2.463)	1.470 (0.681–3.170)
<65	0.983 (0.703–1.375)	1.319 (0.847–2.054)	**1.769** (**1.044–3.096**)	1.550 (0.732–3.280)
≥65	1.051 (0.650–1.700)	0.753 (0.493–1.444)	0.576 (0.342–1.372)	0.975 (0.529–2.887)
Illiterate	1.015 (0.698–1.478)	0.936 (0.778–1.127)	**1.192** (**1.061–1.340**)	1.634 (0.669–3.991)
Literate	0.985 (0.730–1.330)	1.272 (0.854–1.895)	1.361 (0.808–2.291)	1.523 (0.756–3.064)
Heat effect				
Non-accidental	1.091 (0.865–1.377)	0.971 (0.735–1.284)	0.934 (0.662–1.316)	0.980 (0.611–1.570)
Cardiovascular	1.058 (0.729–1.537)	**0.733** (**0.469–0.976**)	0.640 (0.369–1.109)	0.682 (0.322–1.442)
Out-of-hospital	1.072 (0.782–1.468)	0.931 (0.636–1.363)	1.073 (0.671–1.715)	1.077 (0.568–2.042)
Male	1.141 (0.848–1.535)	1.060 (0.743–1.512)	1.127 (0.728–1.746)	1.400 (0.765–2.562)
Female	1.021 (0.712–1.465)	0.847 (0.547–1.312)	0.687 (0.402–1.174)	0.562 (0.370–1.168)
<65	1.004 (0.742–1.359)	0.915 (0.636–1.316)	0.840 (0.539–1.309)	0.923 (0.501–1.699)
≥65	**1.087** (**1.003–1.182**)	1.072 (0.968–1.186)	1.096 (0.967–1.242)	1.152 (0.788–1.385)
Illiterate	1.289 (0.854–1.946)	1.155 (0.703–1.897)	1.192 (0.646–2.201)	1.252 (0.537–2.918)
Literate	1.027 (0.738–1.428)	0.818 (0.549–1.218)	0.760 (0.466–1.238)	0.779 (0.400–1.513)

* The cold effect was calculated by the 1st percentile of temperature (−4.4 °C) relative to the 25th percentile of temperature (3.4 °C). The hot effect was calculated by the 99th percentile of temperature (21.7 °C) relative to the 75th percentile of temperature (15.5 °C). The bold means statistically significant ($p < 0.05$).

3.1. Sensitivity analysis

We varied the *df* for time (range 5–12 per year) to investigate the influence of seasonality and found the results scarcely varied (data not shown). We altered the maximum lag days from 7 to 20 days, and the temperature effects were similar (data not shown). Additionally, the *df* for temperature and lags from 3 to 6 were changed, which also gave similar estimated effects.

4. Discussion

In this study, we analyzed the associations between daily mean temperature and mortality across three counties in Tibet during 2008–2012. Consistent with others, we found that cold effects on mortality lasted longer, while hot effects occurred immediately. We also observed that temperature effects on mortality in three counties varied by cause and demographic group. Some subpopulations had increased vulnerability to hot or cold temperatures, although these effects were not significantly consistent in all study locations. Males, elders (≥65 years), illiterate persons and those with cardiovascular illness tend to be at higher risks of dying from extreme temperatures. This study is, to our best knowledge, the first to examine temperature-related mortality and vulnerable subpopulations in Tibet of China. There are no actions being taken at present to protect Tibetans from extreme temperatures, mainly due to lack of awareness and limited understanding about the range and magnitude of effects. Our study points to the kinds of adaptive strategies that are needed now to minimize temperature-related deaths.

The Tibetan plateau, a part of the world that is particularly sensitive to environmental disruption, has experienced rapid changes in its climate (Du et al., 2011; Liu and Chen, 2000). If the trend continues, it is projected that Tibetans and millions of people in western China will

Table 3
The cumulative relative risks of cold and hot effects* on non-accidental deaths, cardiovascular deaths and out-of-hospital deaths in Naidong. Also shown are relative risks for non-accidental deaths stratified by demographic variables.

	Lag 0	Lags 0–2	Lags 0–7	Lags 0–14
Cold effects				
Non-accidental	1.099 (0.868–1.390)	1.186 (0.844–1.668)	1.185 (0.714–1.968)	0.943 (0.569–1.895)
Cardiovascular	1.148 (0.847–1.557)	**1.549** (**1.006–2.400**)	**1.890** (**1.083–3.627**)	1.056 (0.518–2.666)
Out-of-hospital	0.969 (0.732–1.283)	1.139 (0.759–1.709)	0.970 (0.541–1.738)	0.842 (0.476–1.647)
Male	1.040 (0.766–1.412)	1.098 (0.707–1.829)	1.125 (0.690–2.148)	0.748 (0.403–1.843)
Female	1.160 (0.799–1.683)	1.308 (0.759–2.254)	1.297 (0.672–2.938)	1.272 (0.519–3.858)
<65	1.025 (0.727–1.445)	1.128 (0.687–1.855)	1.632 (0.788–3.381)	1.501 (0.642–4.153)
≥65	1.182 (0.861–1.623)	1.242 (0.781–1.974)	0.813 (0.504–1.634)	0.644 (0.410–1.408)
Illiterate	1.251 (0.896–1.748)	**1.661** (**1.026–2.695**)	1.531 (0.737–3.183)	0.727 (0.456–2.064)
Literate	0.908 (0.645–1.276)	0.786 (0.477–1.294)	0.814 (0.591–1.695)	0.975 (0.567–2.585)
Heat effects				
Non-accidental	1.229 (0.886–1.704)	0.984 (0.659–1.469)	0.691 (0.412–1.161)	0.651 (0.320–1.322)
Cardiovascular	1.312 (0.821–2.099)	1.043 (0.684–1.862)	0.780 (0.466–1.660)	0.764 (0.472–2.143)
Out-of-hospital	1.278 (0.876–1.864)	1.032 (0.650–1.638)	0.746 (0.411–1.355)	0.630 (0.378–1.427)
Male	**1.670** (**1.108–2.519**)	1.392 (0.842–2.301)	1.112 (0.671–2.165)	1.079 (0.630–2.709)
Female	0.714 (0.516–1.226)	0.533 (0.373–1.041)	**0.345** (**0.150–0.795**)	**0.316** (**0.103–0.972**)
<65	0.993 (0.622–1.585)	0.826 (0.463–1.472)	0.690 (0.429–1.444)	0.537 (0.393–1.495)
≥65	**1.893** (**1.026–3.491**)	1.297 (0.614–2.738)	0.578 (0.316–1.546)	0.704 (0.485–2.670)
Illiterate	0.991 (0.613–1.602)	0.874 (0.585–1.575)	0.877 (0.515–1.853)	1.062 (0.676–2.998)
Literate	1.319 (0.812–2.142)	0.886 (0.587–1.609)	0.554 (0.353–1.213)	0.503 (0.375–1.442)

* The cold effect was calculated by the 1st percentile of temperature (−3.4 °C) relative to the 25th percentile of temperature (3.8 °C). The hot effect was calculated by the 99th percentile of temperature (20.2 °C) relative to the 75th percentile of temperature (15.3 °C). The bold means statistically significant ($p < 0.05$).

Table 4
The cumulative relative risks of cold and hot effects* on non-accidental deaths, cardiovascular deaths and out-of-hospital deaths in Jiangzi. Also shown are relative risks for non-accidental deaths stratified by demographic variables.

	Lag 0	Lags 0–2	Lags 0–7	Lags 0–14
Cold effect				
Non-accidental	1.132 (0.869–1.475)	1.272 (0.882–1.835)	**1.578** (**1.016–2.676**)	**2.251** (**1.054–4.849**)
Cardiovascular	1.181 (0.757–1.840)	1.410 (0.753–2.640)	1.431 (0.548–3.730)	3.677 (0.918–7.721)
Out-of-hospital	1.155 (0.879–1.519)	1.257 (0.862–1.833)	1.529 (0.885–2.642)	**2.274** (**1.127–5.015**)
Male	1.155 (0.825–1.616)	1.338 (0.837–2.139)	**2.077** (**1.045–4.127**)	**2.925** (**1.053–8.628**)
Female	1.132 (0.771–1.663)	1.251 (0.734–2.131)	1.233 (0.569–2.671)	2.343 (0.769–7.139)
<65	1.239 (0.865–1.775)	1.441 (0.875–2.375)	1.892 (0.912–3.924)	2.034 (0.711–5.821)
≥65	1.370 (0.838–2.238)	1.639 (0.831–3.233)	1.826 (0.681–4.893)	**4.031** (**1.058–7.150**)
Illiterate	1.253 (0.882–1.780)	1.427 (0.877–2.321)	**2.242** (**1.032–6.665**)	**4.225** (**1.485–7.399**)
Literate	1.011 (0.675–1.513)	1.146 (0.659–1.992)	1.416 (0.645–2.302)	1.227 (0.405–3.929)
Heat effect				
Non-accidental	1.147 (0.887–1.484)	1.233 (0.879–1.730)	1.299 (0.827–2.041)	1.215 (0.658–2.246)
Cardiovascular	1.539 (0.826–2.868)	**2.318** (**1.026–5.238**)	2.276 (0.763–6.789)	1.739 (0.482–6.916)
Out-of-hospital	1.188 (0.906–1.558)	1.281 (0.898–1.829)	1.337 (0.832–2.148)	1.315 (0.691–2.501)
Male	**1.920** (**1.047–3.524**)	1.342 (0.743–2.425)	1.862 (0.861–4.027)	1.807 (0.681–4.795)
Female	1.089 (0.758–1.565)	1.304 (0.810–2.098)	1.427 (0.755–2.696)	1.178 (0.494–2.804)
<65	1.080 (0.771–1.514)	1.180 (0.756–1.840)	1.340 (0.739–2.430)	1.173 (0.521–2.645)
≥65	1.204 (0.850–1.706)	1.216 (0.769–1.922)	1.093 (0.594–2.013)	1.111 (0.487–2.532)
Illiterate	1.267 (0.915–1.754)	1.228 (0.803–1.878)	1.166 (0.663–2.051)	1.316 (0.615–2.817)
Literate	1.331 (0.847–2.093)	**2.032** (**1.118–3.693**)	2.048 (0.911–4.603)	1.461 (0.596–4.395)

* The cold effect was calculated by the 1st percentile of temperature (−7.2 °C) relative to the 25th percentile of temperature (0.2 °C). The hot effect was calculated by the 99th percentile of temperature (15.8 °C) relative to the 75th percentile of temperature (11.8 °C). The bold means statistically significant ($p < 0.05$).

be exposed to more frequent severe weather events (Liu and Chen, 2000). In this analysis, we observed temperature–mortality relationships in different subpopulations across counties. Similar associations were observed in different areas of China including Beijing (Tian et al., 2012), Shanghai (Kan et al., 2003), Tianjin (Guo et al., 2011), Naijing (Si et al., 2011), Changsha (Wu et al., 2013), Guangzhou (Yang et al., 2012), Suzhou (Wang et al., 2013), Kunming (Wu et al., 2013), Zhuhai (Wu et al., 2013) and Hongkong (Goggins et al., 2012).

The county-specific assessment of vulnerability in our study favors more targeted assignments of adaptive interventions and resources. A similar approach was taken in multi-city investigations conducted worldwide (Bell et al., 2008; Braga et al., 2002; Iñiguez et al., 2010; Medina-Ramón et al., 2006; Stafoggia et al., 2006; Wu et al., 2013). Few have focused on the health effects of weather on a county level (Basu et al., 2008; McGregor, 2005). In China, socioeconomic structures can be quite complex, even at a fine scale. Some counties are relatively modernized with high socioeconomic level and ample resources to deal with unfavorable weather, while others, particularly those in rural and remote setting, have few resources to cope with variability and extremes in temperature. These factors may contribute to the different patterns of population vulnerability to temperature across three counties in our analysis. We conclude that county-specific studies will be needed in future research to understand the spread of vulnerability across smaller geographic units and to guide adaptive plans.

The stronger effect of cold on non-external deaths in Jiangzi may reflect the fact that the county has colder weather, longer winters, lower economic level and higher proportion of low-educated population than other two counties. Previous studies showed that the effects of both high or low temperatures were more marked for cardiovascular diseases (Atsumi et al., 2013; Khanjani and Bahrampour, 2013; Madrigano et al., 2013; Zeng et al., 2012). In this study, we observed increases in cardiovascular mortality in association with both cold and heat. In Tibet, living at extreme altitude places special strains on the cardiovascular system (Wu and Miao, 2002; Wu et al., 2007) and the typical high-fat, low-fiber Tibetan diet also contributes to high rates of heart diseases, stroke and obesity (Hu et al., 2003; Yan et al., 2001; Yang et al., 2008; Zheng et al., 2011). Future research may investigate whether temperature-related risk of cardiovascular diseases varies by specific disease category, such as stroke (Chen et al., 2013) and acute myocardial infarction (Wichmann et al., 2013). In the county with the most extreme weather, we found those dying outside a hospital were more susceptible to cumulative cold effects. This has been reported elsewhere (O'Neill et al., 2003) and indicates that community outreach and other out-of-hospital services should be considered as part of temperature adaptation.

Vulnerability to temperature-related mortality has been associated previously with sociodemographic characteristics such as age, sex and socioeconomic status (Bell et al., 2008; Stafoggia et al., 2006; Yang et al., 2012; Yu et al., 2010). In this study, we observed acute hot effects on mortality in the elderly (≥65 years) in Chengguan and Naidong and cumulative cold effects in Jiangzi. These findings were consistent with others (Guo et al., 2012; Tian et al., 2012). However, we suggest that special attention should be paid also to middle aged persons in Tibet. In a recent survey we conducted in Chengguan, we found self-reported heat-related illness was most common in persons aged 42–65 years. This is an age group commonly affected by chronic medical conditions (Hu et al., 2003), and, unlike the elderly, most middle age people are still at work and thus may be exposed more frequently outdoors to unfavorable weather.

We found that males are generally more susceptible than females to effects of cold and heat. The findings of previous studies have been mixed: some have reported that the women had higher risks than men (Stafoggia et al., 2006; Tian et al., 2012; Vaneckova et al., 2008; Yu et al., 2010), while others observed men were more severely affected (Bell et al., 2008). Tibetan men have been found to be less healthy than women in many health surveys, including studies of obesity (Yan et al., 2001), diabetes (Dawa et al., 2006; Yang et al., 2003), high blood pressure (Hu et al., 2003; Zheng et al., 2011), high blood lipids (Yang et al., 2008) and Alzheimer's disease (Zhao et al., 2002). In addition, in Tibet, men are more likely to engage in outdoor jobs and activities, which increases their exposure to extremes in temperatures.

We found that cold had a stronger effect among illiterate persons, compared with those who are literate. Education is one of the most important factors relating to one's overall socioeconomic status. Previous investigations have reported that those with low socioeconomic status have a greater vulnerability to weather-related mortality, which may be related to poorer health status, limited access to health care, poor housing conditions, lack of knowledge and behavior patterns such as smoking (McGeehin and Mirabelli, 2001). Our results suggest that greater investment in education in Tibet may reduce vulnerability to extremes in weather (it should be noted that literacy rates in Tibet have increased dramatically over recent decades).

To date, there have been no systematic measures taken in Tibet to reduce the harmful effects of extreme temperatures on health. It appears to be the case that health implications of climate receive less attention, not only in Tibet but also in some industrialized countries (Maibach et al., 2008), compared with the energy, economic and agriculture implications. Preparation of adaptation strategies in Tibet will face the lack of reliable long-term health data, lack of awareness among both the public and health professionals of the magnitude of health threats due to extreme weather and harsh geographic conditions. The resources to deal with both heat and cold are limited in Tibet. For instance, cooling devices are seldom used in Tibet because heat is not seen to be a serious problem. A survey of 619 respondents that we conducted in Chengguan in 2012 found only 8.7% of participants had air-conditioning at home (Bai et al., 2013). On the basis of the present study, and projections for future climate change in Tibet, we recommend an officially sanctioned and comprehensive temperature adaption plan. The first steps might include upgrading governmental awareness and public knowledge, concentrating on the links between health and other sectors, improvements in housing and exposed workplaces and focusing on most vulnerable populations and monitoring temperature-related health conditions.

There are limitations to this study. First, we examined temperature and mortality in three Tibetan counties only, so it is not certain how the results apply to the entire population. We did not have data on outdoor air pollution, which is independently associated with higher mortality, varies over short periods of time and may modify the temperature–mortality relationship (However, we note that air quality in Tibet is among the best in China), nor was it possible with this study design to control for personal behaviors that may conceivably vary by time and confound the association of temperature with mortality (e.g., intake of alcohol, smoking rates and use of medications).

5. Conclusions

In this study, human vulnerability to temperatures in the three Tibetan counties varies according to the cause and demographic characteristics of death, although we did not find consistent temperature effects on all-cause mortality across all counties. We have identified vulnerable subpopulations that include males, the elderly and illiterate people, but these findings are not consistent across all three locations. We also found that the temperature effect was generally stronger for cardiovascular deaths than all deaths. We conclude that initiatives should be taken to minimize the adverse health effects of extreme temperatures in fast changing Tibet, and these initiatives should pay particular attention to groups at greater risk. Further studies are required to confirm our findings, to examine other vulnerability factors and to include other locations in Tibet.

Competing interests

The authors declare that they have no competing interests.

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References

Atsumi A, Ueda K, Irie F, Sairenchi T, Iimura K, Watanabe H, et al. Relationship between cold temperature and cardiovascular mortality, with assessment of effect modification by individual characteristics: Ibaraki Prefectural Health Study. Circ J 2013; 77(7):1854–61.

Bai L, Cirendunzhu D, Pengcuociren D, Dawa D, Woodward A, Liu X, et al. Rapid warming in Tibet, China: public perception, response and coping resources in urban Lhasa. Environ Health 2013;12(1):71.

Basu R, Ostro BD. A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. Am J Epidemiol 2008;168(6):632–7.

Basu R, Feng WY, Ostro BD. Characterizing temperature and mortality in nine California counties. Epidemiology 2008;19(1):138–45.

Bell ML, O'Neill MS, Ranjit N, Borja-Aburto VH, Cifuentes LA, Gouveia NC. Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City. Mex Int J Epidemiol 2008;37(4): 796–804.

Braga AL, Zanobetti A, Schwartz J. The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Perspect 2002;110(9):859–63.

Chen R, Wang C, Meng X, Chen H, Thach TQ, Wong CM, et al. Both low and high temperature may increase the risk of stroke mortality. Neurology 2013;81(12): 1064–70.

Chung JY, Honda Y, Hong YC, Pan XC, Guo YL, Kim H. Ambient temperature and mortality: an international study in four capital cities of East Asia. Sci Total Environ 2009; 408(2):390–6.

Dawa, Ye XM, Dunzhuduoji, Gesang, Gamacangjue, Gou XQ. Study on the prevalence of major chronic diseases of adults in 2002 in Lhasa, Tibet. Food Sci Technol 2006;10: 19–21. [in Chinese].

Díaz J, García R, Velázquez de Castro F, Hernández E, López C, Otero A. Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997. Int J Biometeorol 2002;46(3):145–9.

Du J, Yang ZG, Shi L, Ma PF. Climate change characteristics of cold and warm winters in Tibet in 50 years. Acta Geograph Sin 2011;66(7):885–94. [in Chinese].

Gasparrini A. Distributed lag linear and non-linear models in R: the package dlnm. J Stat Softw 2011;43(8):1–20.

Gasparrini A, Armstrong B, Kenward MG. Distributed lag non-linear models. Stat Med 2010;29(21):2224–34.

Goggins WB, Chan EY, Ng E, Ren C, Chen L. Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong. PLoS One 2012;7(6):e38551.

Goldberg MS, Burnett RT, Stieb DM, Brophy JM, Daskalopoulou SS, Valois MF, et al. Associations between ambient air pollution and daily mortality among elderly persons in Montreal, Quebec. Sci Total Environ 2013;463–464:931–42.

Guo Y, Barnett AG, Pan X, Yu W, Tong S. The impact of temperature on mortality in Tianjin, China: a case-crossover design with a distributed lag nonlinear model. Environ Health Perspect 2011;119(12):1719–25.

Guo Y, Punnasiri K, Tong S. Effects of temperature on mortality in Chiang Mai city, Thailand: a time series study. Environ Health 2012;11:36.

Hu XJ, Zhao YH, Yang LH, Luosangdawa, Jiang L, Huang GW, et al. Health survey in Tibetan elders in Lhasa. Chin J Geriatr 2003;22(7):434–5. [in Chinese].

Iñiguez C, Ballester F, Ferrandiz J, Pérez-Hoyos S, Sáez M, López A. TEMPRO-EMECAS. Relation between temperature and mortality in thirteen Spanish cities. Int J Environ Res Public Health 2010;7(8):3196–210.

Kan HD, Jia J, Chen BH. Temperature and daily mortality in Shanghai: a time-series study. Biomed Environ Sci 2003;16(2):133–9.

Khanjani N, Bahrampour A. Temperature and cardiovascular and respiratory mortality in desert climate. A case study of Kerman, Iran. Iran J Environ Health Sci Eng 2013; 10(1):11.

Kim YM, Park JW, Cheong HK. Estimated effect of climatic variables on the transmission of Plasmodium vivax malaria in the Republic of Korea. Environ Health Perspect 2012; 120(9):1314–9.

Lin YK, Wang YC, Lin PL, Li MH, Ho TJ. Relationships between cold-temperature indices and all causes and cardiopulmonary morbidity and mortality in a subtropical island. Sci Total Environ 2013;461–462:627–35.

Liu X, Chen B. Climatic warming in the Tibetan Plateay during recent decades. Int J Climatol 2000;20:1729–42.

Madrigano J, Mittleman MA, Baccarelli A, Goldberg R, Melly S, Klot S, et al. Temperature, myocardial infarction, and mortality: effect modification by individual- and area-level characteristics. Epidemiology 2013;24(3):439–46.

Maibach EW, Chadwick A, McBride D, Chuk M, Ebi KL, Balbus J. Climate change and local public health in the United States: preparedness, programs and perceptions of local public health department directors. PLoS One 2008;3:e2838.

Martiello MA, Giacchi MV. High temperatures and health outcomes: a review of the literature. Scand J Public Health 2010;38(8):826–37.

McGeehin MA, Mirabelli M. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. Environ Health Perspect 2001;109(Suppl. 2):185–9.

McGregor GR. Winter North Atlantic Oscillation, temperature and ischaemic heart disease mortality in three English counties. Int J Biometeorol 2005;49(3): 197–204.

McMichael AJ, Wilkinson P, Kovats RS, Pattenden S, Hajat S, Armstrong B, et al. International study of temperature, heat and urban mortality: the 'ISOTHURM' project. Int J Epidemiol 2008;37(5):1121–31.

Medina-Ramón M, Zanobetti A, Cavanagh DP, Schwartz J. Extreme temperatures and mortality: assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis. Environ Health Perspect 2006; 114(9):1331–6.

O'Neill MS, Zanobetti A, Schwartz J. Modifiers of the temperature and mortality association in seven US cities. Am J Epidemiol 2003;157:1074–82.

Schwartz J. Who is sensitive to extremes of temperature?: a case-only analysis. Epidemiology 2005;16(1):67–72.

Si CZ, Chen XD, Zhou L, Sun H, Zhang Q, Qian L. Relationship between temperature and daily mortality in a district of Nanjing: a time-series study. J Environ Health 2011; 28(3):230–2. [In Chinese].

Stafoggia M, Forastiere F, Agostini D, Biggeri A, Bisanti L, Cadum E, et al. Vulnerability to heat-related mortality: a multicity, population-based, case-crossover analysis. Epidemiology 2006;17(3):315–23.

Tian Z, Li S, Zhang J, Jaakkola JJ, Guo Y. Ambient temperature and coronary heart disease mortality in Beijing, China: a time series study. Environ Health 2012;11:56.

Vaneckova P, Beggs PJ, de Dear RJ, McCracken KW. Effect of temperature on mortality during the six warmer months in Sydney, Australia, between 1993 and 2004. Environ Res 2008;108(3):361–9.

Wang C, Chen R, Kuang X, Duan X, Kan H. Temperature and daily mortality in Suzhou, China: a time series analysis. Sci Total Environ 2013;466-467C:985–90.

Wichmann J, Rosengren A, Sjöberg K, Barregard L, Sallsten G. Association between ambient temperature and acute myocardial infarction hospitalisations in Gothenburg, Sweden: 1985-2010. PLoS One 2013;8(4):e62059.

Wu T, Miao C. High altitude heart disease in children in Tibet. High Alt Med Biol 2002; 3(3):323–5.

Wu TY, Ding SQ, Liu JL, Yu MT, Jia JH, Chai ZC, et al. Who should not go high: chronic disease and work at altitude during construction of the Qinghai-Tibet railroad. High Alt Med Biol 2007;8(2):88–107.

Wu W, Xiao Y, Li G, Zeng W, Lin H, Rutherford S, et al. Temperature–mortality relationship in four subtropical Chinese cities: a time-series study using a distributed lag non-linear model. Sci Total Environ 2013;449:355–62.

Yan M, Chen Y, Guan ZF, Yang R. The prevalence and distribution of obesity among 696 Tibetan cadres. Chin J Prev Contr Chron Non-commun Dis 2001;15:62–3. [in Chinese].

Yang LH, Hu XJ, Zhao YH, Huang GW, Liu XQ, Jiang L, et al. A screening survey of diabetes in the middle-aged and elderly Tibetan population of Lhasa City. Chin J Endocrinol Metab 2003;19(5):358–60. [in Chinese].

Yang ZX, Dawa, Zhang J, Zhang SJ, Qu Y, Man QQ, et al. The influence of difference of dietary pattern between elderly Tibetans and Han peoples on blood lipid. Chin J Prev Contr Chron Non-commun Dis 2008;16:239–41. [in Chinese].

Yang J, Ou CQ, Ding Y, Zhou YX, Chen PY. Daily temperature and mortality: a study of distributed lag non-linear effect and effect modification in Guangzhou. Environ Health 2012;11:63.

Yu W, Vaneckova P, Mengersen K, Pan X, Tong S. Is the association between temperature and mortality modified by age, gender and socio-economic status? Sci Total Environ 2010;408(17):3513–8.

Zeng WL, Li GC, Xiao YZ, Xu YJ, Xu XJ, Liu T, et al. The impact of temperature on cardiovascular disease deaths in 4 cities, China: a time-series study. Zhonghua Liu Xing Bing Xue Za Zhi 2012;33(10):1021–5. [in Chinese].

Zhao YH, Hu XJ, Yang LH, Luosangdawa, Jiang L, Huang GW, et al. Distribution of the mini-mental-status examination in the Tibetan resident population aged 55 years and over living in urban and rural areas of Lhasa City. Chin J Neurol 2002;35(6):336–8. [in Chinese].

Zheng X, Wang YD, Yao DK, Cirenzhuoma, Tang J, He Y. Investigation on prevalence and influence factors of hypertension in Lhasa City. China Med 2011;6:390–2. [in Chinese].