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# Climate Change, Cold Waves, Heat Waves, and Mortality: Evidence from a Lower Middle-Income Country

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## Abstract

We estimate the impact of temperature extremes on mortality in Vietnam, using daily data on temperatures and monthly data on mortality during the 2000-2018 period. We find that both cold and heat waves cause higher mortality, particularly among older people. This effect on mortality tends to be smaller in provinces with higher rates of air-conditioning and emigration, and provinces with higher public spending on health. Finally, we estimate economic cost of cold and heat waves using a framework of willingness to pay to avoid deaths, then project the cost to the year 2100 under different Representative Concentration Pathway scenarios.

Keywords: climate change, weather extremes, mortality, health, Vietnam.

JEL classifications: I10; Q54; O15; R23.

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## 1. Introduction

There is widespread agreement that extreme weather and climate change have been and will continue to be the greatest threat to humankind (Stern, 2006 and 2008). The link between climate change and extreme weather, especially heat waves, is well documented (Luber and McGeehin, 2008). Although adaptation and medical advances have mitigated the adverse health effects of extreme events, climate change could reverse this trend (Ebi et al., 2021). As extreme weather events occur more frequently, the number of people affected will increase. A recent estimate from Zhao et al. (2021) indicates that non-optimal temperatures are linked with around 5 million deaths worldwide per year, accounting for 9.43% of all deaths, of which 8.52% are cold-related and 0.91% are heat-related. Understanding the effects of extreme weather on health is extremely important for the design of policies that adapt for climate change.

In this study, we first present a simple model to formalize testable hypotheses about the effects of climate change, heat waves and cold waves on mortality and welfare. Previous theoretical models such as those of Deschenes and Greenstone (2011), and Carleton et al. (2020) did not distinguish the heterogeneous effects neither of the frequency and intensity of hazardous weather shocks nor different kinds of adaptations. Our extending model is able to distinguish the effect of climate change and extreme weather events of differing intensities, measuring by heat waves, cold waves and average temperature. Our model also provides insight to explain different effects of adaptations from public and individual investments for health capital and climate-related mortality reduction. We separate investment in health capital in general (e.g., medical consumption, nutrition and exercise) from adaptive efforts aimed only at reducing the impact of extreme weather events on health (e.g., air-conditioning, warming and cooling energy consumption, and/or migration). Otherwise, it may cause ambiguity in understanding how adaptation reduces the negative effects of climate variability. The framework allows us to study the effect on welfare and on willingness to pay (WTP) for change in climate variability and extreme weather events.

In the empirical sections, we estimate the short-term effect of temperatures on the monthly province-level rate of mortality during the 2000-2018 period. By exploring a

number of ways to measure temperature distribution, we uncover several interesting findings on how temperatures affect mortality. While large literatures consider the mortality impact of increases in average temperature measured by bins, we focus on more complex relationships between the duration and extend of extreme weather events. We begin with examining non-linear relationship between mortality and temperature. Using the number of days (within a month) in 3-degree (or 2-degree) temperature bins to capture the non-linear relationship between temperature and mortality, we do not find significant effects of low and high temperature bins relative to the reference temperature bin (21-24°C). However, if a medium temperature from 15°C to 30°C is used as the reference bin, we find a significant effect of high but not low temperatures. An additional day with a mean temperature over 30°C relative to a 15-30°C day increases the monthly mortality rate by 0.78%.

Measuring the temperature effect using absolute temperature can be associated with bias since local people have the capacity to adapt to steady temperatures, whether high or low. Therefore, we use temperature shocks, which are measured by the number of days with a daily mean temperature below the 5<sup>th</sup> percentile or above the 95<sup>th</sup> percentile of the province-specific temperature distribution during the past 20 years. We find significant effects from both low and high temperature extremes. An additional day with a mean temperature at or below the 5<sup>th</sup> percentile of the temperature distribution relative to a day within the 5<sup>th</sup>-95<sup>th</sup> percentile range, increases the monthly mortality rate by 0.5%. The corresponding figure for the effect of a high temperature extreme is 0.73%. A problem with recording the number of days with temperature extremes is that this does not capture the duration of these extremes. Thus, we define a heat wave as three or more consecutive days with a daily mean temperature at or higher than the 95<sup>th</sup> percentile of the province-specific temperature distribution, and a cold wave as at least three consecutive days with a daily mean temperature at or below the 5<sup>th</sup> percentile of the province-specific temperature distribution. We find that a cold wave longer by one additional day within a month increases the monthly mortality rate by 0.6%. The corresponding figure for an additional day in a heat wave is 0.7%. We estimate that cold and heat waves account for 53% and 47% respectively of the total number of deaths caused by temperature extremes during the study period. Our estimates are robust for different definitions of cold and heat waves as well as different specification and placebo tests.

The findings concerning the smaller effect of temperature bins but higher effect of cold and heat waves suggest that people living in cold or hot areas may be acclimatized or able to adapt to low or high temperatures, but are more vulnerable to temperature shocks, especially when these shocks are prolonged. Cold and heat waves put a strain on human cardiovascular and respiratory systems and as a result, the number of deaths caused by these waves is higher than the number due to excessive temperatures alone. Furthermore, we find a heterogeneous effect from cold waves on mortality across provinces with different adaptive strategies. The effect of cold waves on mortality tends to be lower in provinces with a higher level of air-conditioning and in provinces with higher public spending on health. Cold waves also push people to migrate from their provinces, and provinces with higher emigration rates are less affected by cold waves. Our study confirms the adverse effect of extreme weather on health and suggests the important role of adaptation and coping strategies to reduce this effect.

Using the estimated effect of cold and heat waves on monthly mortality rate, we predict the number of deaths caused by the cold and heat waves over time. It is estimated that cold and heat waves account for 1.42% of all deaths in Vietnam during the 2003-2017 period. Among the deaths caused by these waves, cold waves account for 53%, while heat waves account for 47%. We project the economic cost of mortality caused by cold and heat waves by multiplying the number of deaths with a statistical life value of 0.342 million USD (Viscusi and Masterman, 2017). The cost that we are willing to pay to avoid the mortality of 2,468 people is estimated at 0.84 billion USD (at constant 2015 prices) in 2017, equivalently 0.44% of GDP in that year.

Finally, we use projected daily data for Vietnam to forecast cold and heat waves in the 2020-2100 timeframe using several Representative Concentration Pathway (RCP) scenarios. The number of days with cold waves is expected to drop rapidly, approaching zero in the 2050s. On the other side, the number of days with heat waves grows dramatically, peaking in about 2060. The RCP 6.0 scenario has the most heat waves, whereas the RCP 2.6 scenario has the fewest. Heat-related deaths are expected to rise in the future, reaching a peak around 2060. These findings raise severe concerns regarding the health repercussions of future heat-related events in Vietnam.

Our study contributes to the related literature in several ways. Firstly, it provides recent empirical evidence on the effect of temperature on mortality in a lower middle-income country. While the effect of temperature on mortality has been well documented in high-income countries (e.g. Deschenes and Moretti, 2009; Anderson and Bell, 2011; Barreca, 2012; Deschenes and Greenstone, 2011; Barreca et al., 2016; Karlsson and Ziebarth, 2018; Mullins and White, 2020; Pottier et al., 2021), there is less evidence concerning this effect in low- and middle-income countries (e.g., see a review from Dimitrova et al., 2021). The effect of temperature on health and mortality tends to be greater in lower-income countries (Basu, 2009; Burgess et al., 2017; Carleton et al., 2020; Lee and Li, 2021), partly because of their limited coping and adaptive capacities.

Burgess et al. (2017) find a higher effect from high temperatures on mortality in India than in the US. Recently, Cohen and Dechezleprêtre (2019) estimate that suboptimal temperatures, mainly cold, cause nearly 4% of all deaths in Mexico. Existing studies show a wide diversity of empirical results, a situation which calls for more empirical findings to better understand the effect of temperature on mortality.<sup>1</sup> Our study focuses on Vietnam, an interesting case study. Vietnam is a lower-middle-income country located in South East Asia and has experienced a variety of extreme weather occurrences, including floods and droughts (UNISDR, 2009). It is ranked as one of the top five countries most likely to be affected by climate change (World Bank and Asian Development Bank, 2020). According to MONRE (2009), the average surface temperature in Vietnam is predicted to rise by 1.1–3.6°C this century.

The second contribution of this study is to confirm the short-term effect of cold and heat waves on mortality. A challenge in studying the temperature-mortality relationship is to understand the channels through which temperatures can cause mortality. A direct effect of extreme temperature fluctuations is a deterioration in people's health. Hot temperatures can have direct, short-term effects on mortality by increasing the risks of cardiovascular, respiratory, cerebrovascular and blood cholesterol problems, especially in children and older people (see review by Basu and Samet, 2002; Xu et al., 2012). Extreme temperatures can have a medium-term effect on mortality through increasing the risk of contracting

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<sup>1</sup> Numerous studies show heterogenous effects from climate events on health and infectious diseases (e.g., see review by Jahani and Ahmadnezhad, 2011; Phalkey et al., 2015; Levy et al., 2016).

disease. Climate variability can affect the survival rate and transmission of viruses and bacteria. Temperature and precipitation are found to strongly affect the spread of dengue, cholera, malaria, diarrhea, and several infectious diseases (e.g., Jahani and Ahmadnezhad, 2011; Levy et al., 2016).

Another indirect mechanism through which extreme temperatures cause deteriorating health is their negative effect on income. High temperatures increase discomfort and tiredness, resulting in reduced labor productivity (Zivin and Neidell, 2010; Hübler et al., 2008; Deryugina and Hsiang, 2014; Somanathan et al., 2021). Several studies document the negative effect of extreme temperatures on agricultural production and economic growth (e.g., Deschênes and Greenstone, 2007; Dell et al., 2009; Burke et al., 2020; Miller et al., 2021). Our study shows that cold and heat waves have only a short-term effect on monthly mortality in Vietnam. There are no significant lagged effects of cold and heat waves on mortality. In addition, we do not find significant effects of cold and heat waves on income. These findings suggest that cold and heat waves cause deaths by increasing people's health problems directly.

Recent studies focus on the heterogeneous effects of climate change and adaptation strategies to mitigate the effects of temperature on mortality (e.g., Barreca et al., 2016; Burgess et al., 2017; Banerjee and Maharaj, 2020; Cohen and Dechezleprêtre, 2019; Heutel et al., 2020; Mullins and White, 2020). Several studies find that greater access to air-conditioning mitigates the adverse effect of heat waves (e.g., Barreca et al., 2016; Heutel et al., 2020). Cohen and Dechezleprêtre (2018) investigate the link between temperature and mortality in Mexico and discover that enrolment in Mexico's national health insurance scheme reduces the impact of a cold day on mortality by 35%. On the other hand, Mullins and White (2020) find that access to primary care services mitigates the harmful effects of heat but not cold in the US. Our study supplements related studies by showing that provinces with a higher number of air-conditioners and higher public spending on health are less affected by cold waves.<sup>2</sup> Moreover, we find that people are more likely to emigrated from provinces with more cold waves and as a result, emigration tends to mitigate the effects of

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<sup>2</sup> Although air-conditioners are mainly used to cool airs, they can also warm air. Moreover, it can be associated with electric heaters. In our data sets, there are no information on electric heaters. Possibly, people respond to more temperature extremes by purchasing not only air-conditioners but also electric heaters.

cold waves on mortality.

The remainder of the paper is structured as follows. The second section presents a theoretical framework of the relations between temperature extremes, mortality and adaptation. The third section discusses the data sets used in this study and provides a descriptive analysis of mortality in relation to temperatures in Vietnam. The fourth and fifth sections present the method of estimation and the effect of temperature on mortality, respectively. The sixth section estimates the number of deaths caused by cold and heat waves and projects the number of deaths under different temperature scenarios in the coming years. Finally, the seventh section offers a concluding summary.

## 2. Theoretical framework

Based on Grossman's model of health demand (Grossman, 1972; Grossman, 2000), we present a framework to provide insight on the impact of climate change and extreme weather events on mortality and welfare. We consider a representative agent who faces a probability of death because of climate variability, of intensity  $x$ . That intensity level can be measured by average temperature, heat waves or cold waves. The probability of remaining alive is determined by the conditional probability of survival  $s(h, x)$ ; where  $h$  represents the stock of health capital. Deschenes and Greenstone (2011) use the energy consumption as a good for health capital by assuming such consumption increases the probability of survival. This assumption is a confusing way to explain a biological mechanism between death and health. The literature defines death as occurring when the stock of health capital falls below a given threshold, causing a zero marginal utility of health at that point (Cropper, 1990). Therefore we use health capital instead of the consumption of goods for health and make the assumption that deaths happen when  $\frac{\partial s}{\partial h} = 0$ .

We relax the assumption  $\frac{\partial s}{\partial x} < 0$  (as in Deschenes and Greenstone, 2011; or Donaldson et al., 2013, and Carleton et al., 2020) as it captures only the harmful effect of hot weather on health. This relaxation provides us with the ability to distinguish between the effects of extreme weather events and average temperature based on their intensity. Our assumption is that there are two thresholds  $x_{cold}$  and  $x_{hot}$  such that  $\frac{\partial s}{\partial x} < 0$  for  $x \leq x_{cold}$  or  $x \geq x_{hot}$ . When temperatures are within the range  $x_{cold}$  and  $x_{hot}$ , the effect is unclear,



because rising temperatures can have either positive or negative effects on health. With regard to high temperatures, the marginal damage to health is higher in cold places than in hot places because the reaction of local residents to hot days differs. However, when the regional trend in temperatures is low, an increase in temperature may have a positive effect on health.

Income is assumed to come from available periods of health, which is a function of the stock of health capital,  $t_h = f(h)$ . Thus, we can write income  $wt_h$  as  $wf(h)$  for a concave and increasing production  $f$  and wage  $w$ . Budget constraint is

$$wf(h) = c + bm + I(a), \quad (1)$$

where  $m$  and  $b$  are healthcare consumption and its cost.  $I(a)$  is the cost of adaptation, with  $a \in (0,1)$  as the level of protection via adaptive effort; with  $I' > 0, I'' > 0$  and  $I(0) = I'(0) = 0$ . We assume the agent is endowed with an initial stock of health capital  $h_0$  at the baseline period with no effects. Health expenditure and adaptation mitigate the harm expected in the next period of health capital

$$E[h] = h_0 - \delta h_0 - (1 - a)G(x)h_0 + Amh_0, \quad (2)$$

where  $\delta$  is an exogenous rate of biological deterioration,  $A$  is the state level of medical facilities, including hospital capacity such as beds for patients,  $G(x)$  is the probability that a unit of health capital is damaged depending on the occurrence of extreme weather events with intensity  $x$ . In line with the assumption of the probability of survival, we assume that  $G'(x) > 0$  for  $x \leq x_{cold}$  or  $x \geq x_{hot}$ .

We assume the utility of the agent is a concave, increasing function  $U(c)$  of consumption when being alive and being dead have zero utility. In addition, the agent discounts each future period with a constant discount factor  $\beta \in (0,1)$ . The expected utility in the second period is therefore as follows:

$$\max_{c,a,m} E_x \beta s(h,x) U(c), \quad (3)$$

subject to (1), (2). This optimization problem identifies the solutions which depend on parameters  $(x, b, A, w)$  given by the first order conditions:

$$\frac{\partial s}{\partial h} G h_0 = \frac{\mu}{\beta U(c)} [wf'(h)G h_0 - I'(a)] \quad (4)$$

$$\frac{\partial s}{\partial h} Ah_0 = \frac{\mu}{\beta U(c)} [wf'(h)Ah_0 - b] \quad (5)$$

$$G(x)b = AI'(a) \quad (6)$$

where  $\mu = \beta sU'(c)$ , the Lagrange multiplier is associated with budget constraints measuring the marginal utility of income. In this model, the value of statistical life (VSL) is defined by the marginal rate of substitution between consumption and the probability of survival,  $VSL = -\frac{dc}{ds} = \frac{\beta U(c)}{\mu}$ . As a result, we are able to derive practical expressions for empirical analysis and understand the mechanism of the impact of climate variability on mortality.

The effect of climate and weather extremes on mortality is measured by the total derivative of survival probability  $s(h(x), x)$  on  $x$ . It follows from (2) and (4) we get:

$$\frac{ds}{dx} = \frac{\partial s}{\partial x} + \frac{\partial s}{\partial h} \frac{\partial h}{\partial x} = \frac{\partial s}{\partial x} + \frac{1}{VSL} [I'(a) - wf'(h)Gh_0] aG'(x). \quad (7)$$

Without adaptation ( $a = 0$ ), the effect is equal to the partial derivative  $\frac{\partial s}{\partial x}$ . In the empirical section, we will estimate this effect by regressing the mortality rate on weather extremes. With adaptation, an increase in adaptation incurs a marginal cost  $I'(a)$ , but helps in securing more income by increasing labor productivity  $f'(h)$  as the healthy agent providing more time of working. From (5) and (7), the second term is the effect of the interaction of income, adaptation and the marginal damage of weather events or climate variability on mortality:

$$\frac{ds}{dx} = \frac{\partial s}{\partial x} + \frac{\partial s}{\partial h} \frac{\partial h}{\partial x} = \frac{\partial s}{\partial x} + \frac{1}{VSL} \left[ \frac{G(x)b}{A} - wf'(h)Gh_0 \right] aG'(x). \quad (8)$$

This expression suggests that the effects of extreme weather events on mortality depend on health expenditure, hospital capacity, adaptation, and weather intensity. If we approximate around a reference point of zero effects  $x_0$ ,  $G'(x) \simeq G'(x_0) + G''(x)(x - x_0)$ , where  $G''(x) < 0$ , our theoretical framework will predict the negative or positive coefficient of heat waves or cold waves, depending on the sign of  $G'(x)$ . We consider this effect by some specifications of  $G(x)$ , whereby we assume that  $G$  can be decomposed into  $p(x) = \frac{e^{-\lambda x}}{\lambda}$  and  $q(x) = q_0 e^{\phi x}$ ,  $p(x)$  is the probability of heat/cold waves with intensity  $x$  affecting the agent and  $q(x)$  is the magnitude of harm to health. Since weather events of varying intensity

lead to various probabilities of survival and harm to health, we have:

$$G(\bar{x}) = \int_0^x p(x)q(x)dx = \frac{q_0}{1-\phi\bar{x}} \left[ 1 - e^{\phi X - \frac{X}{\bar{x}}} \right], \quad (9)$$

where  $X$  is the maximal intensity and  $\bar{x} = \frac{1}{\lambda}$  the mean intensity. The sign of  $\frac{dG}{d\bar{x}}$  depends on the gap between  $\bar{x}$  and  $X$ . For example, if  $\bar{x} \ll X$  then  $G'(x) \simeq q_0(1 + \phi\bar{x})$  which is almost a linear function of mean intensity. Thus, the effect of mean temperature on mortality can be negative, as shown in the empirical section.

Moreover, it follows from (4), (5) and (§) we get:

$$I'(a) = \left[ wf'(h) - VSL \frac{\partial s}{\partial h} \right] G(x)h_0, \quad (10)$$

and:

$$b = \left[ wf'(h) - VSL \frac{\partial s}{\partial h} \right] Ah_0. \quad (11)$$

The first expression means the marginal cost of adaptive effort is equal to the marginal benefit of increasing one unit of health capital. The second means the cost of healthcare is the benefit to health capital. These expressions will be included in the econometric models presented in Section 5.

### 3. Data sets and descriptive analysis

This study relies on the two main data sets. The first is the monthly mortality rate of provinces during the 2000-2018 period, provided by General Statistics Office of Vietnam (GSO). The mortality rate is computed from the Population Change and Family Planning Surveys, which have been conducted annually by the GSO since 2000. The sample size of these surveys is representative at the provincial level. Monthly mortality rates can be estimated separately for males and females and for different age groups.

Together with economic growth, Vietnam has experienced improvement in health. Life expectancy has increased from 73 to 75 from 2000-2018 (World Bank, 2020). However, the crude mortality rate has not declined during this period. Estimates from the Population and Planning Surveys show that the mortality rate for all ages was around 5 deaths per 1000 people (Figure 1). A major reason why the mortality rate has not decreased during the past two decades is the decline in the fertility rate. The government has

recommended family planning with a limit of two children per family since 1988. The dramatic decline in birth rates is the most important reason for population aging in Vietnam.<sup>3</sup> When the mortality rate is computed for different age groups, we can see a decline in the mortality rate, especially for children under 5 and people aged 60 and older (Figure 1).

[Figure 1 about here]

The second data set comprises weather data. Temperature and precipitation measurements are sourced from the Vietnam Institute of Meteorology, Hydrology and Climate Change. This data set is an administrative source covering data from all 172 weather stations in Vietnam (as shown in Figure A.1 in the Appendix) and provides daily precipitation, and minimum and maximum temperatures. In this study, we use the daily mean temperature, which is the average of the daily minimum and maximum. Our data on mortality is taken from the province-by-month mortality rate. Thus, we need to link the weather data from the stations to the provincial-level data. Currently, Vietnam has 63 provinces covering 705 districts. We first match each district with the nearest weather station (the shortest distance from the district's centroid to the station). The temperature and precipitation at a weather station are used for the temperature and precipitation of a matched (nearest) district. Next, we estimate temperature and precipitation for a province by the average weighted temperature and precipitation of districts in the province with weight equal to district area.<sup>4</sup>

Vietnam is a tropical country with two areas with different climates. North Vietnam has four seasons and winter has significantly lower temperatures and less precipitation than summer. On the other hand, South Vietnam has two seasons, the dry season from November to April and the rainy season from May to October. Compared with the North, temperatures in the South show lower 12-month variation. The average daily temperature for the whole country is around 25°C. This average is computed from the daily provincial average and

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<sup>3</sup> Viet Nam is among the most rapidly aging countries in the world. According to the GSO (2019), the aging index, which is equal to the ratio of the number of people from 60 to the number of children below 15 (measured in percent), has increased over time. The aging index increased by 13.3 percentage points from 35.5% in 2009 to 35.3% in 2019.

<sup>4</sup> We do not match provinces with the nearest weather stations (using the distance between a province's centroid to the stations) since the weather stations are not located spatially in a random manner (see Figure A.1 in Appendix).

reflects the variation across provinces and the 12-month variation. The average temperature remained very stable during the 2000-2018 period.

Vietnam's 63 provinces are grouped into 6 geographic regions: the Red River Delta, Northern Midlands and Mountains, the Central Coast in the North and the Central Highlands, and the Southeast and Mekong River Delta in the South. Figure 2 presents the average daily regional temperature from 2000-2018. The Southeast and Mekong River Delta have the highest average daily temperature at around 27°C, while the Northern Midlands and Mountains have the lowest average daily temperature at around 22°C. Figures A.2 and A.3 in the Appendix present the average daily temperature across months in six regions. The hottest month is June in the North and April in the South. January and December are the coldest months in all regions.

[Figure 2 about here]

Figure 3 presents the geographic maps of the mortality rate and temperatures (averaged over the 2000-2018 period).<sup>5</sup> The mortality rate and the average temperature were fairly similar between provinces within a region. The correlation between mortality and temperature is not clear from these maps. However, the maps show that the mortality rate was higher in the North, which has a lower average temperature, than in the South.

[Figure 3 about here]

As mentioned earlier, the main objective of this study is to examine the effect of weather extremes on mortality. Thus, we follow previous studies on the effect of temperature on mortality (e.g. Deschenes and Greenstone, 2011; Barreca et al., 2016; Mullins and White, 2020) and construct seven temperature bins according to the number of days per month and daily mean temperatures. The seven bins are comprised of the following temperature groupings, in degrees Celsius: 0-15; 15-18; 18-21; 21-24; 24-27; 27-30; 30+.<sup>6</sup> We use 15°C instead of 12°C to define the lowest temperature bin, since daily mean

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<sup>5</sup> Figure A.4 in the Appendix presents the provincial map of annual rainfall averaged over the 200-2018 period.

<sup>6</sup> In estimating the effect of temperature bins on mortality, we also try 2-degree temperature bins (i.e., below 14°C; 14-16; 16-18; 18-20; 20-22; 22-24; 24-26; 26-30; 30-32; 32+°C). The results are very similar to those obtained by using 3-degree temperature bins. For interpretation, we use the results from 3-degree temperature bins.

temperatures fall below 12°C in only 1% of the number of the province-by-day observations . Similarly, 30°C instead of 33°C is selected to define the highest temperature bin because there are only a few province -by-day observations with the daily mean temperatures above 33°C (accounting for around 0.08%). Moreover, the WHO (2018) suggests that the range of minimum risk for higher temperatures is about 15–30°C. Temperatures lower than 16°C (61°F) with humidity above 65% were associated with respiratory hazards.

Figure 4 shows the average number of days per year with daily mean temperatures falling into seven bins for the 2000-2018 period. The figure presents the temperature distribution for six regions. Compared with other regions, the Red River Delta and Northern Midlands and Mountains have lower average temperatures (Figures 2 and Figure 3), but these two regions have a higher number of days below 15°C as well as above 30°C. Temperatures in the Southeast and Mekong River Delta fall mainly into the 24-30°C range. There are almost no days where the daily mean temperature falls below 15°C in these two regions.

We focus on the effect of weather extremes, which are measured by cold and heat waves occurring within a month. Although there is no universal definition of a heat wave (Meehl and Tebaldi, 2004), it is often measured by a period of abnormally warm weather. There are two issues in defining a heat wave: selection of a temperature threshold and definition of the number of consecutive days of prolonged heat. Most studies use a threshold of a given percentile such as the 90<sup>th</sup>, 95<sup>th</sup> or 98<sup>th</sup> percentile of the temperature distribution of a specific location (e.g., see the review by Perkins and Alexander, 2013; and Perkins, 2015). Several studies use an absolute temperature threshold, such as 30-35°C. However, using a common temperature threshold may not be appropriate in a country with varying climates (Anderson and Bell, 2009, Kent et al., 2014). More important, this definition does not capture exogenous weather shocks for local people. People in warm areas are familiar with high temperatures and have adapted to them. The effect of a 30°C temperature can be very different for people in the Southeast compared with those living in the Central Highlands. Similarly, temperatures below 15°C may be harmful for people in the Southeast and the Mekong River Delta but not for people in the Red River Delta and Northern Midlands and Mountains.

Another issue in measuring heat waves is whether excessively warm periods define a specific season, such as summertime, or the entire year (Perkins and Alexander, 2013). In this study, the threshold for a heat wave is set for all seasons of the year, not just summer or winter. Certainly, heat waves are more likely to happen in summer. The definition of heat waves in winter where there are daily temperatures above the 95<sup>th</sup> percentile of the winter distribution is not appropriate for the purpose of measuring the effect of heat waves on health. Warmer days in winter are not harmful for health.

The second issue in defining a heat wave is the duration of consecutive days equal to or above the temperature threshold. Exposure to hot weather over several consecutive days has a more detrimental effect on health than exposure to a few hot days occurring separately. A heat wave is often defined as at least 3 or 5 consecutive days with daily temperatures above a given threshold (e.g., see review Perkins and Alexander, 2013; and Perkins, 2015).

In this study, we define a heat wave as 3 or more consecutive days with a daily mean temperature at or above the 95<sup>th</sup> percentile of the province-specific temperature distribution during the past 20 years. Similarly, we define a cold wave as occurring when the daily mean temperature over at least 3 consecutive days is equal to or below the 5<sup>th</sup> percentile of the province-specific temperature distribution. For robust analysis, we also define heat waves (and cold waves) as at least 5, 7, and 9 consecutive days when the daily mean temperature is at or above the 95<sup>th</sup> percentile (and at or below the 5<sup>th</sup> percentile) of the province-specific temperature distribution. We also consider thresholds at the 10<sup>th</sup> and 90<sup>th</sup> percentiles of the temperature distribution. The regression results using these thresholds are very similar to those using the thresholds at the 5<sup>th</sup> and 95<sup>th</sup> percentiles.

[Figure 4 about here]

Panel A of Figure 5 presents the average number of days per year of cold and heat waves, defined on the basis of the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the province-specific temperature distribution. The numbers are computed as the annual average across the province. For example, the first bar in Panel A indicates that the annual provincial average number of consecutive days in cold waves, defined as at least 3 consecutive cold days, is 14. The average number of consecutive days in cold waves, defined as at least 9 consecutive cold days, is only 5.2. It should be noted that this average is below 9, since there are a number of provinces which do not experience a cold wave at all in some years. The average

number of consecutive days in heat waves is lower. For example, the average number of consecutive days in heat waves, defined as at least 3 and 9 consecutive hot days, is 10.4 and 2.4, respectively. Figure A.5 in the Appendix shows the fluctuation in the average number of consecutive days in cold and heat waves per year from 2000-2018.

Panel B of Figure 5 presents the average percentage of months in which at least one cold or heat wave occurred during 2000-2018. The percentage is averaged across provinces. It shows that on average, 16.7% of months in 2000-2018 experienced at least one cold wave, defined as at least 3 consecutive cold days. For heat waves, the average percentage of months which experienced at least one heat wave with 3 or more consecutive hot days, is 13.6%. When cold or heat waves are defined as of longer duration (at least 5, 7, and 9 consecutive days), the percentage of months with at least one cold or heat wave is smaller.

[Figure 5 about here]

#### 4. Estimation methods

##### 4.1. Effects of cold and heat waves on mortality

We start with the estimation of the non-linear effect of temperature on mortality. A popular approach to estimate the climate effect is to define the distribution of temperatures by different bins, e.g., the number of days with certain temperature levels within a time period (e.g., Deschenes and Greenstone, 2011; Dell et al., 2012; and Deryugina and Hsiang, 2017).<sup>7</sup> Our regression model is expressed as follows:

$$\log(y_{pmt}) = \alpha_1 + \sum_{j=1}^7 \beta_j Temp_{pmt} + X_{pmt} \theta_1 + P_{pm} + M_{mt} + T_p \delta_{1p} + \varepsilon_{pmt}, \quad (12)$$

where  $y_p$  is the mortality rate of province  $p$  in month  $m$  of year  $t$  (per 100,000). We use both the mortality rate and the log of the mortality rate as the dependent variables.  $Temp_{pmt}$  denotes variables indicating the number of days in a province-year-month where the daily mean temperature falls into one of seven temperature bins, as defined in Figure 4. Thus the 21-24°C bin is used as the reference, and we assume the zero effect of this temperature range on mortality. According to the WHO (1990), comfortable indoor temperatures are between

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<sup>7</sup> For other methods and definitions, see the review by Hsiang (2016) and Kolstad & Moore (2019).



18–24°C (64–75°F). The coefficient of a temperature bin in the regression is interpreted as the effect of an additional day in this bin on the mortality rate relative to the effect of a day in the 21–24°C bin.

One issue in estimating the temperature bins is the assumption that the effect of temperature on the mortality rate is constant within each bin. To examine this assumption, we also try 2-degree temperature bins (i.e., below 14°C; 14–16; 16–18; 18–20; 20–22; 22–24; 24–26; 26–30; 30–32; 32+°C); the results are very similar. For interpretation, we use the results from 3-degree temperature bins.

$X_{pmt}$  is a vector of control variables. Our main control variables include the yearly temperature average, which is calculated by averaging the daily mean temperatures in the province, and total annual precipitation. We do not control for the monthly temperature since it can be affected by the temperature bins. The control variables should not be affected by the treatment variables (Heckman et al. 1999; Angrist and Pischke 2008). Our main purpose is to estimate the total instead of the partial effect of temperature on mortality (Duflo et al., 2007). For sensitivity analysis, we try different models which vary the number of control variables. We also try to control for the monthly mean temperature instead of the annual mean temperature. The results are reported in the Appendix. Overall, the effect of temperatures is very similar in these models.

We also control for the province-by-month fixed effects,  $P_{pm}$ , and year-month fixed-effects  $M_{mt}$ . The monthly province fixed effects control not only for the time-invariant characteristics of a province (including observed time-invariant variables, such as geography, and unobserved time-invariant variables, such as historical culture) but also local seasonality. In addition, we include the province-specific time trend,  $T_p$ , which allows for province-specific time trends in the mortality rate. However, controlling for these time trends might absorb the effect of temperature and bias its effect (Wolfers, 2006; Baum-Snow and Lutz, 2011). Thus, for sensitivity analysis, we also try the model without the province-specific time trend. Several studies also control for quadratic time trends. In our study, a large number of province-specific quadratic time trends are not statistically significant at conventional levels. Moreover, including area-specific quadratic time trends might increase bias in the estimate of the effect of the treatment variable (Wolfers, 2006).

In the Appendix, we also report the estimated effects of temperature from models, including the province-specific quadratic time trends. The results are very similar to those from models using only province-specific linear time trends. For interpretation in the main text, we will use results from models with only province-specific linear time trends.

It should be noted that this section presents several equations. Subscript 1 or 2 in parameters in regression models is used to distinguish parameters in different equations such as Equations (12) or (13).

In the second model, we estimate the effect of cold and heat waves on mortality using the same specification as (1):

$$\log(y_{pmt}) = \alpha_2 + \beta_{2c}Cold_{pmt} + \beta_{2H}Heat_{pmt} + X_{pmt}\theta_2 + P_{pm} + M_{mt} + T_p\delta_{2p} + u_{pmt}, \quad (13)$$

where  $Cold_{pmt}$  is the number of consecutive days in a cold wave and  $Heat_{pmt}$  is the number of consecutive days in heat waves in province  $p$  in month  $m$  of year  $t$ . Cold and heat waves are defined in the previous section. A cold wave is defined as at least a given number of consecutive days (3, 5, 7 and 9 days) with a daily mean temperature at or below the 5<sup>th</sup> percentile of the province-specific temperature distribution, while a heat wave is defined as at least a given number of consecutive days (3, 5, 7 and 9 days) with daily mean temperatures at or above the 95<sup>th</sup> percentile of the temperature distribution. In addition to measuring the variables ‘cold/heat waves’ by the number of consecutive days in the waves, we also use dummy variables indicating whether a cold or heat wave occurs within a month.

The panel data on provinces suggest that the error terms can be correlated within provinces over time. Thus, standard errors should be clustered at the provincial level. In addition, there can be a seasonal effect on mortality. Although we control for year-month fixed effects, the error terms can still be spatially correlated between provinces within a month. We adopt the multiway clustering technique of Cameron et al. (2011), which allows us to deal simultaneously with the correlation of error within provinces over time and between provinces within a month. For sensitivity analysis, we also try one-way clusters at the provincial level and find that the results are very similar. For interpretation, we use results from two-way clustered standard errors.

Another issue is whether to apply weights to the regression of Equations (12) and (13). When using area-level data to estimate the effect of temperature on area mortality, most studies apply weighted regression, where weights are equal to the square root of a province's population (e.g. Deschênes and Moretti, 2009; Deschenes and Greenstone, 2011; Barreca et al., 2016; Mullins and White, 2020). Applying weights can partially address the issue of heteroscedasticity and obtain the effect of temperature on the average person instead of the average province (Deschênes and Moretti, 2009; Barreca et al., 2016). In this study, we use three weighting schemes: no weighting, weighting by the current population of a province, and weighting by a province's population in 1999 (i.e., the population before the 2000-2018 period of analysis). Weather extremes can cause inter-provincial migration in Vietnam (Nguyen, 2021). Using the 1999 population can avoid the effect of temperature on the population of provinces during the 2000-2018 period. The estimated coefficients of cold and heat waves are insensitive to different weighting schemes. For interpretation, we use the results employing weighting by a province's population in 1999. Results without weighting and those using current population weights are reported in the Appendix.

#### 4.2. *Heterogeneous effects and adaption strategies*

Next, we examine the heterogeneous effect of cold and heat waves on mortality across several provincial characteristics. We include interactions between a variable of interest (denoted by  $I_{pt}$ ), such as a province's per capita income, and cold and heat waves in regression:

$$\log(y_{pmt}) = \alpha_3 + \beta_{3c}Cold_{pmt} + \beta_{3H}Heat_{pmt} + \mu_c Cold_{pmt}I_{pt} + \mu_H Heat_{pmt}I_{pt} \\ + I_{pt}\pi + X_{pmt}\theta_3 + P_{pm} + M_{mt} + T_p\delta_{3p} + v_{pmt}. \quad (14)$$

The interaction variables include the proportion of adults with tertiary education, the log of per capita income, the number of households with air conditioners, population density, emigration and immigration rates, government spending on health, and the number of hospitals in the provinces. The variables of air-conditioning, migration and the health care system reflect the adaptation strategies of inhabitants and the local government to cope with weather extremes. The interaction variables are measured annually instead of monthly. A problem with these variables is that they can be affected by temperatures. To mitigate this problem, we use one-year lags of these variables instead of their values in the current year.

It should be noted that we do not estimate Equation (14) using the interactions between temperature extremes and all the interaction variables at the same time, since using many interactions makes it difficult to interpret the results and might cause a multicollinearity problem. For each regression, we include only interactions between one interaction variable, such as per capita income or population density, and cold/heat waves.

The control variables in Equation (14) are the same as those in Equation (13) and include annual average temperature (in degrees Celsius), annual precipitation (mm), province-specific time trends, monthly provincial fixed effects, and year-by-month fixed effects. Standard errors are also clustered at the province and year-by-month levels.

#### 4.3. Estimation of deaths caused by cold and heat waves

We can examine the cost of cold and heat waves by predicting the number of deaths they cause in a province in a given month. In the counterfactual scenario in which there are no cold or heat waves, the expected mortality rate is estimated using Equation (2) as follows:

$$\begin{aligned}\log(\widehat{y_{pmt_0}}) &= \widehat{\alpha}_2 + X_{pmt}\widehat{\theta}_2 + P_{pm} + M_{mt} + T_p\widehat{\delta}_{2p} + \widehat{u_{pmt}} \\ &= \log(y_{pmt}) - \widehat{\beta}_{2c}Cold_{pmt} - \widehat{\beta}_{2H}Heat_{pmt}, \quad (15)\end{aligned}$$

where  $\widehat{y_{pmt_0}}$  is the predicted mortality rate in the absence of cold/heat waves in a province in month  $m$  of year  $t$ , while  $y_{pmt}$  is the observed mortality rate in the province in that month. The observed mortality rate is the mortality rate with cold/heat waves that has already occurred.  $Cold_{pmt}$  and  $Heat_{pmt}$  are the number of days in the cold/heat waves occurring during the month. We use the definition of cold or heat waves of at least 3 consecutive days for estimating the cost of cold/heat waves. Parameters with the elongated circumflex denote estimates from regressions of Equation (13). The mortality rate in the absence of cold or heat waves is then:

$$\widehat{y_{pmt}} = \exp[\log(y_{pmt}) - \widehat{\beta}_{2c}Cold_{pmt} - \widehat{\beta}_{2H}Heat_{pmt}]. \quad (16)$$

The number of deaths caused by the cold or heat waves in a province within a month is the difference in the observed mortality rate and the counterfactual mortality rate multiplied by the population of the province:

$$\widehat{\tau_{pmt}} = (y_{pmt} - \widehat{y_{pmt}})Pop_{pmt}$$

$$= \{y_{pmt} - \exp[\log(y_{pmt}) - \widehat{\beta}_{2c}Cold_{pmt} - \widehat{\beta}_{2H}Heat_{pmt}]\} Pop_{pmt}, \quad (17)$$

where  $Pop_{pmt}$  is the population of province  $p$  in month  $m$  in year  $t$ . We compute the total number of deaths due to cold or heat waves for the whole country in a given year  $t$  by taking the sum of Equation (6) across months ( $m$ ) and provinces ( $p$ ):

$$\widehat{\tau}_t = \sum_{m,p} \{y_{pmt} - \exp[\log(y_{pmt}) - \widehat{\beta}_{2c}Cold_{pmt} - \widehat{\beta}_{2H}Heat_{pmt}]\} Pop_{pmt}. \quad (18)$$

We can use Equation (7) to estimate the number of deaths caused by cold or heat waves separately.

Finally, we estimate the economic cost of mortality caused by cold or heat waves by multiplying the number of deaths with a value of a statistical life (VSL). In this study, we use a VSL of 0.342 million USD. This estimate for Vietnam is taken from Viscusi and Masterman (2017) and is very similar to a VSL estimate for Southeast Asia of 0.359 million USD (Saluja et al., 2020).

## 5. Empirical results

### 5.1. Effect of weather events on mortality

Table 1 reports the effect of temperature on mortality using the regression models specified in Equations (1) and (2). The control variables include the average of yearly temperature, total annual precipitation, provincial monthly fixed effects, year-month fixed effects, and the province-specific time trend. The effects of the temperature bins on the mortality rate and the mortality rate log are reported in columns 1 and 2 of Table 1. The 21-24°C bin is used as the reference. The coefficients of the temperature bins measure the estimated effect of one additional day in these bins on the mortality rate (and the log of the mortality rate) relative to a day in the reference bin. In the regression of the mortality rate, only the number of days in the 0-15°C bin is statistically significant at the 5% level. However, when the log of the mortality rate is used as the dependent variable, none of the temperature bins are statistically significant at the conventional level.

Figure A.6 in the Appendix presents the point estimates and the 95% confidence intervals of the effect of the temperature bins on the mortality rate and the log of the mortality rate. The figures show a U-shaped relation between the temperature and the mortality rate. The estimates of the low- and high-temperature bins are positive but not

statistically significant at the conventional level. In Table A.1 in the Appendix, we use the 2-degree temperature bins, with the 22-24°C bin as the reference. Most coefficients of the temperature bins are not statistically significant.

In columns 3 and 4 of Table 1, we only include the number of days below 15°C and those above 30°C. This means that a temperature range between 15°C and 30°C is used as the reference. The coefficients of the number of days above 30°C are positive and statistically significant at the 5% level. Thus, when middle temperature bins are combined and used as the reference, we find significant effects from high temperatures. An additional day with a mean temperature over 30°C (relative to a day between 15°C and 30°C) leads to an increase in the monthly mortality rate of 0.1774 deaths per 100,000 (column 3 of Table 1). When the dependent variable is a log of the mortality rate, the estimated effect is 0.0078. This means that an additional day with a mean temperature over 30°C increases the monthly mortality rate by 0.78% (column 4 of Table 1). This point estimate is larger than the point estimate that Deschenes and Greenstone (2011) found for the US. They report that an additional day with a mean temperature above 90°F (around 32°C) results in an increase in the annual mortality rate of about 0.11%. The effect on the mortality rate for Vietnam is quite similar to the approximately 0.7% effect of high temperatures on the mortality rate that Burgess et al. (2017) found for India. The two countries are at similar economic levels, and this may explain the similar effect of temperature on mortality in these countries.

We can compute the elasticity of the mortality rate with respect to the number of days with a mean temperature above 30°C to gain insight into the magnitude of the effect of high temperatures. The average number of days with a mean temperature above 30°C within a month across province-by-year observations is only 0.97. At 3.87 days, June is the month with the highest average number of days above 30°C. An additional hot day (above 30°C) means 26% of the average number of hot days occur in June. Roughly speaking, if the number of hot days in June increases by 26%, the mortality rate increases by 0.78%. This implies that the elasticity of the mortality rate to the number of hot days in June is equal to 0.03.

The last two columns in Table 1 show the effect of the number of days with temperature extremes. Days of high temperature extremes are defined as days when the

daily mean temperature is at or higher than the 95<sup>th</sup> percentile of the province-specific temperature distribution during the past 20 years. Days of low temperature extremes are days when the daily mean temperature is equal to or below the 5<sup>th</sup> percentile of the province-specific temperature distribution. The results show that both low and high temperature extremes increase the monthly mortality rate. An additional day with a mean temperature at or below the 5<sup>th</sup> percentile of the temperature distribution, relative to a day within the 5<sup>th</sup>-95<sup>th</sup> percentile range, results in an increase in the monthly mortality rate of 0.5%. The corresponding figure for the effect of high temperature extremes is 0.73. The point estimate of the effect of high temperature extremes is higher than that of low temperature extremes, but the difference is not statistically significant at conventional levels.

[Table 1 about here]

Table 1 shows a positive and significant correlation between annual mean temperature and the mortality rate. According to column (2), a 1°C increase in the annual average temperature is associated with a 2.73% increase in the monthly mortality rate. Annual precipitation is statistically significant at the 10% level in regressions of the mortality rate but not in regressions of the log of the mortality rate.

### *5.2. Effects of cold and heat waves on mortality*

The effects of cold and heat waves on mortality are summarized in Figure 6. In this figure, we graph the point estimate and the 95% confidence interval of the effects of cold and heat waves on the monthly mortality rate (panels A and B of the figure) and the log of the monthly mortality rate (panels C and D of the figure). The full regression results are reported in Tables A.2 and A.3 in the Appendix. The estimated effects of cold and heat waves on the mortality rate and the log of the mortality rate are very similar. For interpretation, we use the results from the effects on the log of the mortality rate.

Panel C plots the estimated coefficients of occurrence of at least one cold or heat wave within a month. All the coefficients of the cold and heat waves are positive, indicating a higher risk of mortality during weather extremes. The effect of cold waves as well as heat waves tends to increase when they last longer. A cold wave with at least 5 consecutive cold days increases the monthly mortality rate by around 4.9% (significant at the 10% level), while a cold wave with at least 9 consecutive cold days increases the mortality rate by 6.5%

(significant at the 5% level). Compared with a cold wave, the effect of a heat wave on the mortality rate is greater and more significant. The mortality rate in a month increases by 13.5% if there is a heat wave of at least 9 consecutive days in the month, indicating the substantial effect of a prolonged severe heat wave. However, a heat wave of at least 9 consecutive days rarely occurs. During the 2000-2018 period, the average percentage of months in which a heat wave of at least 9 consecutive hot days occurred was only 2.1% (Figure 5).

Panel D depicts the estimated coefficients of the number of consecutive days in cold and heat waves on the log of mortality rates. When cold and heat waves are measured by the number of consecutive days, their effect estimates are statistically more significant. All the estimates are positive and statistically significant at the 5% level. The point estimate of the effect of a hot day is greater than that of a cold day, but the difference is not statistically significant. An additional day in a cold wave lasting at least 3 consecutive days (relative to a day within the 5<sup>th</sup>-95<sup>th</sup> percentile temperature range) leads to an increase in the mortality rate of 0.6%. The corresponding figure for an additional day during a heat wave is 0.7%. During a cold or heat wave, defined as at least 9 consecutive days, an additional day increases the mortality rate by 0.6% and 1.2%, respectively.

[Figure 6 about here]

We argue that cold and heat waves cause mortality mainly through the adverse effect on health, for two reasons. Firstly, cold and heat waves have only short-term effects on mortality. To examine the medium-term effect of cold and heat waves, we include one-month and two-month lagged variables of cold and heat waves to examine the sensitivity of the effect estimates as well as the medium-term effect of cold and heat waves. Table A.4 in the Appendix reports the regressions. Most lagged variables of cold and heat waves are positive but not statistically significant at conventional levels. This suggests that cold and heat waves do not have medium- or long-term effects on mortality. Secondly, we do not find a significant effect of cold and heat waves on income (see Table A.20 in the Appendix). Thus, income is not a means through which cold and heat waves increase mortality.

### *5.3. Robustness analysis*



In this section, we conduct a series of robustness checks to examine the interval validity of our estimated effect of weather extremes on mortality. Firstly, we try different measures of the dependent variable. For interpretation, we use the crude mortality rate and the log of the crude mortality rate as the dependent variables in regressions. An issue with the crude mortality rate is that it depends on the age distribution of the population. The effect of weather extremes on the mortality rate may depend on the makeup of the population rather than the risk of death.

To examine this issue, we use age-adjusted mortality rates, which rely on a fixed age distribution over years and across provinces. An age-adjusted mortality rate for province  $p$  in year  $t$  is computed as a weighted average of age-specific mortality rates for the province, with weights equal to the proportion of the population of the corresponding 5-year age group in a baseline year (e.g., see the formula in Mullins and White, 2020). In this study, we divide the population into 5-year age groups, drawing on the 1999 Vietnam Population and Census. These weights are applied for all provinces in all years. Table A.5 presents regressions of the age-adjusted mortality rate and the log of the age-adjusted mortality rate on cold and heat waves using the same model specifications as Tables A.2 and A.3. The estimated effects of cold and heat waves on the age-adjusted mortality rate are very similar to the estimated effects on the crude mortality rate, implying that the effect of cold and heat waves on the crude mortality rate is not the result of age distribution.

Secondly, we use different measures of temperature and weather extremes. As presented in Table 1 and Table A.1, we use different temperature bins to examine the non-linear effects of temperature on mortality. We define cold and heat waves according to duration — 3, 5, 7, and 9 consecutive days. In regressions, cold and heat waves are measured by both dummy variables, which indicate the occurrence of the cold and heat waves, and the number of consecutive days in these waves. In addition to using the 5<sup>th</sup> and 95<sup>th</sup> percentiles to define a cold or heat wave, we also use the thresholds of the 10<sup>th</sup> and 90<sup>th</sup> percentiles. Regressions of the mortality rate on these weather extreme variables are reported in Table A.6 in the Appendix. Overall, the results are very similar to those in which cold and heat waves are defined based on the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the temperature distribution.

Thirdly, we examine the sensitivity of estimates of the impact of cold and heat waves to different model specifications. In previous regressions, we control for the average of yearly instead of monthly temperatures and rainfall to avoid the effect of cold and heat waves on the control variables. In Tables A.7 and A.8, we control for monthly temperatures and rainfall and note that controlling for these variables does not change the coefficients appreciably.

Next, Tables A.9, A.10 and A.11 report different model specifications which differ in the number of control variables. More specifically, Table A.9 reports regressions without controlling for annual mean temperature and rainfall. We also exclude province-specific time trends, since controlling for them might absorb the effect of temperature and bias its effect (Wolfers, 2006; Baum-Snow and Lutz, 2011). In Table A.10, on the other hand, we include both the province-specific time trend and province-specific time trend squared. Regressions presented in Table A.11 feature additional control variables, including number of hospitals, population density, and the proportion of the urban population. The effect estimates of cold and heat waves in Tables A.9 to A.11 are very similar to those from the main models that are used for interpretation in the previous section.

Fourthly, we examine whether the estimates are sensitive to the use of weighting schemes. Table A.12 in the Appendix reports regressions without population weights, and Table A.13 in the Appendix presents regressions which use the weights of the current population instead of the population in 1999. As we can see, different weighting schemes do not affect estimates of the effect of cold and heat waves.

Finally, we conduct a placebo test by running a regression of the mortality rate on the one-month and two-month leads of cold and heat waves. We use both the mortality rate and the log of the mortality rate as the dependent variables. The cold and heat waves are measured by both dummy variables and the number of consecutive days of cold or heat. The regression results are presented in Tables A.14 to A.17 in the Appendix. There are 32 regressions in total. Almost none of the coefficients of cold and heat waves are statistically significant at conventional levels. Among 64 estimated coefficients of cold and heat waves, there is only one estimated coefficient which is statistically at the 10% level. This placebo

test suggests that cold and heat waves are exogenous and can be regarded as random in the mortality equation.

#### *5.4. Heterogeneous effects and adaptations*

This section explores whether the effect of cold and heat waves varies across different population groups and provinces with different characteristics. Children and older people are more vulnerable to weather extremes than others (e.g., see Basu, 2009; Arbuthnott and Hajat, 2017; Geruso and Spears, 2018). Table 2 presents the coefficients of the number of days in cold and heat waves in regressions of the mortality rate for different age groups. There are 32 regressions in total, and the table presents only the estimated coefficients of the number of days in cold and heat waves for each regression. The regression specifications are the same as those in Table A.3 in the Appendix.

The results suggest that only older people, especially those over 80, are affected by weather extremes. Almost no coefficients of cold and heat waves are statistically significant for people below 40. For people aged over 40, all the estimated coefficients of cold and heat waves are positive, indicating an adverse effect on health for this group. The effect on the mortality rate of people over 80 is notably higher than it is for younger people. In Table 2, we also explore the difference in the effect of cold and heat waves on the mortality of men compared with women. Overall, we do not find a significant difference between men and women in the effect on the mortality rate.

It should be noted that we use the mortality rate instead of the log of the mortality rate as the dependent variable, since the monthly mortality rate for some population subgroups in some provinces is equal to zero. We apply the inverse hyperbolic sine transformation ( $\operatorname{arsinh}(x) = \ln(x + \sqrt{1 + x^2})$ ), which has a similar interpretation as the log function but can avoid a zero value of the dependent variable.<sup>8</sup> Regressions of  $\operatorname{arsinh}$  (the mortality rate) are presented in Table A.22 in the Appendix. The effect of cold and heat waves is greater for older people, especially those over 80. An additional day in cold and

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<sup>8</sup> Discussion of the  $\operatorname{arsinh}$  transformation and its application can be found in several studies, such as those of MacKinnon and Magee (1990), Pence (2006), and Card and DellaVigna (2020).

heat waves leads to an increase in the monthly mortality rate of people over 80 by 0.0246% and 0.0396%, respectively.<sup>9</sup>

[Table 2 about here]

We examine the heterogeneous effect of weather extremes across different province characteristics, using the regression specified in Equation (3). We select the characteristics that reflect the different strategies people adopt to adapt to temperature fluctuations. Specifically, eight variables that interact with the number of days in cold and heat waves include education level, per capita income, air-conditioning, population density, emigration and immigration rates, government spending on health care, and the number of hospitals in a province. As mentioned in Section 4.2, to avoid the problem that the interaction variables are also affected by temperature, we use one-year lags of these variables instead of their values in the current year.

Table 3 reports the estimated coefficients on interactions between the number of days in cold and heat waves (measured by 3, 5, 7 or 9 consecutive days with temperature extremes) and interaction variables in regressions of the log of the mortality rate for all ages. There are 32 regressions in total. The control variables include annual average temperature (in degrees Celsius), annual precipitation (mm), province-specific time trends, province-by-month fixed effects, year-by-month fixed effects, and the interaction variables (the same regression specifications as Table A.3 in the Appendix).

The effect of temperature on health tends to be greater in lower income countries (Basu, 2009; Burgess et al., 2017; Carleton et al., 2020). However, in our study almost none of the interactions between weather extremes, education level, and per capita income of the provinces are statistically significant (columns 1 and 2 of Table 3). Possibly, average income does not capture the income distribution for people within a province. Higher per capita income in a province does not mean higher income for most people in it. To explore

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<sup>9</sup> Another model which can address the problem of zero values in the dependent variable is the Poisson regression. We tried to estimate by means of the Poisson model, in which the dependent variables are the number of deaths per 100,000. There are no problems with zero inflation in the dependent variables. However, there is an indication of overdispersion; that is, the variance of the dependent variables is remarkably higher than their mean. Therefore, we also used a negative binomial regression. The estimated coefficients on cold and heat waves are very similar to those in the model using the arsinh of the mortality rate. Table A.19 in the Appendix reports the estimates from the negative binomial regression.

this issue further, we regress the log of per capita income on cold and heat waves using the province-by-year data level (there are no monthly data on per capita income). Cold and heat waves are also determined for a year rather than for a month, as in previous regressions.<sup>10</sup> Compared with a regression using province-by-month observations, a regression using province-by-year observations naturally has larger standard errors because of the smaller sample. Table A.20 in the Appendix shows that cold and heat waves have no significant effect on per capita income or on education level.

We expect that higher access to air-conditioning can mitigate the adverse effect of heat waves (e.g., Heutel et al., 2020; Barreca et al., 2016). However, we do not find a significant effect from the interactions between heat waves and the number of households with air-conditioners (column 3 of Table 3). On the other hand, coefficients on the interaction between cold waves and the air-conditioning variable are negative and significant. This suggests that the effect of cold waves on mortality is smaller in provinces where there is more air-conditioning.

To examine whether people respond to cold waves by purchasing air-conditioners, we regress the number of households with air-conditioning on the number of days in cold and heat waves and other control variables. The regressions use province-by-year observations, since the dependent variables are measured at the provincial level. Cold and heat waves are also defined for a year instead of for a month, as in the previous regressions.<sup>11</sup> Regression results from Table A.20 (column 3) shows that there are no significant effects from cold or heat waves on the number of households with air-conditioning.

Interactions between cold/heat waves, population density, and the immigration rate are not statistically significant, suggesting that the effect of cold/heat waves does not differ across provinces with different population densities and immigration rates. However, coefficients on the interactions between cold waves and the emigration rate are negative and significant (column 5, Table 3). This indicates that provinces with a higher rate of emigration tend to experience a smaller effect from cold waves. People can respond to

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<sup>10</sup> The control variables include annual average temperature (in degrees Celsius), annual precipitation (mm), the log of per capita income of provinces, province fixed effects and year fixed effects.

<sup>11</sup> The control variables include annual average temperature (in degrees Celsius), annual precipitation (mm), province fixed effects and year fixed effects.

temperature extremes by migration (e.g., Deschênes and Greenstone, 2007; Cattaneo and Peri, 2016). Table A.20 in the Appendix reports the regression of emigration and immigration rates on cold and heat waves using province-by-year data. It shows that cold waves tend to increase the emigration rate. Cold waves can drive people directly to emigrate from their provinces for health reasons, or indirectly through income pressures by reducing agricultural production (e.g., Deschênes and Greenstone, 2007; Burke et al. 2020). In this paper, we argue that cold waves mainly cause emigration for reasons of health, since there are no significant effects of cold waves on per capita income (column 2 in Table A.20 in the Appendix). In addition, the effect of cold waves on emigration is similar in regression with and without controlling for per capita income (Tables A.20 and A.21 in the Appendix). This implies that income is not an important channel through which cold waves induce migration.

Better provision of health care can be an important factor reducing the adverse effect of temperature on mortality (e.g., Mullins and White, 2020). We examine this issue by including interactions between cold/heat waves and public spending on health and the number of hospitals in the provinces. This approach shows that the effect of cold waves on the mortality rate tends to be smaller in provinces with higher spending on health. Provinces that spend more on health care tend to have better healthcare facilities and staff, helping to mitigate the adverse effect of weather extremes on people's health. According to column 7 of Table 3, if a province's health spending increases by 1%, the magnitude of the effect of a cold wave (measured by the number of days with at least 3 consecutive days below the 5th percentile of temperature) on the log of the mortality rate decreases by 0.000019 (equal to 0.0019/100). This magnitude is equal to 0.33% of the effect of cold waves on the log of the mortality rate, which is equal to 0.0057 (Panel D of Figure 6).

[Table 3 about here]

Unlike health spending, the variables 'air-conditioning' and 'emigration' are not measured in log form. Thus, we cannot directly compare the role of air-conditioning, emigration and health spending in reducing the effect of cold waves on mortality using estimates from Table 3. For comparison, we can compute estimates of interactions corresponding to the percentage change in the air-conditioning rate and the emigration rate.

Estimates of the interactions between cold waves (measured by the number of days with at least 3 consecutive days below the 5th percentile of temperature) and the air-conditioning rate and the emigration rate are -0.0328 and -0.2445 (columns 3 and 5 of Table 3), respectively. Using these estimates and the rates of air-conditioning and emigration in the pool sampled, we can compute the percentage changes. If the air-conditioning rate increases by 1%, the magnitude of the effect of cold waves (measured by the number of days with at least 3 consecutive cold days) on the log of the mortality rate decreases by 0.000016. The corresponding figure for the emigration rate is 0.000038. This suggests that emigration has a relatively more important role in reducing the effect of cold waves on mortality than air-conditioning and health spending.

## **6. Projection of mortality caused by cold and heat waves**

### *6.1. Mortality caused by cold and heat waves*

Table 4 estimates the number of deaths caused by cold and heat waves over time. In this table, a cold/heat wave is defined as at least 3 consecutive days which have a daily mean temperature at or below the 5th percentile (or at or above the 95th percentile) of the temperature distribution for a specific province. Column 1 reports the number of deaths, which is computed directly from the annual population surveys. Columns 2 and 3 estimate the number of deaths in the absence of cold and heat waves, respectively. The number of deaths caused by cold and heat waves is presented in columns 4 and 5, respectively. In 2017, it is estimated that cold and heat waves caused 617 and 1,851 deaths, respectively. The total number of deaths due to both cold and heat waves (reported in column 6) is estimated at 2,468 for 2017, accounting for 0.74% of all deaths in this year (reported in column 7). The number of deaths caused by cold or heat waves in a year depends on the number of cold and heat waves that occur that year. The number of fatalities due to cold or heat waves was highest in 2015 and lowest in 2009.

To compare mortality caused by cold and heat waves, columns 8 and 9 present the number of cold/heat wave related deaths in total deaths caused by both. For the entire 2003-2017 period, cold and heat waves account for 1.42% of all deaths in Vietnam. Among the deaths caused by these waves, cold waves account for 53%, while heat waves account for 47%.

[Table 4 about here]

We can estimate the economic cost of mortality caused by cold and heat waves by multiplying the number of deaths with a statistical life value of 0.342 million USD (Viscusi and Masterman, 2017). For 2017, the putative cost of preventing the mortality of 2,468 people is estimated at 0.84 billion USD (at constant 2015 prices), the equivalent of around 0.44% of GDP in that year.

[Table 5 about here]

## 6.2. *The projection*

In this section, we project daily data for Vietnam by adopting different Representative Concentration Pathway (RCP) scenarios to predict cold and heat waves in the 2020-2100 period. The RCP is a greenhouse gas concentration trajectory projected for the future. In the IPCC's fifth Assessment Report in 2014, four paths were employed for climate modeling and research. Different climate futures described in the pathways are all considered feasible, depending on the amount of greenhouse gases emitted in the coming years. The RCPs are labelled according to a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m<sup>2</sup>, respectively) (IPCC, 2019).

For simplicity, we assume that people's health status and economic conditions as well as their adaptation to climate changes will remain unmodified in the future. Thus, we use the same 5<sup>th</sup> and 95<sup>th</sup> percentiles, defined from the temperature distribution in 2000-2018, to project the cold and heat waves for 2020-2100. Panels A and B of Figure 7 present the projected number of consecutive days of cold and heat waves under different RCP scenarios. In this graph, a cold (heat) wave is defined as at least 3 consecutive days which have a daily mean temperature at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution for a specific province. Since the average temperature is projected to decrease in the coming year, the number of days of cold waves decreases quickly and is close to 0 in the 2050s. On the other hand, the number of days of heat waves increases significantly and reaches a maximum about 2060. The number of heat waves is largest for the RCP 6.0 scenario and smallest for the RCP 2.6 scenario.

We multiply the projected number of days of cold and heat waves by their estimated effect on the mortality rate (0.18 and 0.14 as indicated in Panel B of Figure 6) to predict the



number of deaths per 100,000 people caused by cold and heat waves in the coming years. It should be noted that we use estimates of the effect of cold and heat waves on the mortality rate instead of on the log of the mortality rate for the projection. The mortality rate is better for measuring the number of deaths caused by temperature extremes in the future. Figure 7 shows that the shape of the number of deaths caused by cold and heat waves (presented in Panels C and D) is very similar to that of the cold and heat waves, since we use constant effect estimates of cold or heat waves on mortality. The number of deaths caused by heat waves will increase in the future, peaking around 2060.<sup>12</sup> These findings raise serious concerns about future heat-related health consequences for Vietnam.

## **7. Conclusion**

Understanding the effect of weather extremes on health has received great attention from scholars and practitioners. In this study, we examine the effects of cold and heat waves on mortality in Vietnam during the 2000-2018 period. There are no medium-term effects from cold and heat waves, but we find robust evidence for the short-term effect of cold and heat waves on mortality. An additional day in a cold wave, defined as at least 3 consecutive cold days, increases the mortality rate by 0.6%. The corresponding figure for a day in a heat wave is 0.7%. For cold/heat waves, which are defined as at least 9 consecutive cold/hot days, an additional day in a cold/heat wave increases the mortality rate by 0.6% and 1.2%, respectively. Cold and heat waves have a higher effect on older people, especially those over 80.

There is a heterogeneous effect from cold waves on mortality across provinces with different adaptation strategies. The effect of cold waves on mortality tends to be lower in provinces with a higher degree of air-conditioning. Cold waves also push people to migrate out of their provinces, and provinces with higher emigration rates are less affected by cold waves. Public spending on health also mitigates the effect of cold waves on mortality.

Our findings suggest several policy implications. Firstly, not only heat but also cold waves are very harmful for health, particularly for older people. In Vietnam, older people over 80 years of age are currently eligible for social pensions and free health insurance.

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<sup>12</sup> Figure A.7 in the Appendix presents the number of deaths caused by cold and heat waves, defined as 5, 7, and 9 consecutive cold and heat days. The patterns are very similar to that graphed in Figure 7.

<sup>13</sup> The government should consider lowering the age threshold to 70 years so that more older people can receive assistance to improve their nutrition and health care in the face of weather-related shocks. Secondly, these findings suggest the important role of adaptive and coping strategies from both the government and households to reduce the adverse effect of climate change and weather extremes. The government needs to improve the health care system, especially in rural and remote areas, while households can install air-conditioning systems to cope with temperature shocks.

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<sup>13</sup> Decree 20/2021/NĐ-CP ‘Provisions on social support policies for social protection people’ issued by the Government of Vietnam on 15/03/2021. Available at: <https://thuvienphapluat.vn/van-ban/Van-hoa-Xa-hoi/Nghi-dinh-20-2021-ND-CP-chinh-sach-tro-giup-xa-hoi-doi-voi-doi-tuong-bao-tro-xa-hoi-467723.aspx>

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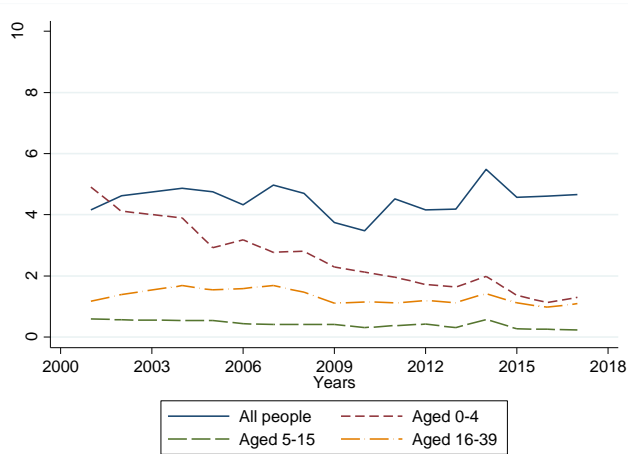
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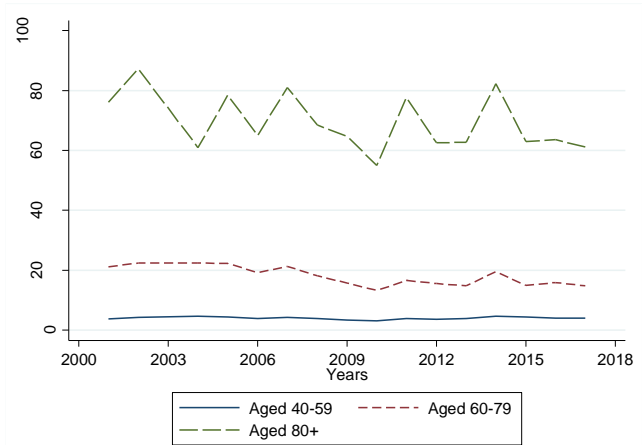
## Figures and Tables

Figure 1. Crude mortality rate (per 1000 people) by age group

Panel A. People aged 0-39

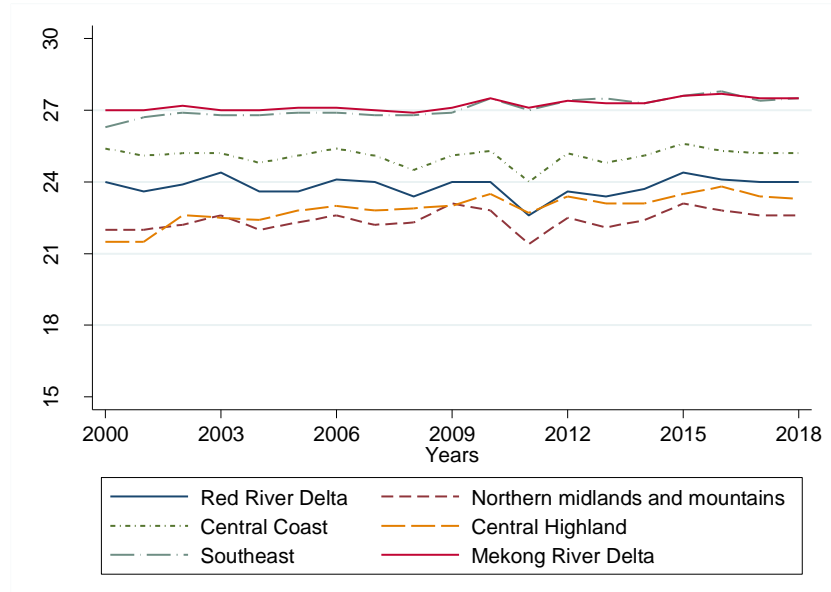


Panel B. People aged 40+



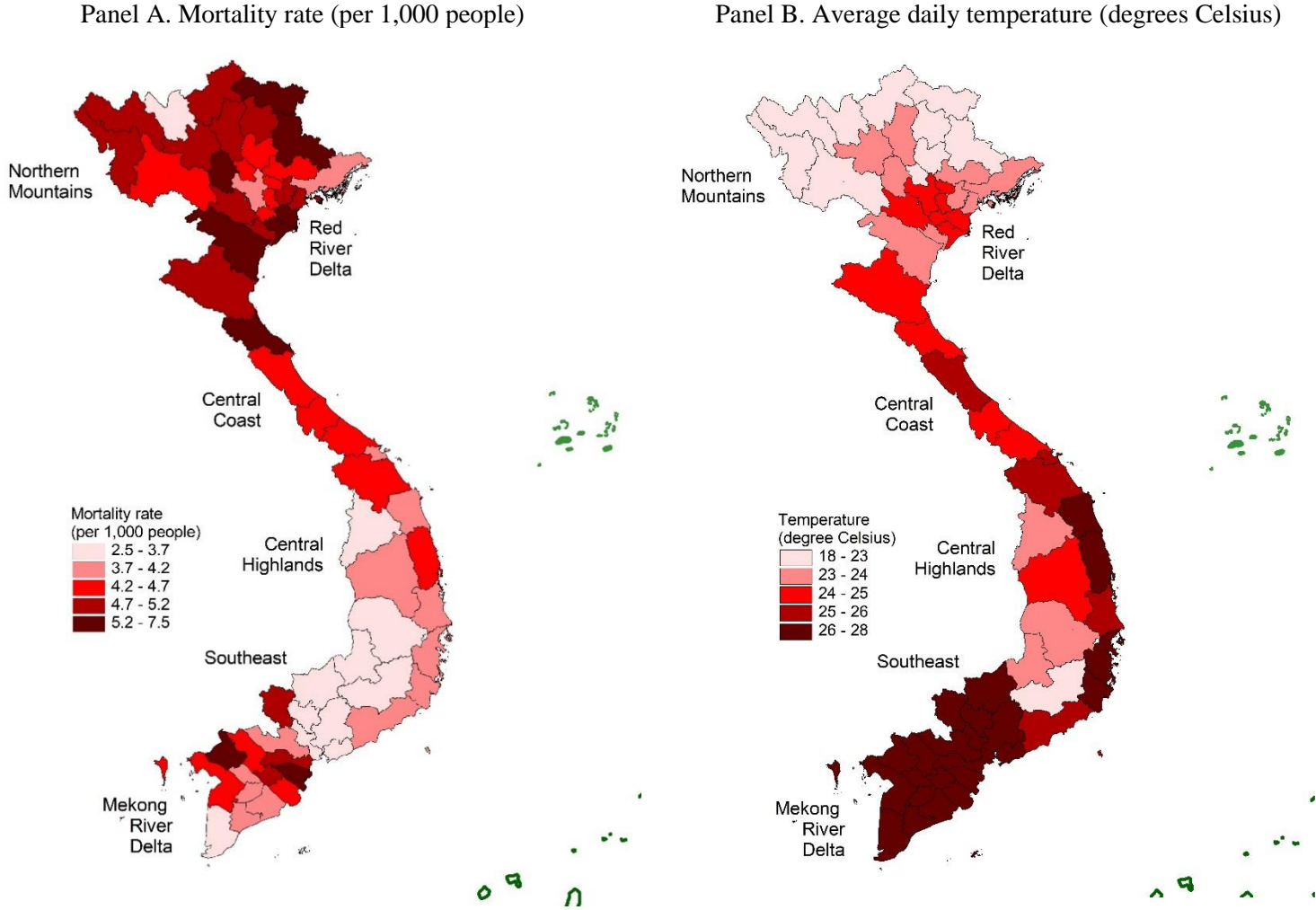
Note: This figure reports the crude mortality rate for different age groups from 2000-2018. Panel A presents the mortality rate for the entire population and population groups below 40 years old, while Panel B presents the mortality rate for those over 40. Panels A and B have different y-axis scales.

Figure 2: Average daily temperature over time



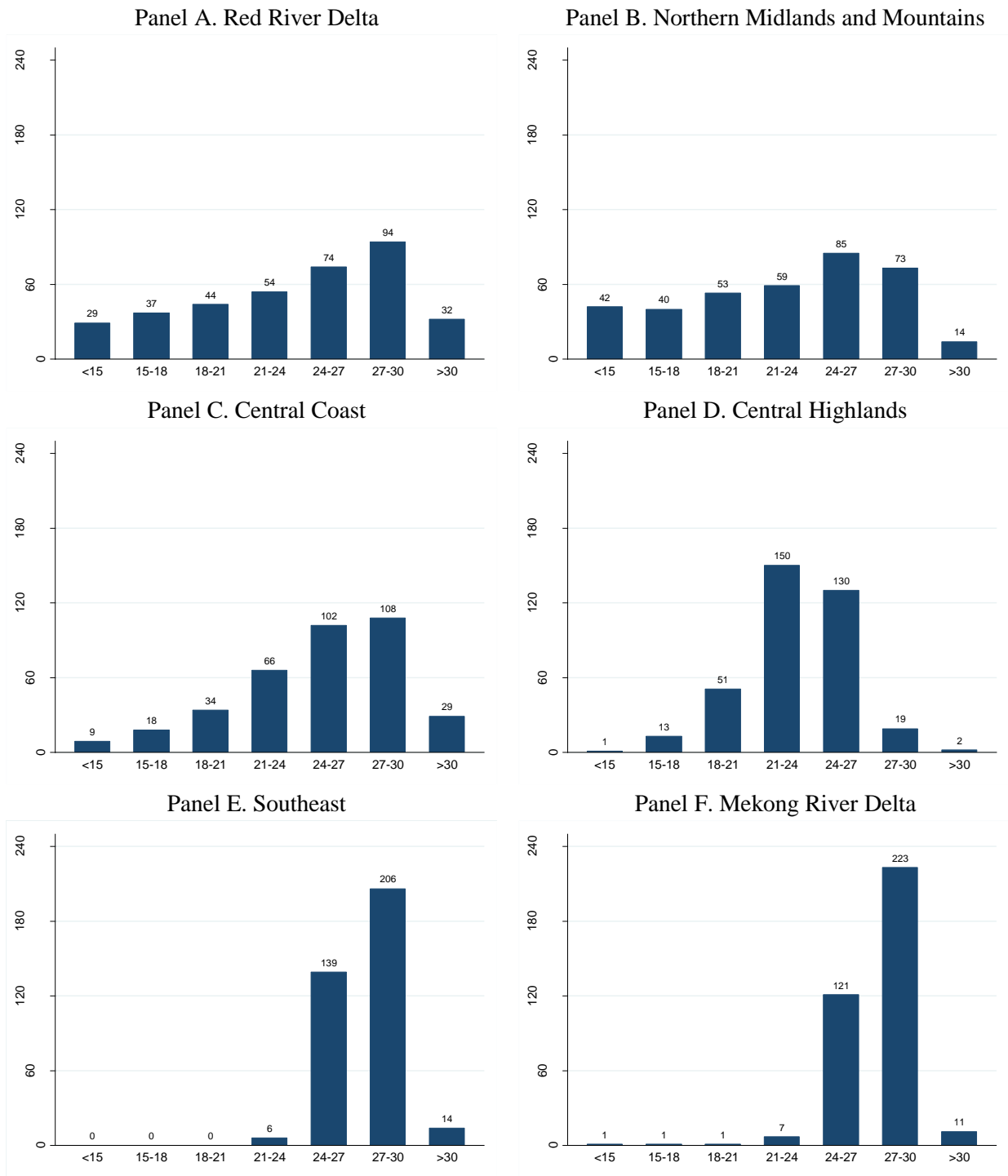
Note: Figure 2 presents the average daily temperature of regions from 2000-2018. The daily mean temperature is averaged across provinces within each region.

Figure 3: Mortality rate and temperatures



Note: Panel A presents the crude death rate of each province in a year, measured by the number of deaths per 1000 of the population. The map shows the mortality averaged over the 2000-2018 period. Panel B presents the average of the daily mean temperature of each province over the same period.

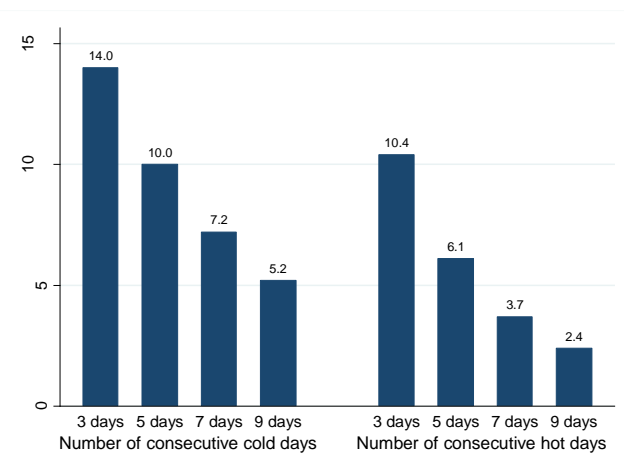
Figure 4: Distribution of daily temperature by bins, 2000-2018



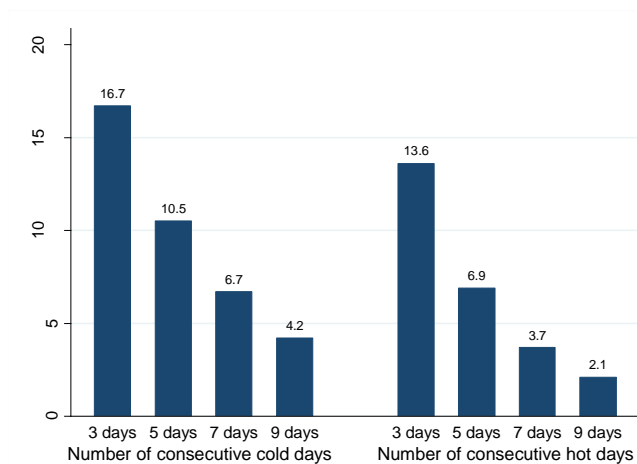
Note: This figure presents the average number of days per year, with daily mean temperatures falling into 7 bins for the 2000-2018 period. The figure presents the temperature distribution for 6 regions.

Figure 5: Cold and heat waves

Panel A. The average number of consecutive days in cold and heat waves



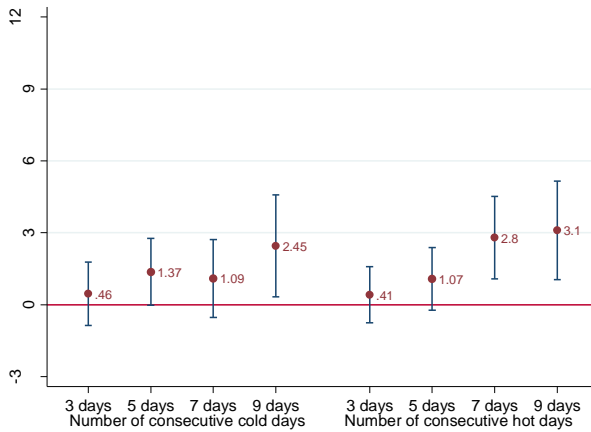
Panel B. The percentage of months with cold and heat waves



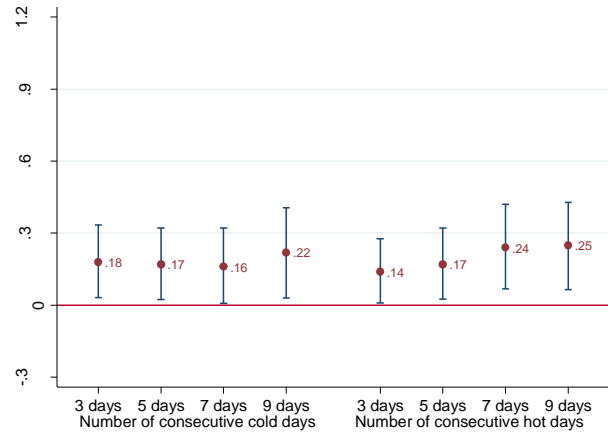
Note: Panel A of this figure presents the average number of days per year in cold and heat waves, defined based on the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the province-specific temperature distribution and varying durations of consecutive days. Panel B presents the average percentage of months in which at least one cold or heat wave (defined on the basis of varying durations of consecutive days) occurred during the 2000-2018 period.

Figure 6: Estimated effects (and 95% confidence interval) of cold and heat waves on the mortality rate for all ages

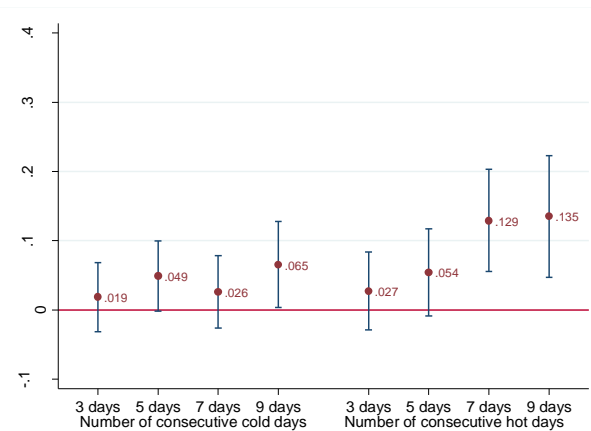
Panel A. Estimated effect on the mortality rate of cold and heat waves



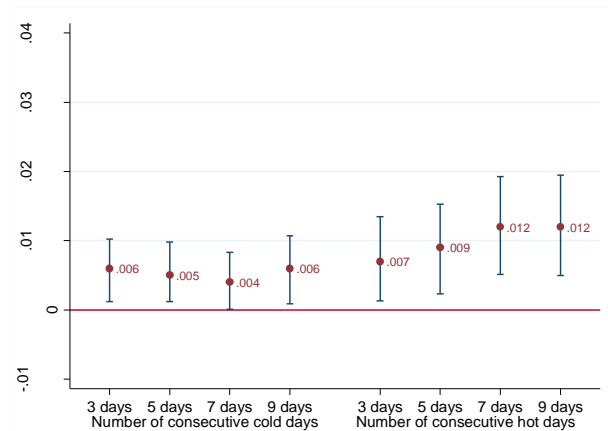
Panel B. Estimated effect on the mortality rate of the number of days in cold and heat waves



Panel C. Estimated effects of cold and heat waves on the log of the mortality rate



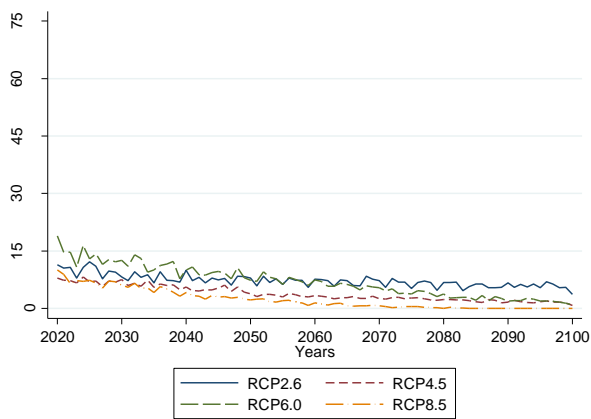
Panel D. Estimated effects of the number days in cold and heat waves on the log of the mortality rate



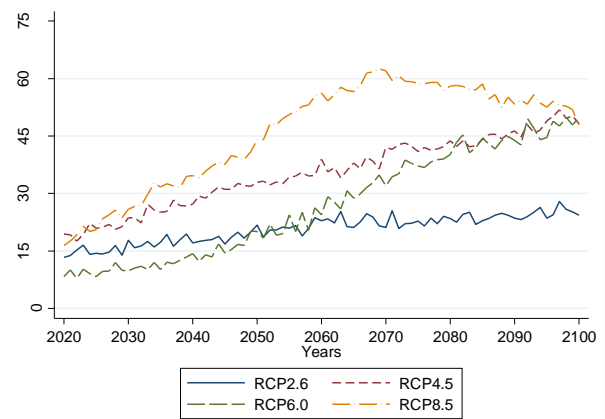
Note: This figure reports the estimated effects and their 95% confidence interval of cold and heat waves on the mortality rate (measured by the number of deaths per 100,000 people in a month) and the log of the mortality rate in the provinces. A cold (heat) wave is defined as at least k (3, 5, 7, and 9) consecutive days with a daily mean temperature at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution of a specific province. The control variables include the annual average temperature (in degrees Celsius), annual precipitation (mm), province-specific time trend, province-by-month fixed effects, and year-by-month fixed effects. The full regression models are presented in Tables A.2 and A.3 in the Appendix.

Figure 7. The projected number of consecutive days in cold and heat waves and the number of deaths under different Representative Concentration Pathway scenarios

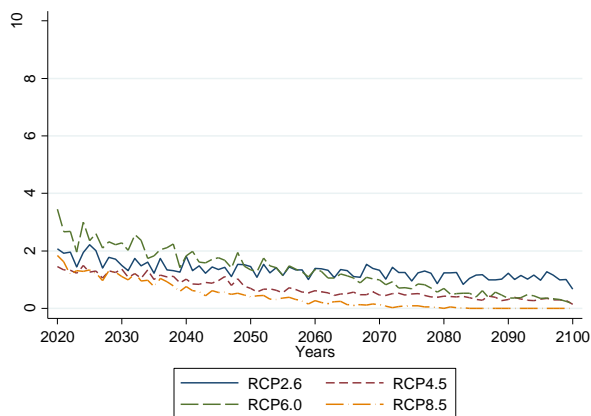
Panel A. The projected number of consecutive days in cold waves



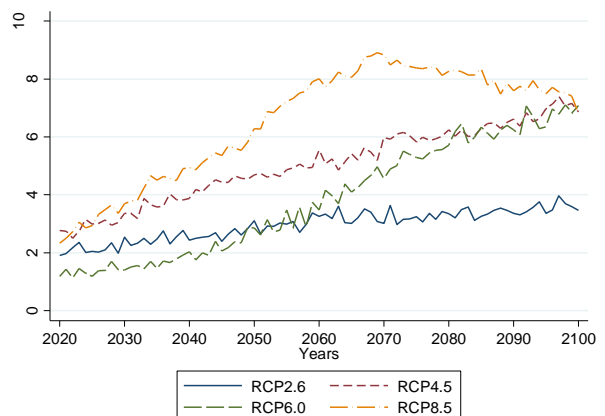
Panel B. The projected number of consecutive days in heat waves



Panel C. The projected number of deaths per 100,000 people due to cold waves



Panel D. The projected number of deaths per 100,000 people due to heat waves



Note: This figure presents the projected number of consecutive days in cold and heat waves according to different Representative Concentration Pathway scenarios and the estimated number of deaths due to these waves from 2020-2100. A cold/heat wave is defined as at least 3 consecutive days with a daily mean temperature at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution for a specific province.

Table 1. Regressions of mortality rates for all ages on climate variables

Explanatory variables	Dependent variables					
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)
Number of days 0-15°C	0.2500** (0.1197)	0.0047 (0.0032)	0.1976 (0.1264)	0.0032 (0.0032)		
Number of days 15-18°C	0.1004 (0.0868)	0.0026 (0.0028)				
Number of days 18-21°C	0.0859 (0.0706)	0.0018 (0.0022)				
Number of days 21-24°C	0	0				
Number of days 24-27°C	-0.0645 (0.0450)	-0.0025 (0.0017)				
Number of days 27-30°C	-0.0589 (0.0586)	-0.0027 (0.0023)				
Number of days 30°C +	0.0855 (0.0989)	0.0036 (0.0042)	0.1774** (0.0753)	0.0078** (0.0036)		
Number of days below the 5 <sup>th</sup> percentile of daily temperature					0.1675** (0.0809)	0.0050** (0.0025)
Number of days above the 95 <sup>th</sup> percentile of daily temperature					0.1288** (0.0626)	0.0073** (0.0029)
Annual average temperature (°C)	0.7554** (0.2981)	0.0273*** (0.0097)	0.6631** (0.3015)	0.0253** (0.0101)	0.6751** (0.3024)	0.0260** (0.0102)
Annual precipitation (mm)	0.2320* (0.1339)	0.0078 (0.0053)	0.2503* (0.1347)	0.0081 (0.0053)	0.2534* (0.1353)	0.0081 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Constant	21.0210*** (7.2461)	3.0228*** (0.2292)	22.3605*** (7.6248)	3.0273*** (0.2527)	22.0299*** (7.6658)	3.0040*** (0.2573)
Observations	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.334	0.306	0.335	0.310	0.335	0.311

Note: This table reports the regression of the mortality rate and the log of the mortality rate on the number of days in different temperature bins in a month, as well as other control variables.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1.



Table 2. Regression of mortality rates for different population groups

Explanatory variables	Dependent variables							
	Mortality rate of people aged 0-4 (deaths per 100,000 people)	Mortality rate of people aged 5-15 (deaths per 100,000 people)	Mortality rate of people aged 16-39 (deaths per 100,000 people)	Mortality rate of people aged 40-59 (deaths per 100,000 people)	Mortality rate of people aged 60-79 (deaths per 100,000 people)	Mortality rate of people aged 80+ (deaths per 100,000 people)	Mortality rate of males (deaths per 100,000 people)	Mortality rate of females (deaths per 100,000 people)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentile of temperature	0.0891 (0.1421)	0.0409 (0.0267)	-0.0401 (0.0587)	0.1513* (0.0760)	0.8443 (0.5369)	5.2655*** (1.9113)	0.2940** (0.1190)	0.0743 (0.0768)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentile of temperature	-0.0294 (0.1517)	-0.0002 (0.0382)	-0.0512 (0.0537)	0.2518** (0.1224)	0.4004 (0.4869)	4.5024** (2.0700)	0.1193 (0.1044)	0.1647* (0.0832)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentile of temperature	0.1617 (0.1482)	0.0318 (0.0224)	-0.0122 (0.0519)	0.1558* (0.0785)	0.8126 (0.4943)	4.3609** (2.0221)	0.2737** (0.1127)	0.0752 (0.0706)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentile of temperature	-0.1212 (0.1499)	0.0264 (0.0430)	-0.0254 (0.0627)	0.2554* (0.1342)	0.5119 (0.4683)	4.5884* (2.3812)	0.1525 (0.1035)	0.1924* (0.1090)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentile of temperature	0.1671 (0.1580)	0.0555* (0.0326)	-0.0505 (0.0544)	0.1288* (0.0749)	0.9184 (0.5677)	4.0651* (2.0609)	0.2349** (0.1161)	0.0972 (0.0729)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentile of temperature	-0.0297 (0.1548)	-0.0143 (0.0438)	-0.0439 (0.0616)	0.2302 (0.1649)	1.0251* (0.5177)	6.9202*** (2.4346)	0.1975* (0.1082)	0.2851** (0.1290)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentile of temperature	0.1640 (0.1717)	0.0485 (0.0299)	-0.0298 (0.0634)	0.1810* (0.1007)	1.3919** (0.6492)	4.1322** (2.0547)	0.3063** (0.1296)	0.1342* (0.0767)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentile of temperature	0.0282 (0.1683)	-0.0018 (0.0494)	-0.0748 (0.0680)	0.2076 (0.1813)	0.8034* (0.4470)	8.6812*** (2.4793)	0.2171** (0.1055)	0.2716** (0.1313)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639

Note: This table reports the coefficients of the number of days in cold and heat waves in regressions of the mortality rate for different age groups. A cold (heat) wave is defined as at least k (3, 5, 7, and 9) consecutive days, where the daily mean temperature is at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution for a specific province. There are 32 regressions in total. The regression specifications are the same as those in Table A.3 in the Appendix. The control variables include annual average temperature (in degrees Celsius), annual precipitation (mm), province-specific time trend, province-by-month fixed effects, and year-by-month fixed effects.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1.

Table 3. Heterogeneous effects of cold and heat waves on log of mortality rate for all ages

Explanatory variables	Interaction variables							
	Interaction with proportion of population with college degrees	Interaction with log of per capita income	Interaction with proportion of population with air conditioning	Interaction with log of population density	Interaction with emigration ratio	Interaction with immigration ratio	Interaction with log of government spending on health	Interaction with log of the number of hospitals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentile of temperature	-0.0589 (0.0363)	-0.0002 (0.0022)	-0.0328** (0.0149)	-0.0013 (0.0015)	-0.2445*** (0.0633)	-0.0149 (0.0933)	-0.0019** (0.0009)	-0.0002 (0.0062)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentile of temperature	0.0319 (0.0510)	0.0043 (0.0030)	0.0204 (0.0203)	0.0027 (0.0018)	0.0916 (0.1586)	-0.0029 (0.1024)	0.0002 (0.0021)	-0.0061 (0.0059)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentile of temperature	-0.0495 (0.0445)	-0.0017 (0.0023)	-0.0327* (0.0192)	-0.0011 (0.0016)	-0.1592** (0.0747)	0.0441 (0.1005)	-0.0019** (0.0009)	0.0016 (0.0063)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentile of temperature	0.0833 (0.0608)	0.0051 (0.0032)	0.0325 (0.0217)	0.0036 (0.0022)	0.2864 (0.1785)	0.0785 (0.1330)	0.0013 (0.0024)	-0.0132** (0.0065)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentile of temperature	-0.0367 (0.0464)	0.0005 (0.0027)	-0.0248 (0.0203)	-0.0013 (0.0015)	-0.2342*** (0.0475)	0.0125 (0.0907)	-0.0015 (0.0010)	0.0016 (0.0064)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentile of temperature	0.0107 (0.0774)	0.0057 (0.0040)	0.0083 (0.0221)	0.0007 (0.0021)	-0.0193 (0.1422)	-0.0352 (0.1079)	0.0010 (0.0030)	-0.0071 (0.0069)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentile of temperature	-0.0730** (0.0352)	0.0002 (0.0033)	-0.0371** (0.0171)	-0.0021 (0.0015)	-0.2821*** (0.0681)	-0.0508 (0.1106)	-0.0018* (0.0011)	0.0051 (0.0061)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentile of temperature	0.0133 (0.0914)	0.0048 (0.0047)	0.0213 (0.0242)	0.0013 (0.0025)	0.1644 (0.1501)	0.0800 (0.1088)	0.0041 (0.0031)	-0.0063 (0.0068)
Observations	11,252	11,252	11,252	12,639	11,387	11,387	11,252	9,227

Note: This table reports the estimated coefficients on interactions between the number of days in cold and heat waves and interaction variables in the regression of the log of the mortality rate. A cold (heat) wave is defined as at least k (3, 5, 7, and 9) consecutive days with a daily mean temperature at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution in a specific province. There are 32 regressions in total. The control variables include annual average temperature (degrees Celsius), annual precipitation (mm), province-specific time trend, province-by-month fixed effects, and year-by-month fixed effects, and the interaction variables.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1.

Table 4. Estimation of the number of deaths caused by cold and heat waves

Year	Observed number of deaths	Number of deaths if no cold waves	Number of deaths if no heat waves	Number of deaths due to cold waves	Number of deaths due to heat waves	Total number of deaths due to cold and heat waves	Percentage of deaths caused by cold and heat waves	Percentage of cold wave related deaths	Percentage of heat wave related deaths
	(1)	(2)	(3)	(4)=(1)-(2)	(5)=(1)-(3)	(6)=(4)+(5)	(7)=(6)/(1)	(8)=(4)/(6)	(9)=(5)/(6)
2003	326,319	325,255	325,093	1,064	1,226	2,290	0.70	46.5	53.5
2004	324,901	322,160	323,177	2,741	1,724	4,465	1.37	61.4	38.6
2005	312,682	309,701	311,049	2,981	1,633	4,614	1.48	64.6	35.4
2006	367,523	366,302	366,027	1,221	1,496	2,717	0.74	44.9	55.1
2007	349,754	348,057	347,820	1,697	1,934	3,631	1.04	46.7	53.3
2008	300,264	295,260	300,064	5,004	200	5,204	1.73	96.2	3.8
2009	283,293	280,652	282,431	2,641	862	3,503	1.24	75.4	24.6
2010	338,773	338,018	333,329	755	5,444	6,199	1.83	12.2	87.8
2011	350,934	345,986	350,718	4,948	216	5,164	1.47	95.8	4.2
2012	368,245	366,201	366,673	2,044	1,572	3,616	0.98	56.5	43.5
2013	394,071	390,140	392,056	3,931	2,015	5,946	1.51	66.1	33.9
2014	375,823	371,507	372,525	4,316	3,298	7,614	2.03	56.7	43.3
2015	355,470	352,482	350,330	2,988	5,140	8,127	2.29	36.8	63.2
2016	373,777	371,649	368,117	2,128	5,660	7,788	2.08	27.3	72.7
2017	335,408	334,791	333,557	617	1,851	2,468	0.74	25.0	75.0
Total	5,157,237	5,118,161	5,122,966	39,076	34,271	73,346	1.42	53	47

Note: This table estimates the number of deaths caused by cold and heat waves over time. A cold (heat) wave is defined here as at least 3 consecutive days with a daily mean temperature at or below the 5th percentile (at or above the 95th percentile) of the temperature distribution in a specific province. Column 1 reports the number of deaths, computed directly from annual population surveys. Columns 2 and 3 estimate the number of deaths in the absence of cold and heat waves, respectively. The number of deaths caused by cold and heat waves is presented in columns 4 and 5, respectively. The number of deaths due to both cold and heat waves and the corresponding percentage of all deaths are reported in columns 6 and 7, respectively. The percentage of cold wave and heat wave related deaths in total deaths caused by cold and heat waves are presented in columns 8 and 9, respectively.

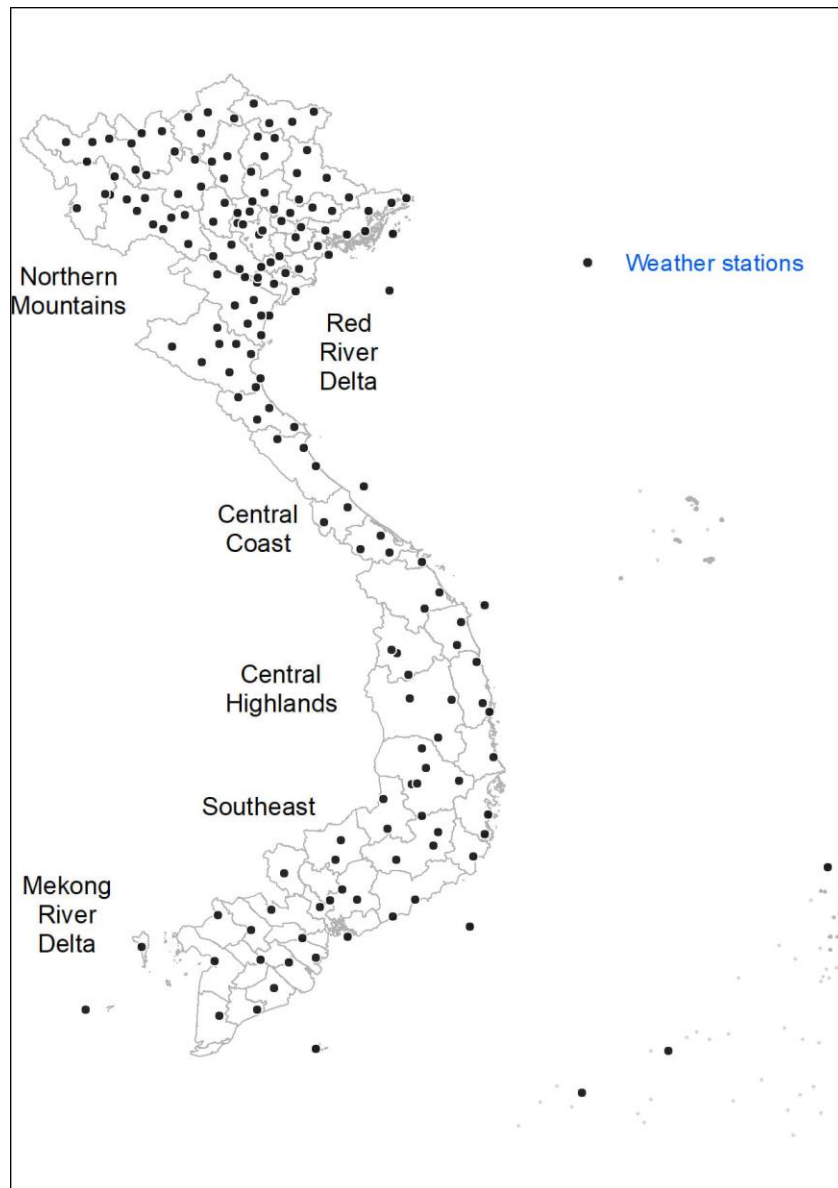
Table 5. Estimated economic cost of cold and heat waves

Year	Number of deaths due to cold and heat waves	WTP to reduce deaths caused by cold and heat waves (constant 2015 US\$ billion)	GDP (constant 2015 US\$ billion)	WTP as a percentage of GDP (%)
	(1)	(2)	(3)	(4)
2003	2,290	0.78	80.22	0.98
2004	4,465	1.53	86.26	1.77
2005	4,614	1.58	92.77	1.70
2006	2,717	0.93	99.25	0.94
2007	3,631	1.24	106.32	1.17
2008	5,204	1.78	112.34	1.58
2009	3,503	1.20	118.41	1.01
2010	6,199	2.12	126.01	1.68
2011	5,164	1.77	133.88	1.32
2012	3,616	1.24	140.90	0.88
2013	5,946	2.03	148.54	1.37
2014	7,614	2.60	157.43	1.65
2015	8,127	2.78	167.94	1.66
2016	7,788	2.66	178.38	1.49
2017	2,468	0.84	190.53	0.44

Note: This table estimates at 0.342 million USD the economic cost of mortality caused by cold and heat waves, multiplying the number of deaths by statistical life value (Viscusi and Masterman, 2017). It also reports this cost as a proportion of GDP.

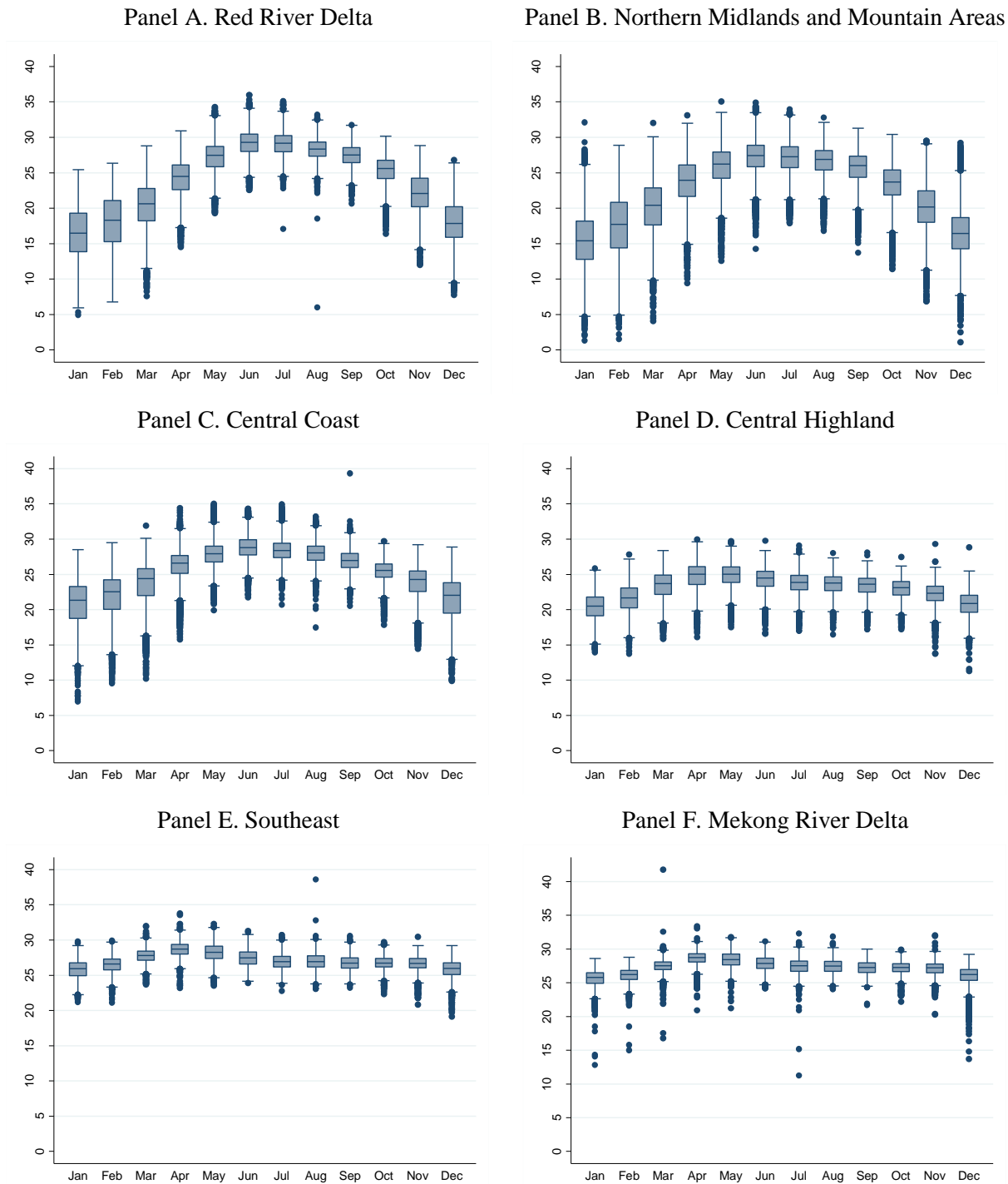
## Appendix: Figures and Tables

Figure A.1. Location of weather stations in Vietnam



Note: This figure shows the location of weather stations across provinces in Vietnam. Vietnam has 63 provinces covering 705 districts. We first match each district with the nearest weather station (the shortest distance from the district's centroid to the station). Temperature and precipitation of a weather station are used for temperature and precipitation of a matched (nearest) district. Next, we estimate temperature and precipitation for a province by the average weighted temperature and precipitation of districts in the province with weights equal to districts' areas.

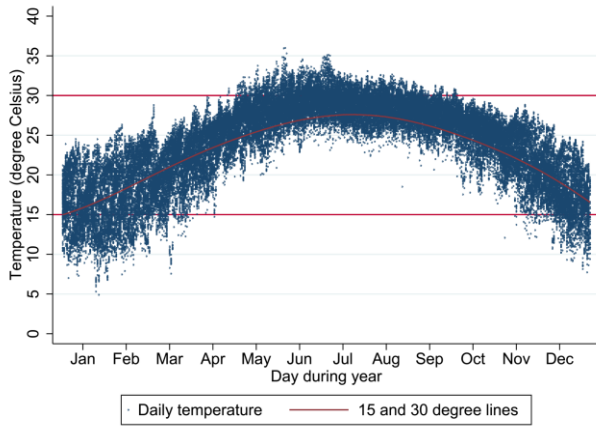
Figure A.2: Average daily temperature over months, 2000-2018



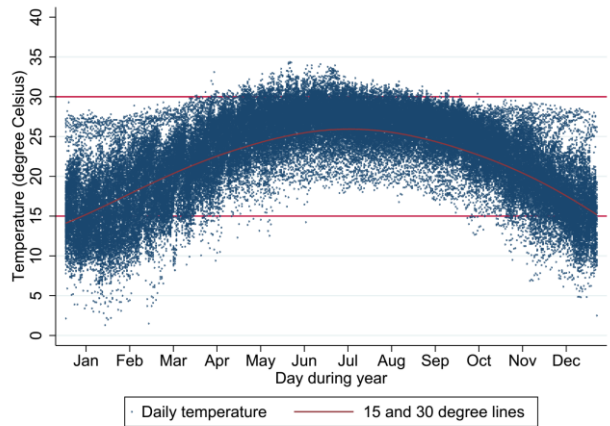
Note: This figure presents the median of daily mean temperature of months over the 2000-2018 period. The estimates are averaged across provinces within a region. The hottest month is June in the North (Red Rive Delta, Northern Midlands and Mountain Areas, Central Coast) and April in the South (Central Highland, Southeast, Mekong River Delta). January and December are the coldest months in all regions.

Figure A.3: Daily temperature during year, 2000-2018

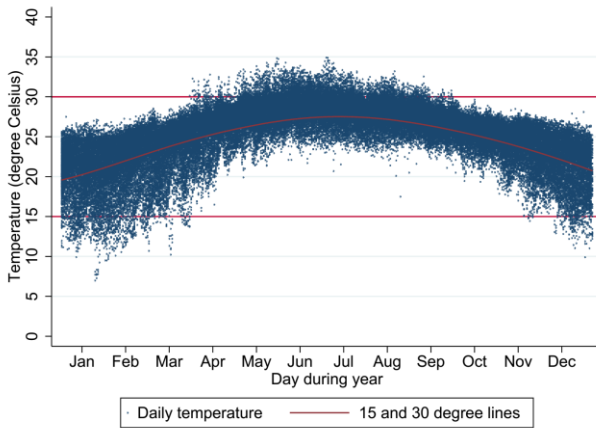
Panel A. Red River Delta



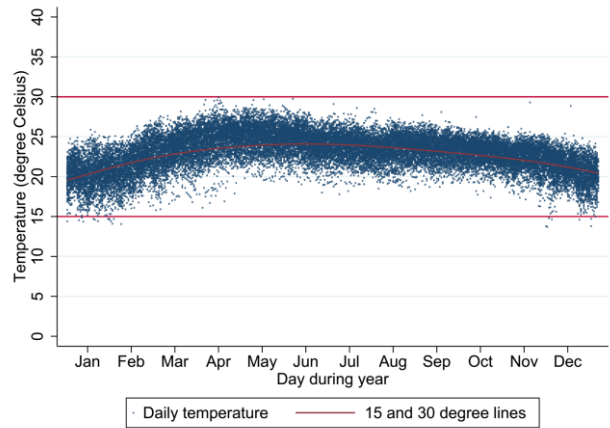
Panel B. Northern midlands and mountain areas



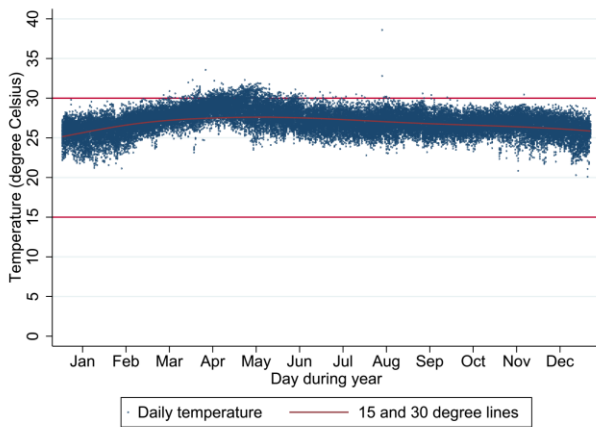
Panel C. Central Coast



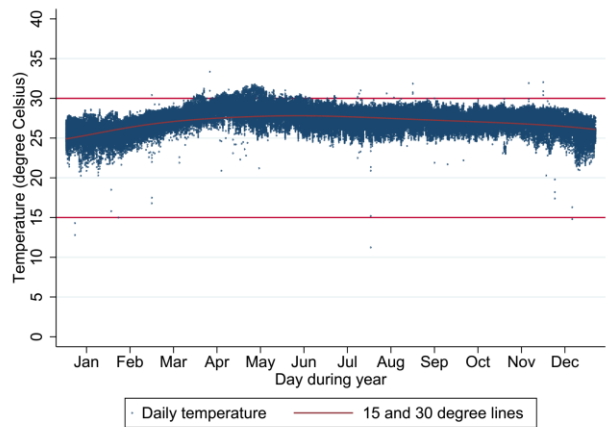
Panel D. Central Highland



Panel E. Southeast

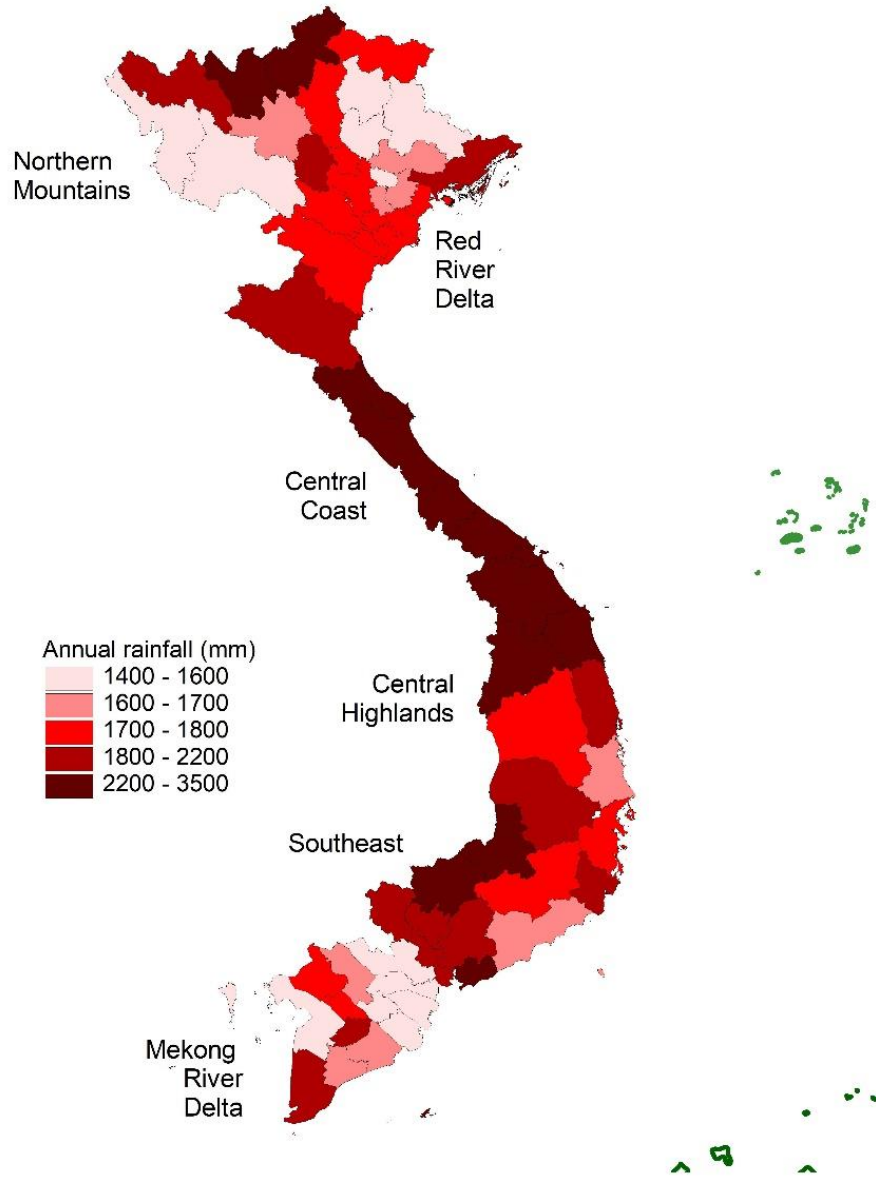


Panel F. Mekong River Delta



Note: This figure presents the mean temperature of days for 6 regions over the 2000-2018 period. Each dot represents an average temperature of a day of a province.

Figure A.4. Average annual precipitation (mm)

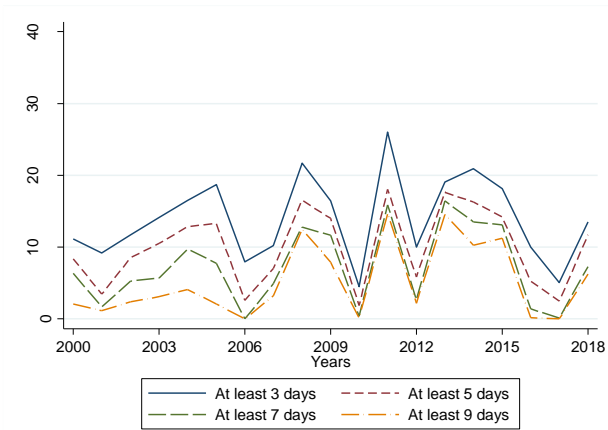


Note: This figure presents the average annual rainfall (mm) of provinces during the 2000-2018 period.

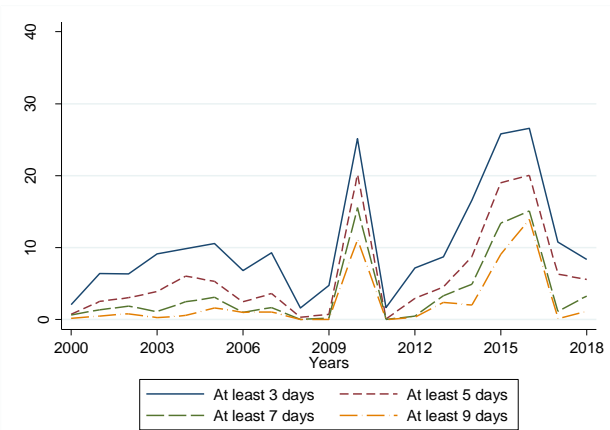


Figure A.5. The number of consecutive days in cold and heat waves within a year

Panel A. The average number of consecutive days in cold waves



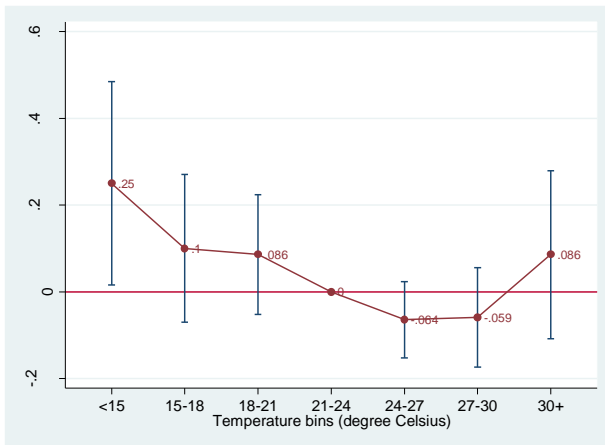
Panel B. The average number of consecutive days in heat waves



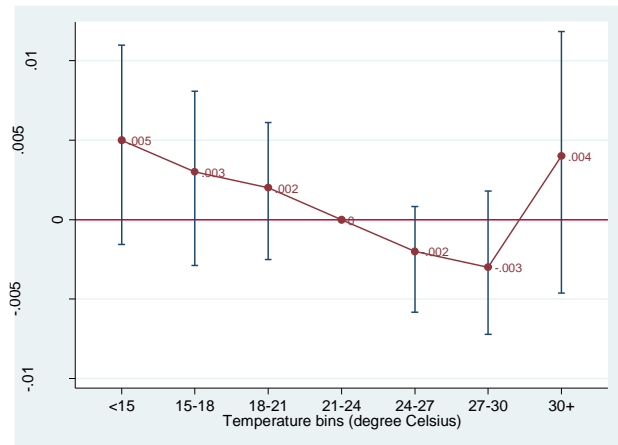
Note: This figures present the average (across provinces) number of consecutive days in cold and heat waves over the 2000-2018 period. The variable of cold (heat) waves is measured by the number of days with at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature below the 5<sup>th</sup> percentiles (above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Figure A.6. The estimated effect of temperature bins on mortality

Panel A. Effect on the mortality rate



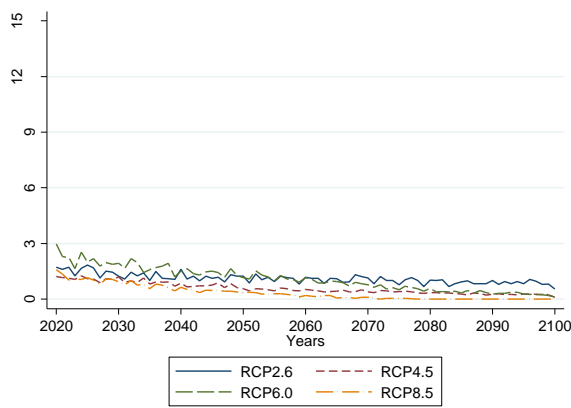
Panel B. Effect on log of the mortality rate



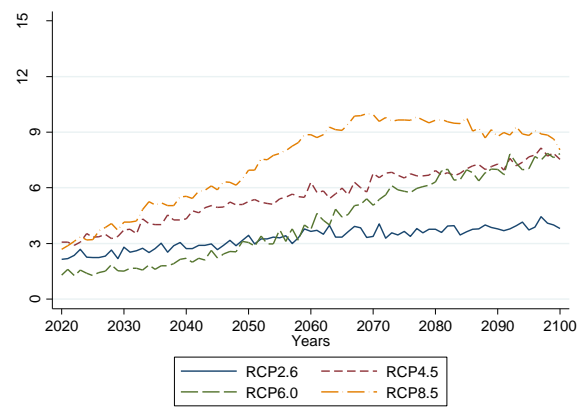
Note: This figure presents the point estimates and the 95% confidence intervals of the effect of the temperature bins on the mortality rate and log of the mortality rate. The estimates are reported in Table 1. The figures show a U-shaped relation between the temperature and mortality rate. However, most of the effect estimates of the temperature bins, relative to the 21-24 °C bin, are not statistically significant.

Figure A.7. The projected number of deaths due to consecutive days in cold and heat waves under different Representative Concentration Pathway scenarios

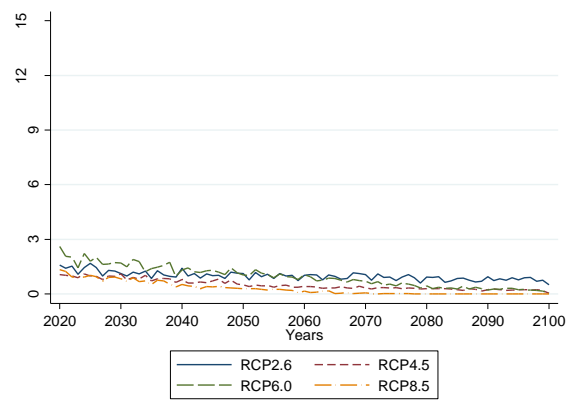
Panel A. The projected number of deaths per 100,000 people due to cold waves (5 consecutive days)



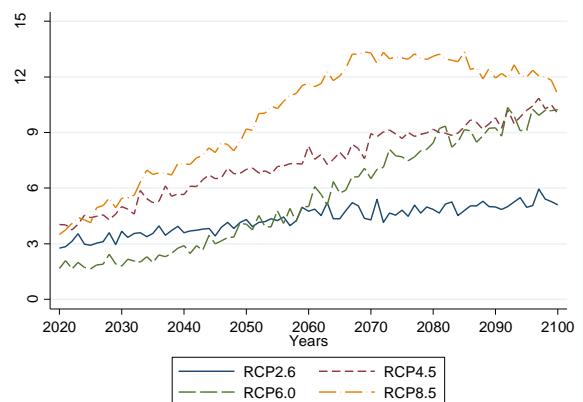
Panel B. The projected number of deaths per 100,000 people due to heat waves (5 consecutive days)



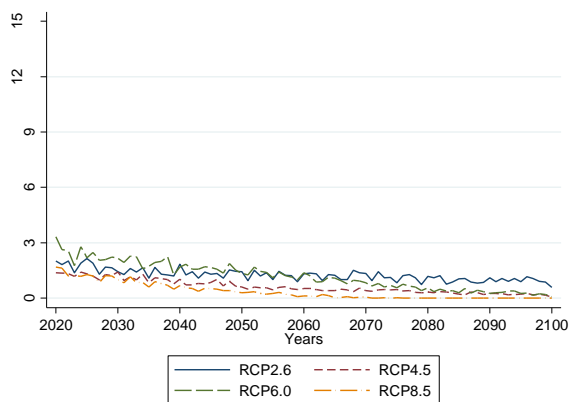
Panel C. The projected number of deaths per 100,000 people due to cold waves (7 consecutive days)



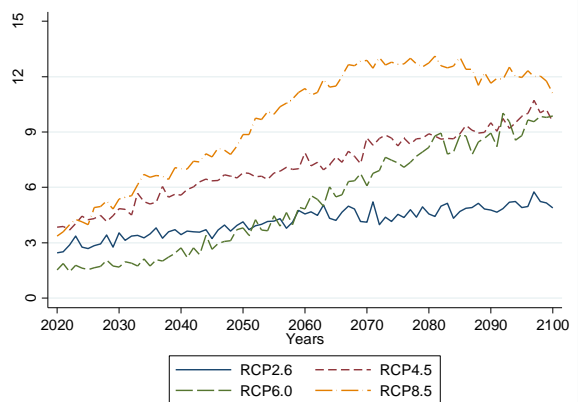
Panel D. The projected number of deaths per 100,000 people due to heat waves (7 consecutive days)



Panel E. The projected number of deaths per 100,000 people due to cold waves (9 consecutive days)



Panel F. The projected number of deaths per 100,000 people due to heat waves (9 consecutive days)



Note: This figures presents the estimated number of deaths due to the projected number of consecutive days in cold and heat waves under different Representative Concentration Pathway scenarios over the 2020-2100 period. A cold (heat) wave is defined as at least 5, 7 or 9 consecutive days which have daily mean temperature at or below the 5th percentiles (at or above the 95th percentile) of the temperature distribution of specific province.

Table A.1. Regression of the all-age mortality rate on temperature bins

Explanatory variables	Dependent variables			
	Mortality rate (deaths per 100,000 people)	Age-adjusted mortality rate (deaths per 100,000 people)	Log of mortality rate	Log of age- adjusted mortality rate
	(1)	(2)	(3)	(4)
The number of days 0-14 °C	0.2859* (0.1497)	0.1286 (0.1222)	0.0048 (0.0042)	0.0039 (0.0044)
The number of days 14-16 °C	0.1773* (0.1023)	0.0753 (0.0821)	0.0049 (0.0032)	0.0044 (0.0033)
The number of days 16-18 °C	0.1020 (0.1124)	0.0748 (0.0993)	0.0018 (0.0039)	0.0022 (0.0042)
The number of days 18-20 °C	0.1714 (0.1097)	0.0682 (0.0908)	0.0039 (0.0035)	0.0030 (0.0037)
The number of days 20-22 °C	0.0357 (0.0736)	0.0232 (0.0619)	0.0005 (0.0025)	0.0003 (0.0024)
The number of days 22-24 °C	0	0	0	0
The number of days 24-26 °C	-0.0541 (0.0490)	-0.0384 (0.0448)	-0.0018 (0.0019)	-0.0029 (0.0018)
The number of days 26-28 °C	-0.0583 (0.0584)	-0.0326 (0.0554)	-0.0032 (0.0025)	-0.0036 (0.0027)
The number of days 28-30 °C	-0.0899 (0.0684)	-0.0379 (0.0621)	-0.0024 (0.0028)	-0.0026 (0.0029)
The number of days 30 °C +	0.0677 (0.0974)	0.0612 (0.0805)	0.0035 (0.0043)	0.0026 (0.0042)
Annual average temperature (°C)	0.8000** (0.3038)	0.4740* (0.2525)	0.0278*** (0.0098)	0.0258** (0.0103)
Annual precipitation (mm)	0.2302* (0.1348)	0.2372** (0.1074)	0.0079 (0.0053)	0.0077 (0.0054)
Province-specific time trend	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes
Constant	19.8998*** (7.3008)	19.5727*** (6.0864)	3.0071*** (0.2279)	2.7342*** (0.2366)
Observations	12,639	12,639	12,639	12,639
R-squared	0.334	0.371	0.306	0.320

Note: This tables report regressions of mortality rate on the number of days in the 2-degree temperature bins. The number of days in the 22-24 °C bin is used as the reference group.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1.

Table A.2. Regression of all-age mortality rate on cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
At least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month	0.4559 (0.6711)	0.0185 (0.0255)						
At least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month	0.4145 (0.5968)	0.0273 (0.0287)						
At least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month			1.3675* (0.7094)	0.0488* (0.0259)				
At least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month			1.0715 (0.6656)	0.0542* (0.0320)				
At least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month					1.0932 (0.8320)	0.0261 (0.0267)		
At least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month					2.7999*** (0.8780)	0.1292*** (0.0377)		
At least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month							2.4481** (1.0854)	0.0654** (0.0317)
At least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month							3.1017*** (1.0454)	0.1349*** (0.0449)
Annual average temperature (°C)	0.6506** (0.3000)	0.0261** (0.0103)	0.6687** (0.2952)	0.0267** (0.0101)	0.6671** (0.3055)	0.0260** (0.0103)	0.7737** (0.3080)	0.0293*** (0.0102)
Annual precipitation (mm)	0.2528* (0.1356)	0.0079 (0.0053)	0.2538* (0.1360)	0.0080 (0.0053)	0.2674* (0.1355)	0.0085 (0.0053)	0.2674* (0.1344)	0.0085 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	22.9608*** (7.5481)	3.0132*** (0.2568)	22.4634*** (7.4439)	2.9985*** (0.2525)	22.4149*** (7.6887)	3.0130*** (0.2561)	19.7638** (7.7483)	2.9321*** (0.2554)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.336	0.311	0.336	0.311

Note: This table reports regression of mortality rate on dummy variables indicating whether at least a cold or a heat wave occur in a month. A cold (heat) wave is defined as occurrence of  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature below the 5<sup>th</sup> percentiles (above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.3. Regression of all-age mortality rate on the number of days of cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1822** (0.0772)	0.0057** (0.0023)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1425** (0.0682)	0.0074** (0.0031)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1723** (0.0760)	0.0055** (0.0022)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1735** (0.0756)	0.0088** (0.0033)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1645** (0.0801)	0.0042* (0.0021)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2438*** (0.0899)	0.0122*** (0.0036)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.2179** (0.0957)	0.0058** (0.0025)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2463** (0.0930)	0.0122*** (0.0037)
Annual average temperature (°C)	0.6809** (0.3000)	0.0266** (0.0102)	0.6848** (0.3012)	0.0270** (0.0102)	0.7022** (0.3056)	0.0273** (0.0103)	0.7480** (0.3075)	0.0287*** (0.0103)
Annual precipitation (mm)	0.2536* (0.1358)	0.0081 (0.0053)	0.2578* (0.1361)	0.0082 (0.0053)	0.2603* (0.1360)	0.0083 (0.0053)	0.2586* (0.1352)	0.0082 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	21.9630*** (7.5972)	2.9930*** (0.2556)	21.9394*** (7.6215)	2.9860*** (0.2564)	21.4927*** (7.7168)	2.9785*** (0.2581)	20.4043** (7.7581)	2.9454*** (0.2586)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.336	0.311	0.336	0.311	0.336	0.311	0.336	0.311

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.4. Regression of log of all-age mortality rate on cold and heat waves and their lags

Explanatory variables	Dependent variables							
	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Number of days with at least 3 consecutive cold days	0.0052** (0.0022)				0.0052** (0.0022)			
Number of days with at least 3 consecutive hot days	0.0067** (0.0029)				0.0068** (0.0029)			
One-month lag of number of days with at least 3 consecutive cold days	0.0030 (0.0029)				0.0030 (0.0028)			
One-month lag of number of days with at least 3 consecutive hot days	0.0038 (0.0030)				0.0034 (0.0029)			
Two-month lag of number of days with at least 3 consecutive cold days					-0.0001 (0.0022)			
Two-month lag of number of days with at least 3 consecutive hot days					0.0021 (0.0028)			
Number of days with at least 5 consecutive cold days		0.0051** (0.0021)				0.0052** (0.0021)		
Number of days with at least 5 consecutive hot days		0.0081*** (0.0030)				0.0083*** (0.0031)		
One-month lag of number of days with at least 5 consecutive cold days		0.0031 (0.0028)				0.0030 (0.0028)		
One-month lag of number of days with at least 5 consecutive hot days		0.0030 (0.0031)				0.0026 (0.0030)		
Two-month lag of number of days with at least 5 consecutive cold days						0.0006 (0.0021)		
Two-month lag of number of days with at least 5 consecutive hot days						0.0020 (0.0027)		
Number of days with at least 7 consecutive cold days			0.0039* (0.0020)				0.0040* (0.0021)	
Number of days with at least 7 consecutive hot days			0.0109*** (0.0031)				0.0106*** (0.0032)	
One-month lag of number of days with at least 7 consecutive cold days			0.0024 (0.0030)				0.0023 (0.0030)	
One-month lag of number of days with at least 7 consecutive hot days			0.0064 (0.0040)				0.0067* (0.0039)	
Two-month lag of number of days with at least 7 consecutive cold days							0.0013 (0.0020)	

Explanatory variables	Dependent variables							
	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Two-month lag of number of days with at least 7 consecutive hot days							-0.0017 (0.0034)	
Number of days with at least 9 consecutive cold days				0.0056** (0.0024)				0.0056** (0.0024)
Number of days with at least 9 consecutive hot days				0.0114*** (0.0032)				0.0108*** (0.0032)
One-month lag of number of days with at least 9 consecutive cold days				0.0018 (0.0034)				0.0016 (0.0033)
One-month lag of number of days with at least 9 consecutive hot days				0.0038 (0.0042)				0.0050 (0.0042)
Two-month lag of number of days with at least 9 consecutive cold days								0.0018 (0.0019)
Two-month lag of number of days with at least 9 consecutive hot days								-0.0043 (0.0039)
Annual average temperature	0.0267** (0.0102)	0.0275*** (0.0102)	0.0276*** (0.0102)	0.0293*** (0.0103)	0.0265** (0.0105)	0.0276*** (0.0103)	0.0285*** (0.0104)	0.0305*** (0.0106)
Annual precipitation (mm)	0.0092* (0.0053)	0.0091* (0.0053)	0.0092* (0.0053)	0.0090* (0.0053)	0.0086 (0.0054)	0.0085 (0.0054)	0.0085 (0.0055)	0.0083 (0.0054)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	2.9806*** (0.2559)	2.9672*** (0.2547)	2.9613*** (0.2557)	2.9266*** (0.2594)	2.9875*** (0.2623)	2.9643*** (0.2584)	2.9441*** (0.2604)	2.9012*** (0.2645)
Observations	12,630	12,630	12,630	12,630	12,621	12,621	12,621	12,621
R-squared	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310

Note: This table reports regression of mortality rate on the number of days in cold and heat waves in current months and in lagged months. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .



Table A.5. Regression of age-adjusted (all-age) mortality rate on the number of days of cold and heat waves

Explanatory variables	Dependent variables							
	Age-adjusted mortality rate	Log of age-adjusted mortality rate	Age-adjusted mortality rate	Log of age-adjusted mortality rate	Age-adjusted mortality rate	Log of age-adjusted mortality rate	Age-adjusted mortality rate	Log of age-adjusted mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1189* (0.0656)	0.0054* (0.0027)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.0781 (0.0536)	0.0051 (0.0031)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1297** (0.0606)	0.0055** (0.0026)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.0952 (0.0574)	0.0066** (0.0032)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1208* (0.0661)	0.0046* (0.0026)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.1454** (0.0610)	0.0096*** (0.0033)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.1683** (0.0790)	0.0060* (0.0030)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.1361** (0.0664)	0.0096*** (0.0035)
Annual average temperature (°C)	0.4367* (0.2476)	0.0252** (0.0109)	0.4446* (0.2487)	0.0254** (0.0109)	0.4536* (0.2519)	0.0257** (0.0110)	0.4914* (0.2536)	0.0270** (0.0111)
Annual precipitation (mm)	0.2162* (0.1126)	0.0069 (0.0056)	0.2190* (0.1129)	0.0071 (0.0056)	0.2207* (0.1128)	0.0072 (0.0056)	0.2198* (0.1124)	0.0071 (0.0056)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	19.5132*** (6.2588)	2.6839*** (0.2724)	19.3427*** (6.2801)	2.6794*** (0.2741)	19.1118*** (6.3517)	2.6712*** (0.2756)	18.2005*** (6.3953)	2.6407*** (0.2770)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.364	0.318	0.364	0.318	0.364	0.318	0.364	0.318

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province. The age-adjusted mortality rate is the mortality rate (deaths per 100,000 people) adjusted by age distribution of the provinces in 1999.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.6. Regression of all-age mortality rate on the number of days of cold and heat waves measured by the 10<sup>th</sup> and 90<sup>th</sup> percentiles of daily temperature distribution

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 10 <sup>th</sup> percentiles of temperature	0.1409** (0.0577)	0.0037* (0.0021)						
# days with at least 3 consecutive days above the 90 <sup>th</sup> percentiles of temperature	0.1237*** (0.0442)	0.0067*** (0.0019)						
# days with at least 5 consecutive days below the 10 <sup>th</sup> percentiles of temperature			0.1505*** (0.0549)	0.0042** (0.0019)				
# days with at least 5 consecutive days above the 90 <sup>th</sup> percentiles of temperature			0.1004** (0.0478)	0.0051** (0.0021)				
# days with at least 7 consecutive days below the 10 <sup>th</sup> percentiles of temperature					0.1217** (0.0545)	0.0035* (0.0018)		
# days with at least 7 consecutive days above the 90 <sup>th</sup> percentiles of temperature					0.0924* (0.0516)	0.0047** (0.0020)		
# days with at least 9 consecutive days below the 10 <sup>th</sup> percentiles of temperature							0.0573 (0.0573)	0.0016 (0.0018)
# days with at least 9 consecutive days above the 90 <sup>th</sup> percentiles of temperature							0.1035* (0.0552)	0.0047** (0.0023)
Annual average temperature (°C)	0.6530** (0.3000)	0.0248** (0.0102)	0.6858** (0.2958)	0.0266** (0.0100)	0.6854** (0.2992)	0.0269** (0.0101)	0.6654** (0.3008)	0.0265** (0.0102)
Annual precipitation (mm)	0.2567* (0.1340)	0.0083 (0.0052)	0.2549* (0.1345)	0.0081 (0.0052)	0.2581* (0.1349)	0.0082 (0.0053)	0.2599* (0.1347)	0.0082 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	22.4490*** (7.5780)	3.0281*** (0.2559)	21.8142*** (7.4849)	2.9938*** (0.2524)	21.9352*** (7.5445)	2.9902*** (0.2541)	22.5304*** (7.5898)	3.0025*** (0.2553)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.336	0.311	0.336	0.311	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.7. Regression of all-age mortality rate on the number of days of cold and heat waves with controlling for month average temperature

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1320** (0.0655)	0.0052** (0.0023)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1683** (0.0707)	0.0078** (0.0031)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1278* (0.0679)	0.0050** (0.0022)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1934** (0.0771)	0.0091*** (0.0033)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1147 (0.0706)	0.0032* (0.0019)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2601*** (0.0921)	0.0125*** (0.0036)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.1701* (0.0909)	0.0049** (0.0024)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2589*** (0.0929)	0.0124*** (0.0037)
Month average temperature (°C)	-0.2183 (0.2856)	0.0009 (0.0095)	-0.2254 (0.2849)	0.0007 (0.0095)	-0.2523 (0.2791)	-0.0020 (0.0092)	-0.1927 (0.2784)	0.0001 (0.0092)
Annual precipitation (mm)	0.1949 (0.1360)	0.0061 (0.0053)	0.1956 (0.1367)	0.0061 (0.0053)	0.1955 (0.1365)	0.0061 (0.0053)	0.1928 (0.1361)	0.0060 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	44.9160*** (7.2848)	3.6507*** (0.2435)	45.1786*** (7.2717)	3.6610*** (0.2454)	45.8515*** (7.1087)	3.7266*** (0.2355)	44.4298*** (7.1188)	3.6779*** (0.2357)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.8. Regression of all-age mortality rate on the number of days of cold and heat waves with controlling for monthly mean temperature and rainfall

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1266* (0.0637)	0.0051** (0.0022)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1647** (0.0707)	0.0078** (0.0031)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1243* (0.0657)	0.0049** (0.0021)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1920** (0.0772)	0.0091*** (0.0033)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1168* (0.0694)	0.0033* (0.0019)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2614*** (0.0920)	0.0126*** (0.0035)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.1797* (0.0907)	0.0053** (0.0024)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2608*** (0.0927)	0.0125*** (0.0037)
Monthly average temperature (°C)	-0.3686 (0.2991)	-0.0041 (0.0096)	-0.3763 (0.2972)	-0.0044 (0.0096)	-0.4014 (0.2920)	-0.0070 (0.0093)	-0.3384 (0.2905)	-0.0048 (0.0093)
Monthly precipitation (mm)	0.0060 (0.0395)	0.0010 (0.0015)	0.0054 (0.0392)	0.0009 (0.0015)	0.0055 (0.0395)	0.0009 (0.0015)	0.0068 (0.0398)	0.0009 (0.0015)
Annual average temperature (°C)	0.7778** (0.3192)	0.0277*** (0.0103)	0.7909** (0.3196)	0.0283*** (0.0103)	0.8151** (0.3235)	0.0293*** (0.0105)	0.8417** (0.3248)	0.0301*** (0.0105)
Annual precipitation (mm)	0.2421* (0.1413)	0.0072 (0.0056)	0.2442* (0.1421)	0.0072 (0.0057)	0.2459* (0.1420)	0.0073 (0.0057)	0.2440* (0.1414)	0.0072 (0.0056)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	28.8170*** (8.6337)	3.0680*** (0.3170)	28.7571*** (8.7181)	3.0644*** (0.3209)	28.7562*** (8.6686)	3.1035*** (0.3139)	26.5649*** (8.7367)	3.0304*** (0.3151)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.336	0.311	0.336	0.311	0.336	0.311	0.336	0.311

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province. Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.9. Regression of all-age mortality rate on the number of days of cold and heat waves using a small specification model

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.3785*** (0.0925)	0.0109*** (0.0028)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.2117*** (0.0618)	0.0101*** (0.0025)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.3607*** (0.0905)	0.0106*** (0.0026)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.2429*** (0.0675)	0.0116*** (0.0027)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.3695*** (0.0983)	0.0104*** (0.0027)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.3474*** (0.0747)	0.0159*** (0.0028)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.3957*** (0.1139)	0.0112*** (0.0031)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.3625*** (0.0635)	0.0163*** (0.0023)
Province fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	33.1208*** (0.2444)	3.3683*** (0.0089)	33.3280*** (0.2235)	3.3753*** (0.0081)	33.4212*** (0.2155)	3.3788*** (0.0078)	33.4989*** (0.2108)	3.3817*** (0.0076)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.222	0.206	0.222	0.205	0.222	0.206	0.222	0.205

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.10. Regression of all-age mortality rate on the number of days of cold and heat waves with controlling for province-specific time trend squared

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1751*	0.0055**						
	(0.0919)	(0.0027)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1178	0.0066*						
	(0.0829)	(0.0037)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1626*	0.0052*				
			(0.0951)	(0.0027)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1500*	0.0079**				
			(0.0869)	(0.0039)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1601*	0.0041*		
					(0.0895)	(0.0025)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2145**	0.0113**		
					(0.1012)	(0.0042)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.2061*	0.0055*
							(0.1170)	(0.0029)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2316**	0.0118***
							(0.1069)	(0.0043)
Annual average temperature (°C)	0.7267*	0.0281**	0.7279*	0.0284**	0.7482**	0.0287**	0.7894**	0.0300**
	(0.3657)	(0.0125)	(0.3652)	(0.0125)	(0.3704)	(0.0126)	(0.3722)	(0.0126)
Annual precipitation (mm)	0.1386	0.0039	0.1427	0.0039	0.1444	0.0040	0.1447	0.0040
	(0.1874)	(0.0076)	(0.1858)	(0.0076)	(0.1860)	(0.0076)	(0.1846)	(0.0075)
Province-specific time trend squared	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	18.6852**	2.9355***	18.7548**	2.9328***	18.2755*	2.9258***	17.2439*	2.8947***
	(9.2623)	(0.3174)	(9.2471)	(0.3165)	(9.3622)	(0.3186)	(9.3939)	(0.3184)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.351	0.326	0.351	0.326	0.351	0.326	0.351	0.326

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.11. Regression of all-age mortality rate on the number of days of cold and heat waves using a large specification model

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.2408*** (0.0748)	0.0072*** (0.0024)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1287 (0.0828)	0.0074* (0.0037)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.2061** (0.0793)	0.0063** (0.0025)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1840** (0.0886)	0.0089** (0.0037)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.2286*** (0.0791)	0.0060** (0.0023)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2704** (0.1075)	0.0141*** (0.0044)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.2589*** (0.0936)	0.0072*** (0.0027)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2638** (0.1031)	0.0139*** (0.0042)
Annual average temperature (°C)	0.5994 (0.4356)	0.0229 (0.0152)	0.5766 (0.4397)	0.0227 (0.0153)	0.6186 (0.4290)	0.0233 (0.0149)	0.6785 (0.4330)	0.0256* (0.0150)
Annual precipitation (mm)	0.0157 (0.2155)	0.0031 (0.0081)	0.0242 (0.2153)	0.0032 (0.0081)	0.0216 (0.2148)	0.0032 (0.0081)	0.0272 (0.2155)	0.0032 (0.0081)
Log of the number of doctors and healthcare workers per 1000 people	-0.0037 (1.0492)	-0.0007 (0.0439)	-0.0140 (1.0479)	-0.0012 (0.0438)	-0.0173 (1.0468)	-0.0016 (0.0438)	-0.0335 (1.0458)	-0.0023 (0.0438)
Log of the number of hospital per 1000 people	-2.2556 (3.1609)	-0.0503 (0.1377)	-2.2910 (3.1578)	-0.0518 (0.1376)	-2.1763 (3.1767)	-0.0478 (0.1381)	-2.1432 (3.1741)	-0.0460 (0.1379)
Log of population density (thousand people per km <sup>2</sup> )	-11.9198 (11.5515)	-0.5473 (0.5226)	-12.4667 (11.6020)	-0.5554 (0.5236)	-13.0341 (11.2766)	-0.5719 (0.5127)	-13.1481 (11.1741)	-0.5695 (0.5093)
Proportion of urban population	8.8930 (11.3874)	0.4938 (0.4269)	8.7972 (11.4330)	0.4887 (0.4299)	8.6218 (11.3860)	0.4855 (0.4277)	8.5142 (11.3287)	0.4807 (0.4272)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	14.5043 (16.3594)	2.3834*** (0.8252)	14.5733 (16.1523)	2.3879*** (0.8200)	12.5267 (15.8372)	2.3434*** (0.8079)	11.0168 (15.8291)	2.2960*** (0.8051)
Observations	9,227	9,227	9,227	9,227	9,227	9,227	9,227	9,227
R-squared	0.362	0.325	0.362	0.325	0.362	0.326	0.362	0.326

Note: This table reports regression of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.12. Regression of all-age mortality rate on the number of days of cold and heat waves without weighting

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.2071*** (0.0654)	0.0064*** (0.0020)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1413** (0.0651)	0.0072** (0.0029)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1939*** (0.0663)	0.0059*** (0.0019)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1484** (0.0710)	0.0075** (0.0031)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1847*** (0.0692)	0.0047** (0.0020)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2386*** (0.0867)	0.0120*** (0.0035)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.2379*** (0.0835)	0.0063*** (0.0023)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2288** (0.0891)	0.0116*** (0.0036)
Annual average temperature (°C)	0.6373** (0.2904)	0.0240** (0.0093)	0.6439** (0.2921)	0.0245** (0.0093)	0.6530** (0.2937)	0.0244** (0.0094)	0.6980** (0.2930)	0.0259*** (0.0093)
Annual precipitation (mm)	0.2374* (0.1327)	0.0080 (0.0051)	0.2413* (0.1332)	0.0080 (0.0052)	0.2438* (0.1331)	0.0082 (0.0052)	0.2417* (0.1326)	0.0080 (0.0052)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	23.2131*** (7.3703)	3.0593*** (0.2343)	23.1513*** (7.4040)	3.0509*** (0.2355)	22.9055*** (7.4319)	3.0508*** (0.2360)	21.8532*** (7.4039)	3.0174*** (0.2343)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.334	0.307	0.334	0.307	0.334	0.307	0.334	0.307

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .



Table A.13. Regression of all-age mortality rate on the number of days of cold and heat waves with weight of current population

Explanatory variables	Dependent variables							
	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate	Mortality rate	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.1875** (0.0776)	0.0059** (0.0023)						
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.1390** (0.0676)	0.0073** (0.0031)						
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			0.1747** (0.0763)	0.0056** (0.0022)				
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.1722** (0.0759)	0.0088** (0.0033)				
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.1685** (0.0803)	0.0043* (0.0022)		
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.2423*** (0.0901)	0.0123*** (0.0036)		
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.2210** (0.0964)	0.0059** (0.0026)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.2409** (0.0937)	0.0121*** (0.0037)
Annual average temperature (°C)	0.6839** (0.3007)	0.0264** (0.0102)	0.6859** (0.3024)	0.0268** (0.0102)	0.7046** (0.3063)	0.0271** (0.0103)	0.7508** (0.3082)	0.0285*** (0.0104)
Annual precipitation (mm)	0.2461* (0.1342)	0.0082 (0.0053)	0.2509* (0.1345)	0.0083 (0.0053)	0.2534* (0.1344)	0.0084 (0.0053)	0.2514* (0.1336)	0.0083 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	21.8932*** (7.5906)	2.9961*** (0.2558)	21.9136*** (7.6290)	2.9907*** (0.2571)	21.4320*** (7.7118)	2.9821*** (0.2584)	20.3401** (7.7536)	2.9491*** (0.2590)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.337	0.312	0.337	0.312	0.337	0.312	0.337	0.312

Note: This table reports regressions of mortality rate on the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.14. Regression of all-age mortality rate on the one-month lead variable of cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
One-month lead: At least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month	0.3617 (0.5444)	0.0243 (0.0177)						
One-month lead: At least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month	0.4170 (0.5370)	0.0059 (0.0236)						
One-month lead: At least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month			0.1432 (0.6743)	0.0243 (0.0206)				
One-month lead: At least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month			0.0848 (0.6932)	0.0044 (0.0287)				
One-month lead: At least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month					0.7564 (0.6599)	0.0343 (0.0226)		
One-month lead: At least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month					1.2992 (0.8540)	0.0332 (0.0333)		
One-month lead: At least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month							0.8453 (0.8783)	0.0406 (0.0287)
One-month lead: At least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month							0.5759 (1.1324)	0.0244 (0.0415)
Annual average temperature (°C)	0.6447** (0.2952)	0.0269*** (0.0100)	0.6472** (0.2913)	0.0266*** (0.0099)	0.6555** (0.2917)	0.0270*** (0.0100)	0.6723** (0.2977)	0.0276*** (0.0102)
Annual precipitation (mm)	0.2542* (0.1352)	0.0078 (0.0053)	0.2543* (0.1355)	0.0079 (0.0053)	0.2595* (0.1352)	0.0081 (0.0053)	0.2568* (0.1352)	0.0081 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	23.1144*** (7.4334)	2.9957*** (0.2519)	23.1606*** (7.3294)	3.0053*** (0.2480)	22.8436*** (7.3561)	2.9954*** (0.2517)	22.4912*** (7.5150)	2.9821*** (0.2567)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on dummies indicating one-month leads of cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.15. Regression of all-age mortality rate on the two-month lead variable of cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Two-month lead: At least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month	0.2812 (0.5278)	0.0184 (0.0219)						
Two-month lead: At least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month	0.4036 (0.6207)	-0.0037 (0.0218)						
Two-month lead: At least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month			-0.4283 (0.6507)	-0.0074 (0.0231)				
Two-month lead: At least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month			0.1114 (0.6883)	-0.0089 (0.0261)				
Two-month lead: At least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month					-1.2184 (0.7585)	-0.0413 (0.0274)		
Two-month lead: At least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month					0.2687 (1.0302)	-0.0259 (0.0381)		
Two-month lead: At least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature in the month							-0.7037 (0.8052)	-0.0203 (0.0306)
Two-month lead: At least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature in the month							-0.3200 (1.2419)	-0.0421 (0.0424)
Annual average temperature (°C)	0.6339** (0.2963)	0.0268** (0.0104)	0.6460** (0.2902)	0.0266** (0.0101)	0.6529** (0.2929)	0.0269** (0.0102)	0.6458** (0.2935)	0.0263** (0.0102)
Annual precipitation (mm)	0.2545* (0.1357)	0.0078 (0.0053)	0.2558* (0.1351)	0.0080 (0.0053)	0.2561* (0.1352)	0.0080 (0.0053)	0.2553* (0.1357)	0.0079 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	23.4039*** (7.4496)	3.0012*** (0.2584)	23.2275*** (7.3247)	3.0107*** (0.2537)	23.0682*** (7.3784)	3.0041*** (0.2554)	23.2337*** (7.3890)	3.0191*** (0.2544)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on dummies indicating one-month leads of cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.16. Regression of all-age mortality rate on the one-month lead variable of the number of days of cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
One-month lead: # days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0282 (0.0476)	0.0001 (0.0016)						
One-month lead: # days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.0710 (0.0656)	0.0015 (0.0026)						
One-month lead: # days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			-0.0049 (0.0446)	0.0024 (0.0349)				
One-month lead: # days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.0730 (0.0744)	0.0027 (0.0029)				
One-month lead: # days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					0.0079 (0.0365)	0.0012 (0.0013)		
One-month lead: # days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.1318* (0.0736)	0.0042 (0.0028)		
One-month lead: # days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							0.0129 (0.0482)	0.0012 (0.0015)
One-month lead: # days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							0.1052 (0.0937)	0.0043 (0.0030)
Annual average temperature (°C)	0.6247** (0.2940)	0.0260** (0.0100)	0.6394** (0.2927)	0.0264** (0.0100)	0.6457** (0.2944)	0.0265** (0.0101)	0.6513** (0.2950)	0.0267** (0.0101)
Annual precipitation (mm)	0.2576* (0.1344)	0.0080 (0.0053)	0.2561* (0.1346)	0.0081 (0.0053)	0.2578* (0.1347)	0.0081 (0.0053)	0.2564* (0.1349)	0.0081 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	23.6804*** (7.3889)	3.0206*** (0.2500)	23.3184*** (7.3624)	3.0095*** (0.2507)	23.1051*** (7.4230)	3.0067*** (0.2529)	23.0103*** (7.4387)	3.0030*** (0.2540)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on dummies indicating one-month leads of the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.17. Regression of all-age mortality rate on the two-month lead variable of the number of days of cold and heat waves

Explanatory variables	Dependent variables							
	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate	Mortality rate (deaths per 100,000 people)	Log of mortality rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Two-month lead: # days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0007 (0.0732)	-0.0009 (0.0027)						
Two-month lead: # days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.0280 (0.0846)	-0.0020 (0.0030)						
Two-month lead: # days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature			-0.0232 (0.0718)	-0.0015 (0.0027)				
Two-month lead: # days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature			0.0030 (0.0917)	-0.0027 (0.0034)				
Two-month lead: # days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature					-0.0721 (0.0815)	-0.0036 (0.0029)		
Two-month lead: # days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature					0.0062 (0.1123)	-0.0032 (0.0037)		
Two-month lead: # days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature							-0.0239 (0.0842)	-0.0013 (0.0030)
Two-month lead: # days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature							-0.0688 (0.1204)	-0.0041 (0.0036)
Annual average temperature (°C)	0.6413** (0.2942)	0.0265** (0.0103)	0.6451** (0.2938)	0.0264** (0.0102)	0.6473** (0.2938)	0.0263** (0.0102)	0.6399** (0.2935)	0.0259** (0.0102)
Annual precipitation (mm)	0.2552* (0.1349)	0.0079 (0.0053)	0.2544* (0.1350)	0.0079 (0.0053)	0.2532* (0.1350)	0.0079 (0.0053)	0.2542* (0.1353)	0.0079 (0.0053)
Province-specific time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-by-month fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	23.2900*** (7.4144)	3.0133*** (0.2572)	23.2453*** (7.4110)	3.0176*** (0.2557)	23.2156*** (7.3986)	3.0209*** (0.2552)	23.4004*** (7.3904)	3.0281*** (0.2542)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639
R-squared	0.335	0.310	0.335	0.310	0.335	0.310	0.335	0.310

Note: This table reports regressions of mortality rate on dummies indicating one-month leads of the number of consecutive days in cold and heat waves. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.18. Regression of arsinh(the mortality rate) for different population groups

Explanatory variables	Dependent variables							
	arsinh (Mortality rate of people aged 0-4)	arsinh (Mortality rate of people aged 5-15)	arsinh (Mortality rate of people aged 16-39)	arsinh (Mortality rate of people aged 40-59)	arsinh (Mortality rate of people aged 60-79)	arsinh (Mortality rate of people aged 80+)	arsinh (Mortality rate of males)	arsinh (Mortality rate of females)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0060 (0.0090)	0.0058 (0.0042)	-0.0082 (0.0098)	0.0071 (0.0055)	0.0058 (0.0052)	0.0246*** (0.0088)	0.0061** (0.0026)	0.0052 (0.0049)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0115 (0.0115)	0.0001 (0.0058)	-0.0088 (0.0091)	0.0189** (0.0075)	0.0159* (0.0081)	0.0396*** (0.0148)	0.0061 (0.0046)	0.0122* (0.0066)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0138 (0.0095)	0.0034 (0.0034)	-0.0023 (0.0093)	0.0057 (0.0056)	0.0084 (0.0051)	0.0211** (0.0085)	0.0052** (0.0025)	0.0050 (0.0047)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0149 (0.0126)	0.0029 (0.0057)	-0.0081 (0.0107)	0.0227** (0.0090)	0.0130 (0.0079)	0.0431** (0.0174)	0.0073 (0.0047)	0.0158** (0.0079)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0162 (0.0102)	0.0057 (0.0047)	-0.0051 (0.0093)	0.0001 (0.0044)	0.0061 (0.0043)	0.0148* (0.0078)	0.0035 (0.0022)	0.0061 (0.0047)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0091 (0.0134)	0.0003 (0.0064)	-0.0123 (0.0100)	0.0203* (0.0116)	0.0207* (0.0104)	0.0518*** (0.0187)	0.0097* (0.0050)	0.0224** (0.0095)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0120 (0.0109)	0.0051 (0.0047)	-0.0030 (0.0105)	0.0039 (0.0049)	0.0078 (0.0059)	0.0136* (0.0074)	0.0064** (0.0029)	0.0071 (0.0045)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0040 (0.0128)	0.0012 (0.0071)	-0.0203* (0.0109)	0.0185 (0.0117)	0.0178* (0.0106)	0.0660*** (0.0196)	0.0094* (0.0050)	0.0236** (0.0096)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639

Note: This table reports the coefficients of the number of consecutive days in cold and heat waves in regressions of arsinh of the mortality rate of people at different age groups. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

There are 32 regressions in total. The regression specifications are the same as those in Table A.3 in Appendix. The control variables include annual average temperature (°C), annual precipitation (mm), province-specific time trend, province-by-month fixed-effects, and year-by-month fixed-effects.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1.

Table A.19. Poisson regression of the number of deaths per 100,000 people

Explanatory variables	Dependent variables							
	The number of deaths per 100,000 people aged 0-4	The number of deaths per 100,000 people aged 5-15	The number of deaths per 100,000 people aged 16-39	The number of deaths per 100,000 people aged 40-59	The number of deaths per 100,000 people aged 60-79	The number of deaths per 100,000 people aged 80+	The number of deaths per 100,000 males	The number of deaths per 100,000 females
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0005 (0.0105)	0.0192 (0.0163)	-0.0068 (0.0049)	0.0016 (0.0034)	0.0077*** (0.0028)	0.0119*** (0.0029)	0.0056*** (0.0020)	0.0037 (0.0025)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.0172 (0.0124)	0.0175 (0.0153)	-0.0054 (0.0055)	0.0081** (0.0034)	0.0011 (0.0027)	-0.0012 (0.0033)	0.0008 (0.0021)	0.0055** (0.0027)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0004 (0.0104)	0.0262 (0.0164)	-0.0027 (0.0049)	0.0022 (0.0033)	0.0069** (0.0028)	0.0090*** (0.0028)	0.0050** (0.0020)	0.0032 (0.0024)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0016 (0.0145)	0.0071 (0.0177)	-0.0038 (0.0066)	0.0105*** (0.0039)	0.0031 (0.0031)	0.0007 (0.0038)	0.0024 (0.0024)	0.0081** (0.0032)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature	0.0043 (0.0109)	0.0456*** (0.0173)	-0.0070 (0.0050)	0.0021 (0.0033)	0.0070** (0.0029)	0.0073** (0.0029)	0.0043** (0.0021)	0.0030 (0.0025)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0015 (0.0176)	-0.0219 (0.0199)	-0.0060 (0.0074)	0.0103** (0.0046)	0.0086** (0.0036)	0.0066 (0.0044)	0.0045 (0.0028)	0.0124*** (0.0037)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0015 (0.0117)	0.0427** (0.0184)	-0.0043 (0.0054)	0.0038 (0.0035)	0.0095*** (0.0031)	0.0062** (0.0031)	0.0055** (0.0022)	0.0039 (0.0026)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature	0.0001 (0.0204)	-0.0236 (0.0230)	-0.0087 (0.0086)	0.0103** (0.0051)	0.0079** (0.0040)	0.0112** (0.0046)	0.0058* (0.0032)	0.0117*** (0.0040)
Observations	12,639	12,639	12,639	12,639	12,639	12,639	12,639	12,639

Note: This table reports the coefficients of the number of consecutive days in cold and heat waves in regressions of  $\text{arsinh}$  of the mortality rate of people at different age groups. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province.

There are 32 regressions in total. The regression specifications are the same as those in Table A.3 in Appendix. The control variables include annual average temperature (°C), annual precipitation (mm), province-specific time trend, province-by-month fixed-effects, and year-by-month fixed-effects.

Robust standard errors in parentheses. Standard errors are clustered at the province and year-by-month levels.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table A.20. Regression of outcomes on the number of days in cold and heat waves

	Dependent variables							
	Proportion of college degree (in percent)	Log of per capita income	Proportion of having air conditioner (in percent)	Log of population density	The out-migration ratio (in percent)	The in-migration ratio (in percent)	Log of government spending on health	Log of the number of hospitals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0065 (0.0040)	0.0002 (0.0003)	-0.0008 (0.0010)	-0.0003*** (0.0001)	0.0076** (0.0037)	0.0051 (0.0044)	0.0027 (0.0036)	-0.0001 (0.0004)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0052 (0.0048)	0.0002 (0.0004)	-0.0006 (0.0011)	0.0001 (0.0002)	0.0010 (0.0039)	0.0013 (0.0032)	0.0024 (0.0031)	0.0004 (0.0004)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0060* (0.0031)	0.0002 (0.0003)	-0.0007 (0.0010)	-0.0003 (0.0002)	0.0091* (0.0046)	0.0062 (0.0052)	0.0021 (0.0039)	-0.0002 (0.0005)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0058 (0.0043)	0.0002 (0.0004)	-0.0011 (0.0012)	0.0001 (0.0002)	0.0028 (0.0066)	0.0009 (0.0046)	0.0000 (0.0059)	0.0005 (0.0006)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0048 (0.0041)	0.0000 (0.0003)	-0.0007 (0.0011)	-0.0002* (0.0001)	0.0079** (0.0039)	0.0047 (0.0045)	0.0024 (0.0025)	-0.0008 (0.0005)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0034 (0.0042)	0.0001 (0.0004)	-0.0000 (0.0009)	0.0001 (0.0002)	0.0060 (0.0048)	0.0007 (0.0035)	0.0005 (0.0058)	0.0003 (0.0004)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0043 (0.0040)	0.0002 (0.0003)	-0.0005 (0.0010)	-0.0002* (0.0001)	0.0095** (0.0040)	0.0050 (0.0047)	0.0043* (0.0023)	-0.0005 (0.0004)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0062 (0.0043)	-0.0002 (0.0004)	-0.0004 (0.0009)	0.0001 (0.0001)	0.0023 (0.0043)	-0.0024 (0.0031)	0.0008 (0.0067)	0.0001 (0.0003)
Observations	1,054	1,054	991	1,175	1,039	1,039	991	816

Note: This table reports the estimated coefficients of the number of consecutive days in cold and heat waves within a year in regressions of the 6 dependent variables. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province. The regressions use the provincial-by-year observations, since the dependent variables are measured at the provincial level. The control variables include annual average temperature (°C), annual precipitation (mm), province fixed-effects and year fixed-effects, and province-specific time trend. Unlike regression specifications in Table A.19, regression specifications in this table do not control for log of per capita income of provinces.

Robust standard errors in parentheses. Standard errors are clustered at the provincial level.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .



Table A.21. Regression of outcomes on the number of days in cold and heat waves (with controlling for log of per capita income of provinces)

	Dependent variables						
	Proportion of college degree (in percent)	Proportion of having air conditioner (in percent)	Log of population density	The out-migration ratio (in percent)	The in-migration ratio (in percent)	Log of government spending on health	Log of the number of hospitals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
# days with at least 3 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0069 (0.0042)	-0.0009 (0.0011)	-0.0002** (0.0001)	0.0105*** (0.0034)	0.0052 (0.0039)	0.0025 (0.0035)	-0.0002 (0.0005)
# days with at least 3 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0056 (0.0048)	-0.0007 (0.0011)	-0.0001 (0.0001)	-0.0007 (0.0042)	0.0027 (0.0039)	0.0021 (0.0031)	0.0006 (0.0004)
# days with at least 5 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0063* (0.0032)	-0.0008 (0.0009)	-0.0002 (0.0001)	0.0109** (0.0039)	0.0061 (0.0043)	0.0019 (0.0038)	-0.0003 (0.0003)
# days with at least 5 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0062 (0.0044)	-0.0012 (0.0011)	-0.0002 (0.0002)	0.0016 (0.0074)	0.0022 (0.0068)	-0.0004 (0.0056)	0.0007 (0.0006)
# days with at least 7 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0049 (0.0041)	-0.0008 (0.0011)	-0.0002** (0.0001)	0.0089** (0.0035)	0.0046 (0.0043)	0.0023 (0.0025)	-0.0006 (0.0005)
# days with at least 7 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0036 (0.0042)	-0.0001 (0.0010)	-0.0002** (0.0001)	0.0052 (0.0049)	0.0027 (0.0050)	0.0002 (0.0058)	0.0007 (0.0005)
# days with at least 9 consecutive days below the 5 <sup>th</sup> percentiles of temperature	-0.0048 (0.0042)	-0.0006 (0.0010)	-0.0002*** (0.0001)	0.0110*** (0.0037)	0.0051 (0.0047)	0.0039* (0.0022)	-0.0003 (0.0004)
# days with at least 9 consecutive days above the 95 <sup>th</sup> percentiles of temperature	-0.0058 (0.0044)	-0.0004 (0.0009)	-0.0002*** (0.0001)	0.0005 (0.0041)	-0.0010 (0.0042)	0.0007 (0.0067)	0.0005 (0.0004)
Observations	1,054	991	991	915	915	991	753

Note: This table reports the estimated coefficients of the number of consecutive days in cold and heat waves within a year in regressions of the 6 dependent variables. A cold (heat) wave is defined as at least  $k$  (3, 5, 7, and 9) consecutive days which have daily mean temperature at or below the 5<sup>th</sup> percentiles (at or above the 95<sup>th</sup> percentile) of the temperature distribution of specific province. The cold and heat waves are defined for a year instead of for a month as the previous regressions. The regressions use the provincial-by-year observations, since the dependent variables are measured at the provincial level. The control variables include annual average temperature (°C), annual precipitation (mm), log of per capita income of provinces, province fixed-effects, year fixed-effects, and province-specific time trend.

Robust standard errors in parentheses. Standard errors are clustered at the provincial level.

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .