Multiple Threshold Effects for Temperature and Mortality

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Abstract

Heat waves and cold fronts have become frequent of late, and have caused serious disruptions around the world, especially in the mid- and high-latitudes. In future, human beings are likely to face more serious, frequent and long-lasting extreme climate events, with consequent greater damage to human life. This paper uses the multiple panel threshold model to test whether there are threshold effects between temperature and mortality, using a panel of 78 major cities in 22 OECD countries for 1990-2008. From the empirical analysis, we find that the relationship between temperature and mortality has three threshold effects, namely 15.21°F (-9.33℃), 46.97°F (8.32℃), and 87.53°F (30.85℃). If the temperature is below 15.21°F (-9.33℃), the magnitude of the temperature effect below 15.21°F (-9.33℃) is greater than the effect between 15.21°F (-9.33$_0$C) and 46.97°F (8.32$_0$C). When the temperature exceeds 87.53°F (30.85℃), higher temperature leads to higher mortality rate. Based on the estimated coefficients of mean temperatures in four regimes, we separate 78 cities into five areas with latitudes below 30°, 31°-40°, 41°-50°, and 61°-70°, and predict the impacts of future climate change on mortality for 2021-2040, 2041-2060, and 2061-2100. In summer, climate is predicted to increase mortality rates for 2021-2040, 2041-2060, and 2061-2100. For latitudes 41°-50° and 51°-60°, the increased mortality rate is much larger than for other latitudes. In winter, the increased magnitude induced by climate change is found to be greater than in summer.

1. Introduction

According to the Intergovernmental Panel on Climate Change (hereafter IPCC) report in 2007, the phenomenon of the sustained increase in global surface temperatures cause a higher frequency of heat waves. This report also predicted that extreme weather events will become more serious and frequent in the future. Schar et al. (2004) predicted that in the late 21st Century, changes in extreme temperatures in Europe will increase considerably and make summer mean temperatures higher and their variability greater. Moreover, Clark et al. (2006) found that the maximum temperatures for June, July, and August will become much warmer, and the higher number of extremely hot days will be more significant than the mean temperatures for Europe, North and South America, and East Asia. The expected greater intensity, frequency, and duration of heat waves will occur in these areas, especially in the mid- and high-latitudes. Moreover, even slight changes in mean climate or variability might increase the frequency of extreme weather and have a significant impact on human health and safety.

In Europe, many have suffered from both heat waves and cold waves in recent years. The European Heat Wave in 2003 resulted in the deaths of nearly 35,000 people, while nearly 15,000 people died in France. Since then, heat waves and cold waves have occurred more frequently, such as the European Heat Wave and Cold Wave in 2006, the European Heat Wave in 2007, and the European Cold Wave in 2009-2010. In fact, during the European Cold Wave in 2009-2010, UK experienced the coldest winter since 1963, with over 40,000 deaths. Not only Europe, but also North America, Australia and Asia, have been unable to avoid heat waves and cold waves, such as the Northeast United States Cold Wave in 2004, the North American Heart Wave in 2006, the Northern Hemisphere Cold Wave in 2007, the Asian Heat Wave in 2007, the Australian Heat Waves in 2008 and 2009, and the Japanese Heat Wave in 2010.

Some studies (Hajat et al., 2002, 2007) have suggested that average temperature is more appropriate in explaining mortality, and that average temperatures in summer and winter have more significant influences on mortality than those in spring and autumn (Ballester et al., 1997; Gemmell et al., 2000; Schwarts, 2005).

Some researchers have suggested that lower temperatures might have serious negative impacts on human health (Bull and Morton, 1975; Diaz et al., 2002; Nicholls et al., 2008; Loughna et al., 2010). However, Alfesio et al. (2002), Laaidi et al. (2006), and Hajat et al. (2007) have suggested that not only decreases in winter temperatures, but also increases in summer temperatures, would affect the mortality rate. In light of the impact of unusual weather events on mortality, researchers have also concluded that extreme temperatures, such as heat waves and cold waves, markedly increase mortality (Baccini et al. 2008; Basu and Samet, 2003; Fouillet et al., 2006; Healy 2003; Johnson et al., 2005; Keatinge et al. 1997; Keatinge et al., 2004; Kovats and Koppe, 2005; McMichael et al., 2008; Montero et al., 2010; Nastos and Matzarakis, 2008; Rey et al., 2009; Tobías et al., 2010; Vandentorren et al., 2004, 2006, 2008; Wenbiao et al., 2008). Furthermore, outdoor workers, the elderly (65+ years), and the young (15- years) are at high risk (Analitis et al., 2008; Basu et al., 2008; Chaudhury et al., 2000; Díaz et al., 2005; Gouveia, 2003; Hajat et al., 2007; Ranhoff, 2000; Yip et al., 2008).

In addition, many researchers have attempted to determine the relationship between mortality and temperature, which could be the V-, U- or J-shaped (Pan et al., 1995; Huynen et al., 2001; Alfesio et al., 2002; Curriero et al., 2002; Kalkstein and Davis, 1989; McMichael et al., 2008, Armstrong, 2006; Laaidi et al., 2006). The V-, U- or J-shapes show clear evidence of rising mortality with colder and hotter temperatures.

The estimated relationships between temperature and mortality could exhibit one or more segments (or thresholds). Some studies have used other methods to estimate temperature-mortality thresholds , such as the least total sum of squares (Kalkstein and Davis, 1989), application of smoothing curves to find the temperature point where mortality is the lowest (EL-Zein et al., 2004), using a hockey stick (linear spline) model, assuming a log-linear increase in risk below a cold threshold and above a heat threshold (McMichael et al., 2008), the mortality anomaly, which is the deviation of the actual death rate from the smoothed death rate (Nicholls et al., 2008; Loughnan et al., 2010), and the 90th or 99th percentiles of temperature (Anderson and Bell, 2009).

The traditional approach determines the threshold level exogenously, which may create some problems, such that we are unable to obtain confidence intervals for the threshold level, and the estimates from the traditional approach may be sensitive to the chosen threshold level (Hansen 1999, 2000). Hansen (1999) suggested the panel threshold regression model to test for threshold effects and to search for two or more regimes endogenously. This paper assumes there is an optimal average temperature, and uses the panel threshold model to estimate average temperatures and the mortality-temperature threshold. We use Hanson (1999)'s model to test whether there exists a threshold effect between mortality and temperature, search for two or more regimes endogenously, and then estimate the effects of different temperature regimes on mortality.

For policy purposes, it is important to construct a reliable alert system for checking extreme temperatures (high and low), which can trace temperatures effectively, and predict heat waves and cold waves for increasing life safety and expectancy. In other words, if a government knows in advance the critical temperature for heat waves, it would be better prepared to avoid tragedies arising from heat waves. The empirical findings in the paper should assist in determining how average temperatures can have significant impacts on crude mortality rates, and thereby assist in public health policy.

The organization of the paper is as follows. In Section II, we discuss the data. In Section III, we discuss the panel threshold regression model. The empirical results are interpreted in Section IV, and some concluding remarks are presented In Section V.

2. Data Description

The 78 major cities in 22 OECD countries in the sample were selected based on availability of data (see Table 2). Monthly data for 1990-2008 were arranged in panel data form. The crude mortality rate is the number of monthly deaths in each city divided by the mid-month average total population of each city, and multiplied by 1,000, and are obtained from the statistical bureaux in each country.

Real GDP per capita based on 2,000 US dollars is viewed as a measure of the national economic development index. Data on real GDP and unemployment rate are obtained from the OECD database. Mean temperatures and precipitation are obtained from the International Research Institute for Climate and Society. We transform data on daily average temperatures and dew points obtained from the National Climatic Data Center into monthly temperature variations and mean dew points. The aforementioned temperature indices are expressed in Fahrenheit.

The 22 OECD countries are Austria, Australia, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, Greece, Hungary, Italy, Japan, Korea, the Netherlands, Norway, Poland, Portugal, Sweden, the United Kingdom, and the United States. The 78 major cities used in the paper are shown in the Appendix, with 42 cities located in Europe and 36 cities located outside Europe.

The statistical descriptions for all the variables are shown in Table 1. The average mortality rate for the 78 major cities in 22 OECD countries is 0.863, while mortality ranges from 0.255 to 10.066. Table 1 also shows that the average GDP per capita in the 78 major cities is approximately US$ 2,941.53, which is higher than the global average. The average unemployment rate for the 78 major cities in 22 OECD countries is 7.205%, which is higher than that for developing countries. As economies become more highly developed, the unemployment rate may remain at a higher level as compared with developing countries. The mean average temperature for the 78 major cities is 53.214°F, with standard deviation 16.071. Mean precipitation is 68.386 mm, with standard deviation 66.145, which means there are large changes in the 78 major cities for 22 OECD countries over time. The mean variance of temperatures is 36.778, with the range of the variance of temperatures being 0.685 to 140.215.

3. Empirical Model

3.1 Single panel threshold model

This paper follows Hansen (1999)'s panel threshold model to examine whether the mortality-temperature threshold exists for 78 major cities in the OECD. The structure of the single panel threshold model follows Hansen (1999), as follows:

$$y_{it} = \mu_i + \beta_1^{'} x_{it} I(q_{it} \leq \gamma) + \beta_2^{'} x_{it} I(q_{it} > \gamma) + e_{it} \qquad (1)$$

where the data are from a balanced panel, i and t denote indexes of the individual ($1 \leq i \leq N$) and time ($1 \leq t \leq T$), respectively, y_{it} and the threshold variable, q_{it}, are scalars, x_{it} is a k vector of explanatory variables, $I(\bullet)$ is an indicator function, μ_i is the fixed effect (or heterogeneity of individuals), and the error term, e_{it}, is assumed to be independent and identically distributed, $e_{it} \sim iid(0, \sigma^2)$. Equation (1) can be written, as follows:

$$y_{it} = \mu_i + \beta^{'} x_{it}(\gamma) + e_{it} \qquad (2)$$

where $\beta^{'} x_{it}(\gamma) = \begin{cases} \beta_1^{'} x_{it} I(q_{it} \leq r) \\ \beta_2^{'} x_{it} I(q_{it} > r) \end{cases}$.

The data are separated into two regimes, whereby the threshold variable, q_{it}, is less than or greater than the threshold value, γ. The two regimes have different regression slopes, $\beta_1^{'}$ and $\beta_2^{'}$, respectively.

Averaging equation (2) over time leads to:

$$\bar{y}_{it} = \mu_i + \beta' \bar{x}_i(\gamma) + \bar{e}_i \tag{3}$$

where $\bar{y}_i = 1/T\sum_{t=1}^{T} y_{it}$, $\bar{x}_i = 1/T\sum_{t=1}^{T} x_{it}$, and $\bar{e}_i = 1/T\sum_{t=1}^{T} e_{it}$.

Subtracting equation (3) from (2) leads to:

$$y_{it}^* = \beta' x_{it}^*(\gamma) + e_{it}^* \tag{4}$$

or, in vector form:

$$y_i^* = \begin{bmatrix} y_{i2}^* \\ \vdots \\ y_{iT}^* \end{bmatrix}, \quad x_i^*(\gamma) = \begin{bmatrix} x_{i2}^*(\gamma) \\ \vdots \\ x_{iT}^*(\gamma) \end{bmatrix}, \text{ and } \; e_i^* = \begin{bmatrix} e_{i2}^* \\ \vdots \\ e_{iT}^* \end{bmatrix}$$

We stack the data over individuals into Y^*, X^*, and e^*, and derive equation (5), which is the model for estimating threshold effects:

$$Y^* = \begin{bmatrix} y_1^* \\ \vdots \\ y_N^* \end{bmatrix}, \quad X^*(\gamma) = \begin{bmatrix} x_1^*(\gamma) \\ \vdots \\ x_N^*(\gamma) \end{bmatrix}, \text{ and } \; e^* = \begin{bmatrix} e_1^* \\ \vdots \\ e_N^* \end{bmatrix}$$

$$Y^* = \beta' X^*(\gamma) + e^* . \tag{5}$$

Ordinary least squares (OLS) is used to estimate β for a given γ :

$$\widehat{\beta}(\gamma) = (X^*(\gamma)' X^*(\gamma))^{-1} X^*(\gamma)' Y^* . \tag{6}$$

The vector of regression residuals is:

$$\widehat{e}^*(\gamma) = Y^* - X^*(\gamma)\widehat{\beta}(\gamma) , \tag{7}$$

which is minimized for SSE to estimate γ :

$$SSE_1(\gamma) = \widehat{e}^*(\gamma)' \widehat{e}^*(\gamma) \tag{8}$$

where

$$\widehat{\gamma} = \arg\min_{\gamma} SSE_1(\gamma) \tag{9}$$

The estimated slope coefficient is $\widehat{\beta} = \widehat{\beta}(\widehat{\gamma})$, the vector of residuals is $\widehat{e}^* = \widehat{e}^*(\widehat{\gamma})$, and the estimated variance of the residuals is:

$$\hat{\sigma}^2 = \frac{1}{N(T-1)} \hat{e}^{*'}(\hat{\gamma})' \hat{e}^{*}(\hat{\gamma}) = \frac{1}{N(T-1)} SSE_1(\hat{\gamma}) . \tag{10}$$

3.2 Multiple panel threshold model

Hansen (1999) extended the panel threshold model with more than one threshold, as follows:

$$y_{it} = \mu_i + \beta_1' x_{it} I(q_{it} \le \gamma_1) + \beta_2' x_{it} I(\gamma_1 < q_{it} \le \gamma_2) + \beta_3' x_{it} I(q_{it} > \gamma_2) + e_{it} \tag{11}$$

where the threshold value, γ_1 ,is less than γ_2. Generally speaking, estimation of the multiple threshold model is similar to the single threshold model. Three-stage estimation is used for the two threshold parameters. The first stage for estimating the multiple threshold model is the same as the single threshold model. $SSE_1(\gamma)$ is the single threshold sum of squared errors, as defined in equation (8), and $\hat{\gamma}_1$ is the estimated threshold parameter. Given the estimated threshold, $\hat{\gamma}_1$, minimizing the SSE of equation (11) estimates the second-stage threshold estimate, $\hat{\gamma}_2^r$. The third stage is to re-estimate the first-stage threshold, γ_1, while the second-stage threshold estimate remains fixed, thereby leading to asymptotically efficient estimators, $\hat{\gamma}_1^r$ and $\hat{\gamma}_2^r$.

Another difference is to determine the number of thresholds. If the F1 statistic rejects the null hypothesis of no thresholds, a further test is required to distinguish between one and two thresholds. The test is similar to the bootstrap procedure of the single threshold model. In orer to minimize the second-stage SSE, $SSE_2^r(\hat{\gamma}_2^r)$, with the residual variance estimate, $\hat{\sigma}^2 = SSE_2^r(\hat{\gamma}_2^r) / N(T-1)$, the likelihood ratio test of one versus two thresholds is based on F_2:

$$F_2 = (SSE_1(\hat{\gamma}_1) - SSE_2^r(\hat{\gamma}_2^r)) / \hat{\sigma}^2 . \tag{12}$$

For constructing the confidence region of two estimated thresholds, $\hat{\gamma}_1$ and $\hat{\gamma}_2$, the estimators have identical asymptotic distributions to the single threshold model (Bai, 1997), so that the confidence intervals are based on the same method as for the single threshold model:

$$LR_2^r(\gamma) = (SSE_2^r(\hat{\gamma}) - SSE_2^r(\hat{\gamma}_2^r)) / \hat{\sigma}^2$$

and

$$LR_1^r(\gamma) = (SSE_1^r(\hat{\gamma}) - SSE_1^r(\hat{\gamma}_1^r)) / \hat{\sigma}^2 .$$

The asymptotic (1-α)% confidence intervals for $\hat{\gamma}_2$ and $\hat{\gamma}_1$ are the threshold values, γ, for $LR_2^r(\gamma) \le c(\alpha)$ and $LR_1^r(\gamma) \le c(\alpha)$, respectively.

This paper presumes there is an optimal average temperature, and uses the panel threshold model to investigate whether threshold effects exist between average temperature and crude mortality rate. The empirical threshold model is as follows:

$$\begin{aligned} Mor_{it} &= \mu_i + \beta_1 temp_{it} I(temp_{it} \le \gamma_1) + \beta_2 temp_{it} I(\gamma_1 < temp_{it} \le \gamma_2)) \\ &+ \beta_3 temp_{it} I(temp_{it} > \gamma_1 + \theta_1 prec_{it} + \theta_2 dew_{it} + \theta_3 \operatorname{var} temp_{it} + \theta_4 gdp_{it} \\ &+ \theta_5 unemp_{it} + e_{it} \end{aligned} \tag{13}$$

for a balanced panel, where *i* is the index of city *i* for 22 OECD countries, and *t* is the index of the time period (1990 to 2008). Mor_{it} represents monthly crude mortality rate, pre_{it} represents monthly precipitation, dew_{it} represents monthly average dew point temperature, $\operatorname{var} temp_{it}$ represents monthly variance of temperature, gdp_{it} represents monthly real gross domestic product per capita in 2000 US dollars, $unemp_{it}$ represents monthly unemployment rate, $temp_{it}$ is both an explanatory variable and the threshold variable, which represents monthly average temperature, and γ is the threshold value.

3.3 Testing for thresholds

It is necessary to test whether the estimated threshold effect is statistically significant. The null hypothesis is $H_0 : \beta_1 = \beta_2$. Implementing the fixed-effect transformation of equation (4) under the null hypothesis of no threshold effects, we derive:

$$y_{it}^* = \beta_1^{'} x_{it}^*(\gamma) + e_{it}^* . \tag{14}$$

OLS is used to estimate the parameters, leading to the slope coefficient ($\tilde{\beta}_1$), the residuals ($\tilde{e}_{it}$), and the sum of squared errors ($SSE_0 = \tilde{e}^{*'}\tilde{e}^{*}$). The likelihood ratio test of H_0 is given by:

$$F_1 = (SSE_0 - SSE_1(\hat{\gamma}))/\hat{\sigma}^2 . \tag{15}$$

The unidentified threshold, γ, under H_0 leads to the problem of classical tests with non-standard distribution. Hansen (1996) proposed using a bootstrap to estimate the model under the null and alternative hypotheses, equations (4) and (14), respectively, and computing the bootstrap value of the likelihood ratio test in equation (15). Repeating this step and computing the percentage of simulated statistics beyond the actual value, the asymptotic p-value of F_1 under H_0 may be found. If the p-value is less than the critical value, the null hypothesis of no threshold effect is rejected.

After determining the existence of threshold effects, we test whether the estimated $\hat{\gamma}$ is consistent with the true value, γ_0. According to Chan (1993) and Hansen (1999), when threshold effects exist, $\hat{\gamma}$ is consistent. However, there still exists the problem of the non-standard asymptotic distribution. Hansen (1999) derived an optimal method for the non-rejection region to test the threshold value, γ, where the null hypothesis is $H_0 : \gamma = \gamma_0$. The likelihood ratio test of γ is given as follows:

$$LR_1(\gamma) = \frac{SSE_1(\gamma) - SSE_1(\hat{\gamma})}{\hat{\sigma}^2} . \tag{16}$$

Using specified assumptions (see Hansen, 1999, p.363), $LR_1(\gamma) =_d \xi$, where ξ is a random variable with asymptotic distribution and critical value given by:.

$$P(\xi \le x) = (1 - \exp(\frac{-x}{2}))^2 \tag{17}$$

Based on Hansen (1999), the distribution function (17) can be written in equation (18). Therefore, the non-rejection region for confidence level, $1-\alpha$, is the set of threshold values (γ) for $LR_1(\gamma) \le c(\alpha)$:

$$c(\alpha) = -2\log\left(1-\sqrt{1-\alpha}\right). \tag{18}$$

4. Empirical Results

This section presents the estimates for stationarity of the empirical model using panel LM unit root tests, and tests whether there is a threshold relationship between mortality and temperature, the number of mortality-temperature thresholds, and the effects of climatic and macroeconomic factors on mortality. Finally, we combine the estimated results of the panel threshold model and future climate data of the ECHAM5 model to predict how climate change influences mortality rate. This paper uses the GAUSS9.0 software package to obtain the estimates of the panel LM unit root tests and panel threshold models.

4.1 Panel LM unit root test

In order to avoid spurious regressions, all variables have to be stationary. We use the panel LM tests (Im et al., (2005)) to test the stationarity of the six variables. If the null hypothesis of the panel LM unit root test is rejected, all variables are stationary. The results are reported in Table 2. Based on the outcomes of the LM panel unit root test results with no break, one break, and two breaks, the LM unit root test with no break and with one break support the non-stationarity of real GDP per capita and unemployment rate, but the LM unit root test with two breaks supports the stationarity of all series at the 1% significance level. Hence, in the case of the panel LM unit root test with two breaks, all series are stationary.

4.2 Testing for multiple thresholds

We use the bootstrap method with 500 replications to derive the p-values and F statistics of the thresholds. We examine sequentially the number of thresholds in the model, and the threshold test results are given in Table 3. We can see the bootstrap p-values of the single threshold are not significant. The test results of the double and triple thresholds are significant at the 5% level, so there is strong evidence that triple thresholds exist. Based on these results, we will use the triple threshold regression model.

4.3 Panel threshold model results

The paper uses average temperature as the threshold variable to determine whether the relationship between the average temperature and the mortality rate has a threshold effect. We transform the data sets in the empirical model into logarithmic form to capture the elasticity of mortality and climatic factors, and macroeconomic conditions. Thus, a 1% variation in an individual factor, such as mean temperature, precipitation, mean dew point temperature, real gdp per capita, and unemployment rate, induces a % variation in the mortality rate.

Table 4 presents the three thresholds, their asymptotic 95% confidence intervals, regression estimates, conventional OLS standard errors, and White standard errors. The estimates are 15.21°F(-9.33℃), 46.97°F(8.32℃), and 87.53°F(30.85℃), that is, temperature is separated into four regimes, namely very low temperature, low temperature, moderate temperature, and very high temperature. Furthermore, the narrow asymptotic confidence intervals for the threshold means there is little doubt about the nature of the partition.

The four regression slopes in each of the four regimes are different. In the first regime, if the average temperature is less than 15.21°F (-9.33℃), a 1% increase in average temperature results in 0.41% decrease in the mortality rate. In the second regime, if the average temperature ranges from 15.21°F (-9.33℃) to 46.97°F (8.32℃), a 1%

increase in average temperature results in 0.23% decrease in mortality rate. In the third regime, if the average temperature ranges from 46.97°F (8.32℃) to 87.53°F (30.85℃), a 1% increase in the average temperature results in 0.074% increase in mortality rate. In the last regime, if average temperature is greater than 87.53°F (30.85℃), a 1% increase in average temperature results in 0.30% increase in mortality rate.

The climate factors, namely the amount of precipitation, have significantly positive effects on mortality rate, which is consistent with Ebi et al. (2004). The effects of average dew point temperature on mortality rate are significantly positive, which is similar to the finding in Guest et al. (1999). Temperature variation has a significant positive effect on mortality rate, which is a similar to Applegate et al. (1981), Bull and Morton (1975, 1978), Conti et al. (2005), Ellis et al. (1973), Ellis et al. (1980), Greenberg et al. (1983), Jones et al. (1982), and Schwaetz (2000). In terms of macroeconomic conditions, real GDP per capita has a significantly negative influence on mortality rate, which indicates that higher income leads to lower mortality. Such outcomes are consistent with the findings in Breault (1988), Buckley et al. (2004), Burr (1997), Chung and Huang (2003), Gerdtham (2004), Gunnell et al. (2000), Huang and Huang (1996), Mcleod et al. (2003), Neumayer (2003), and Smith (1999).

The unemployment rate influences mortality rate both significantly and positively, which is similar to the findings in Brenner (1979, 1987), Brenner and Moonry (1983), Platt (1984), and Stack (2000a, b). Although precipitation has a significant positive impact on mortality using OLS standard errors, White’s standard errors suggest the estimate is not significant.

4.4 Impacts of future climate change on mortality

We integrate the estimated results of the panel threshold model with future climatic data, which are generated by a generalized downscaling and data generation method, taking the outputs of the ECHAM5 model for the A1B Scenario from IPCC's Fourth Assessment (2007). We separate the 78 cities into five areas with latitudes 30°, 31°-40°, 41°-50°, 51°-60°, and 61°-70°, and use the summer and winter months in three time slices including 2021-2040 (denoted 2030), 2041-2060 (denoted 2050), and 2061-2100 (denoted 2080), to determine the influence of climate change, especially extreme weather events, on mortality rate. Then we calculate the percentage change in monthly total precipitation and monthly temperature variation relative to the baseline (1990-2008), and monthly mean temperatures in 2030, 2050, and 2080 for the A1B Scenario (see Table 5).

Combining the estimated results (Table 4) and the percentage changes in monthly total precipitation and monthly temperature variations (Table 5), we evaluate the changes in mortality rate caused by a 1% change in individual climate factors, namely monthly total precipitation and monthly temperature variation. Regarding monthly mean temperatures, we base the estimated coefficients of mean temperatures in the four regimes to compute the impacts of relative changes between the 2030, 2050, and 2080 monthly mean temperatures and corresponding threshold temperatures on mortality rates.

The effects of individual climatic factors and the composite impacts of climate change on mortality rates in 2030, 2050, and 2080 for the A1B Scenario are given in Table 6. In summer, future climate change increases the 2030, 2050, and 2080 mortality rates. Especially, in latitudes 41°-50° and 51°-60°, the higher temperatures are much larger than in other latitudes. In winter, the higher temperatures induced by climate change are larger than in summer. Nevertheless, changes in mortality rates caused by climate change gradually decrease. Especially for latitudes 41°-50°, 51°-60°, and 61°-70°, the diminishing ranges are more remarkable than for other latitudes.

Examining summer and winter separately, the impacts of climate change on mortality rate in summer and winter are shown in Table 7 and Figures 1. The impacts of summer climate change on mortality rate rise by degrees. Moreover, in 2080, the increased mortality rate latitudes 41°-50° and 51°-60° exceed the same areas in winter. Below latitude 30°, changes in mortality rate have a slightly increased trend. In latitude 61°-70°, the higher mortality rate is reduced in 2050, but is increased substantially in 2080.

5. Conclusion

This paper used Hansen's (1999) multiple panel threshold model to estimate the effect of climatic and macroeconomic factors on the mortality rate of 78 major cities in 22 OECD countries. We used average temperature as the threshold variable to determine whether the relationship between average temperature and mortality rate involved threshold effects.

The empirical results showed three thresholds, namely 15.21℉ (-9.33℃) , 46.97℉ (8.32℃), and 87.53℉ (30.85℃), when temperature was separated into four regimes, namely very low temperature, low temperature, moderate temperature, and very high temperature. In the very low temperature regime, average temperature was less than 15.21℉ (-9.33℃), a 1% increase in average temperature resulted in 0.41% decrease in mortality rate. In the low temperature regime, average temperature ranged from 15.21℉ (-9.33℃) to 46.97℉(8.32℃), a 1% increase in average temperature resulted in 0.23 decrease in mortality rate. In the moderate temperature regime, average temperature ranged from 46.97℉ (8.32℃) to 87.53℉ (30.85℃), a 1% increase in average temperature resulted in 0.074% increase in mortality rate. In the very high temperature regime, average temperature was greater than 87.53℉ (30.85℃), a 1% increase in average temperature resulted in 0.30% increase in mortality rate.

In addition, the effects of precipitation, dew point temperature and temperature variation are significantly positive on mortality rate. However, macroeconomic conditions, namely real GDP per capita, have a significantly negative influence on mortality rate, which indicates that higher income leads to lower mortality. On the other hand, the unemployment rate has a significant and positive influence on mortality rate.

Finally, we integrated the estimates from the multiple panel threshold models with future climate data to predict the impacts of future climate change on mortality for 2021-2040 (denoted 2030), 2041-2060 (denote 2050), and 2061-2100 (denoted 2080). We separated 78 cities into five areas, with latitude below 30°, 31°-40°, 41°-50°, and 61°-70°, and used summer and winter months in three time slices in 2030, 2050, and 2080 to determine the influence of climate change especially extreme weather events, on mortality rate. Based on the estimated coefficients of mean temperatures in four regimes, we predicted the impacts of future climate change on mortality. In summer, future climate is predicted to increase the 2030, 2050, and 2080 mortality rates. For latitudes 41°-50° and 51°-60°, the increased mortality rate is much larger than for other latitudes. In winter, the increased magnitude induced by climate change is found to be greater than in summer.

Extreme climate, whether cold or hot, has obvious significant influences on human health. Using thresholds of the average temperatures on mortality rates to establish policies, such as watch-warming systems, may help to prevent or mitigate the potential damage to humans that are induced by climate change.

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Figure 1. Impacts of summer and winter climate change on mortality rate in five latitude areas under the ECHAM5 model for A1B Scenario

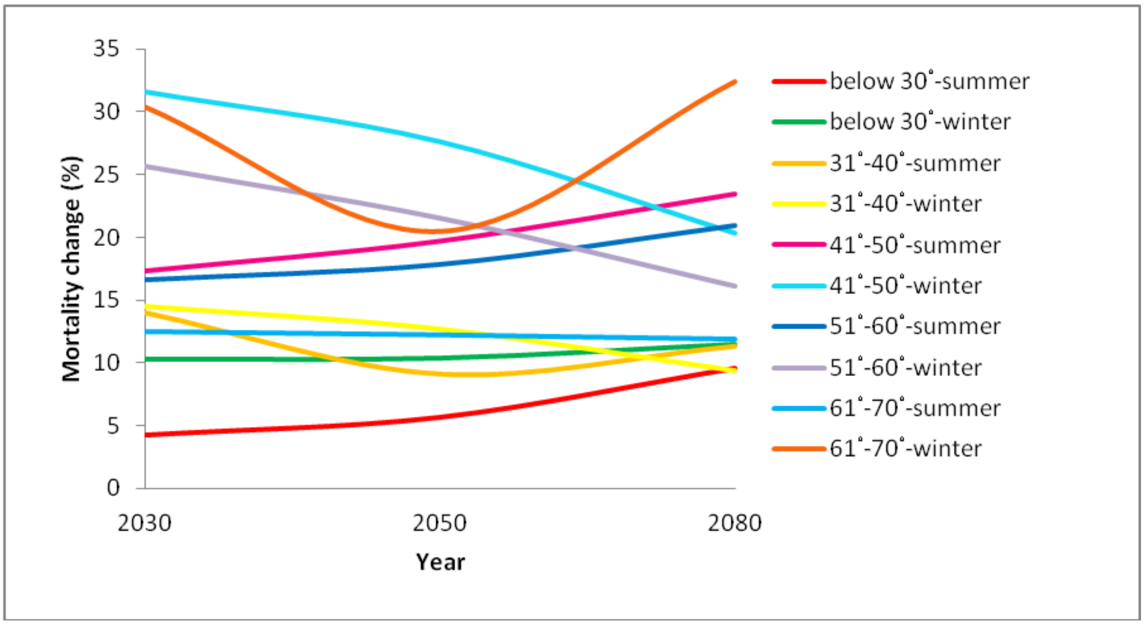

Table 1. Descriptive statistics for 22 OECD countries

	Unit	Mean	Median	Maximum	Minimum	Std. Dev.
Mortality	**%**	0.863	0.744	10.066	0.255	0.691
GDP	USD	2941.526	2656.437	13899.580	516.799	1431.144
Unemployment	**%**	7.205	5.930	34.765	1.260	4.205
Temperature	°F (℃)	53.214 (11.786)	54.600 (12.556)	96.500 (35.833)	0.003 (-17.776)	16.071 (9.640)
Precipitation	Mm	68.386	51.600	1003.000	0.100	66.145
Variance of Temperature	°F^2 (℃)^2	36.776 (10.998)	26.008 (8.389)	140.215 (57.844)	0.685 (0.558)	37.458 (16.492)

Table 2. Panel LM unit root test with no break, one break, and two breaks

Variables	With no break	With one break	With two breaks
	LM statistic	LM statistic	LM statistic
Mortality rate	-1.708**	-1.963**	-7.296***
Real GDP per capita	-0.096	-0.952	-6.485***
Unemployment rate	-0.423	-1.031	-6.362***
Average temperature	-1.424*	-1.776**	-7.109***
Precipitation	-1.409*	-1.438*	-7.220***
Dew point temperature	-1.637**	-2.079**	-8.053***
Temperature variation	-1.410*	-2.035**	-8.166***

Notes: *, **, and ***, respectively, denote significance at the 10%, 5%, and 1% level.

Table 3. Test for threshold effects

Test for single threshold	
F_1	165.902
P-value	0.191
Critical values (10%, 5%, 1%)	184.062, 211.834, 303.573
Test for double threshold	
F_2	228.176
P-value	0.024
Critical values (10%, 5%, 1%)	174.825, 218.336, 348.094
Test for triple threshold	
F_3	142.538
P-value	0.033
Critical values (10%, 5%, 1%)	100.267, 124.625, 187.803

Table 4. Endogenous threshold regression for the triple threshold model

	Threshold	Estimates	95% Confidence
Threshold Estimates	Threshold1	15.206	[14.117, 15.328]
	Threshold2	46.973	[46.829, 47.215]
	Threshold3	87.526	[87.434, 87.660]
Regime-dependent			
Variable	Coefficient	OLS S.E.	White S.E.
temp<15.206	-0.406***	0.020	0.045
46.973>temp>15.206	-0.233***	0.021	0.043
87.526>temp>46.973	0.074*	0.018	0.042
temp>87.526	0.295***	0.017	0.042
Regime-independent			
Variable	Coefficient	OLS S.E.	White S.E.
Unemployment rate	0.287**	0.022	0.021
Real gdp per capita	-0.973**	0.183	0.187
Temperature variation	0.488***	0.062	0.103
Dew point temperature	0.029**	0.005	0.008
Precipitation	0.005*	0.001	0.002

Note: White denotes heteroscedasticity-consistent standard errors.

*, **, and ***, respectively, denote significance at the 10%, 5%, and 1% levels using White’s standard errors.

Table 5. Percentage change of future precipitation and temperature variation in 2030, 2050, and 2080 mean temperatures under the ECHAM5 model for A1B Scenario

Year	Month	variable	below 30°	31°-40°	41°-50°	51°-60°	61°-70°
2030	Summer-1	temp (°F)	88.820	81.970	75.387	69.715	64.333
		prec(%)	0.537	-3.083	-2.488	1.998	5.233
		tempvar(%)	2.941	1.942	2.674	2.250	2.459
	Summer-2	temp (°F)	88.640	86.861	80.442	73.921	68.563
		prec(%)	-3.973	4.630	3.687	0.291	-1.221
		tempvar(%)	2.415	0.628	0.789	3.353	1.766
	Summer-3	temp (°F)	88.340	87.557	80.010	73.419	65.143
		prec(%)	-5.186	1.127	-3.022	2.744	5.605
		tempvar(%)	1.265	1.886	1.502	3.804	2.900
	Winter-1	temp (°F)	59.540	37.721	27.428	28.485	9.388
		prec(%)	-4.688	8.487	-4.062	-17.283	0.942
		tempvar(%)	2.960	4.692	4.332	2.554	3.598
	Winter-2	temp (°F)	60.920	39.028	28.724	29.812	11.030
		prec(%)	1.382	-2.156	-7.197	-2.710	0.511
		tempvar(%)	3.704	1.639	4.925	1.194	1.577
	Winter-3	temp (°F)	61.400	40.828	30.351	31.593	14.090
		prec(%)	-16.883	7.645	2.764	-15.430	-2.433
		tempvar(%)	1.515	-0.470	0.348	-2.568	-3.590
2050	Summer-1	temp (°F)	90.080	83.480	77.288	71.287	65.053
		prec(%)	2.542	1.178	-4.299	0.591	4.830
		tempvar(%)	2.733	1.942	3.381	2.960	2.066
	Summer-2	temp (°F)	90.080	88.708	82.810	75.039	69.215
		prec(%)	-5.198	6.797	2.822	-1.094	-1.333
		tempvar(%)	2.634	0.853	1.638	3.463	1.353
	Summer-3	temp (°F)	89.780	89.342	82.501	74.783	65.975
		prec(%)	-4.651	1.667	-4.900	1.538	8.046
		tempvar(%)	1.265	1.995	2.635	4.241	2.383
	Winter-1	temp (°F)	60.560	38.950	29.271	30.380	12.808
		prec(%)	-6.349	7.240	-2.419	-10.156	3.539
		tempvar(%)	2.960	4.864	2.905	0.265	-0.113
	Winter-2	temp (°F)	61.820	40.593	30.798	31.214	14.180
		prec(%)	2.283	0.242	-4.896	0.670	5.041
		tempvar(%)	3.400	1.806	4.045	1.194	-1.655
	Winter-3	temp (°F)	62.600	42.323	32.230	33.383	16.745
		prec(%)	-8.434	5.778	3.474	-8.337	2.320
		tempvar(%)	0.865	-0.145	0.316	-3.776	-5.867
2080	Summer-1	temp (°F)	92.420	86.070	80.283	74.300	67.550
		prec(%)	-1.091	6.296	-3.085	-4.576	4.149
		tempvar(%)	2.941	2.247	4.259	4.638	2.000
	Summer-2	temp (°F)	92.900	91.243	86.684	77.265	70.903
		prec(%)	-5.270	10.903	-0.832	-3.534	7.317
		tempvar(%)	3.718	0.718	2.937	4.414	0.163
	Summer-3	temp (°F)	92.360	91.995	86.958	77.256	67.708
		prec(%)	-2.931	3.591	-7.724	-9.402	13.591
		tempvar(%)	2.598	1.798	4.471	5.688	0.798
	Winter-1	temp (°F)	62.660	41.141	32.482	33.743	16.903
		prec(%)	-2.682	5.132	3.308	2.234	9.023
		tempvar(%)	3.422	5.011	1.098	-1.745	-4.983
	Winter-2	temp (°F)	63.620	42.910	33.843	32.938	18.388
		prec(%)	6.957	5.184	-0.798	1.629	8.607
		tempvar(%)	3.400	1.185	1.273	-0.083	-6.412
	Winter-3	temp (°F)	65.180	44.475	35.514	36.244	20.503
		prec(%)	0.735	1.680	3.984	2.432	8.394
		tempvar(%)	0.373	0.303	-0.509	-3.776	-8.915

Table 6. Impacts of mean temperature, precipitation, temperature changes on mortality rate under the ECHAM5 model for the A1B Scenario

Year	Month	variable	below 30°	31°-40°	41°-50°	51°-60°	61°-70°
2030	Summer-1	temp	0.436	5.513	4.476	3.583	2.735
		prec	0.003	-0.015	-0.012	0.010	0.026
		tempvar	1.435	0.948	1.305	1.098	1.200
		total	1.874	6.445	5.769	4.691	3.961
	Summer-2	temp	0.375	6.284	5.273	4.245	3.401
		prec	-0.020	0.023	0.018	0.001	-0.006
		tempvar	1.178	0.306	0.385	1.636	0.862
		total	1.534	6.613	5.676	5.883	4.257
	Summer-3	temp	0.274	0.011	5.204	4.166	2.862
		prec	-0.026	0.006	-0.015	0.014	0.028
		tempvar	0.617	0.920	0.733	1.856	1.415
		total	0.866	0.936	5.923	6.036	4.305
	Winter-1	temp	1.980	4.589	9.695	9.170	15.535
		prec	-0.023	0.042	-0.020	-0.086	0.005
		tempvar	1.444	2.290	2.114	1.246	1.756
		total	3.401	6.922	11.789	10.330	17.296
	Winter-2	temp	2.197	3.941	9.052	8.513	11.150
		prec	0.007	-0.011	-0.036	-0.014	0.003
		tempvar	1.807	0.800	2.404	0.583	0.770
		total	4.011	4.730	11.420	9.082	11.922
	Winter-3	temp	2.273	3.048	8.245	7.629	2.980
		prec	-0.084	0.038	0.014	-0.077	-0.012
		tempvar	0.739	-0.229	0.170	-1.253	-1.752
		total	2.928	2.857	8.428	6.299	1.216
2050	Summer-1	temp	0.861	5.751	4.776	3.830	2.848
		prec	0.013	0.006	-0.021	0.003	0.024
		tempvar	1.334	0.948	1.650	1.444	1.008
		total	2.207	6.705	6.404	5.278	3.880
	Summer-2	temp	0.861	0.398	5.646	4.421	3.504
		prec	-0.026	0.034	0.014	-0.005	-0.007
		tempvar	1.286	0.416	0.799	1.690	0.660
		total	2.120	0.848	6.459	6.106	4.157
	Summer-3	temp	0.760	0.612	5.597	4.381	2.994
		prec	-0.023	0.008	-0.025	0.008	0.040
		tempvar	0.617	0.974	1.286	2.070	1.163
		total	1.354	1.594	6.858	6.458	4.197

Year	Month	variable	below 30°	31°-40°	41°-50°	51°-60°	61°-70°
	Winter-1	temp	2.140	3.980	8.781	8.231	6.404
		prec	-0.032	0.036	-0.012	-0.051	0.018
		tempvar	1.444	2.374	1.418	0.129	-0.055
		total	3.553	6.390	10.186	8.309	6.366
	Winter-2	temp	2.339	3.165	8.023	7.817	2.739
		prec	0.011	0.001	-0.024	0.003	0.025
		tempvar	1.659	0.881	1.974	0.583	-0.808
		total	4.010	4.047	9.973	8.403	1.957
	Winter-3	temp	2.462	2.307	7.313	6.741	14.994
		prec	-0.042	0.029	0.017	-0.042	0.012
		tempvar	0.422	-0.071	0.154	-1.843	-2.863
		total	2.842	2.265	7.484	4.857	12.142
2080	Summer-1	temp	1.649	6.159	5.248	4.305	3.242
		prec	-0.005	0.031	-0.015	-0.023	0.021
		tempvar	1.435	1.096	2.078	2.263	0.976
		total	3.079	7.287	7.311	6.545	4.238
	Summer-2	temp	1.811	1.253	6.256	4.772	3.770
		prec	-0.026	0.055	-0.004	-0.018	0.037
		tempvar	1.814	0.350	1.433	2.154	0.079
		total	3.599	1.658	7.685	6.909	3.886
	Summer-3	temp	1.629	1.506	6.299	4.771	3.266
		prec	-0.015	0.018	-0.039	-0.047	0.068
		tempvar	1.268	0.878	2.182	2.776	0.389
		total	2.883	2.402	8.442	7.500	3.724
	Winter-1	temp	2.471	2.893	7.188	6.562	14.916
		prec	-0.013	0.026	0.017	0.011	0.045
		tempvar	1.670	2.446	0.536	-0.851	-2.432
		total	4.128	5.364	7.740	5.722	12.529
	Winter-2	temp	2.623	2.016	6.513	6.962	14.179
		prec	0.035	0.026	-0.004	0.008	0.043
		tempvar	1.659	0.578	0.621	-0.040	-3.129
		total	4.316	2.620	7.130	6.930	11.093
	Winter-3	temp	2.868	1.239	5.684	5.322	13.130
		prec	0.004	0.008	0.020	0.012	0.042
		tempvar	0.182	0.148	-0.248	-1.843	-4.350
		total	3.054	1.395	5.456	3.491	8.822

Table 7. Impacts of summer and winter climate change on mortality rate under the ECHAM5 model for the A1B Scenario

Season	Year	below 30°	31°-40°	41°-50°	51°-60°	61°-70°
summer	2030	4.274	13.995	17.367	16.610	12.523
	2050	5.681	9.147	19.721	17.842	12.234
	2080	9.561	11.347	23.438	20.954	11.848
winter	2030	10.340	14.509	31.637	25.711	30.434
	2050	10.405	12.702	27.643	21.569	20.466
	2080	11.498	9.379	20.326	16.143	32.444

Appendix. The list of 78 major cities in 22 OECD countries

City	Country	City	Country	City	Country
Sapporo	Japan	Krakow	Poland	Sydney	Australia
Sendai	Japan	Gdansk	Poland	Darwin	Australia
Tokyo	Japan	Oulu	Finland	Brisbane	Australia
Nagoya	Japan	Helsinki	Finland	Adelaide	Australia
Osaka	Japan	Vaasa	Finland	Hobart	Australia
Hiroshima	Japan	Stockholm	Sweden	Melbourne	Australia
Fukuoka	Japan	Malmo	Sweden	Boston	USA
Edmonton	Canada	Umea	Sweden	St. Paul	USA
Vancouver	Canada	Manchester	UK	Memphis	USA
Winnipeg	Canada	London	UK	Kansas City	USA
St. John's	Canada	Edinburgh	UK	Denver	USA
Yellowknife	Canada	Berlin	Germany	Seattle	USA
Toronto	Canada	Hamburg	Germany	Los Angeles	USA
Montreal	Canada	Dusseldorf	Germany	Dallas	USA
Whitehorse	Canada	München	Germany	Chicago	USA
Seoul	Korea	Frankfurt	Germany	Washington	USA
Zurich	Switzerland	Paris	France	Miami	USA
Oslo	Norway	Nantes	France	New York	USA
Trondheim	Norway	Lyon	France		
Tromso	Norway	Marseille	France		
Athens	Greece	Lisbon	Portugal		
Budapest	Hungary	Brussels	Belgium		
Roma	Italy	København	Denmark		
Palermo	Italy	Madrid	Spain		
Milano	Italy	Santander	Spain		
Groningen	Netherlands	Barcelona	Sapin		
Amsterdam	Netherlands	Valencia	Sapin		
Maastricht	Netherlands	Malaga	Spain		
Wien	Austria	Canberra	Australia		
Warszawa	Poland	Perth	Australia		