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Variation in vulnerability to extreme-temperature-related mortality in Japan: A 40-year time-series analysis

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ABSTRACT

Background: Although the impact of extreme heat and cold on mortality has been documented in recent years, few studies have investigated whether variation in susceptibility to extreme temperatures has changed in Japan.
Methods: We used data on daily total mortality and mean temperatures in Fukuoka, Japan, for 1973–2012. We used time-series analysis to assess the effects of extreme hot and low temperatures on all-cause mortality, stratified by decade, gender, and age, adjusting for time trends. We used a multivariate meta-analysis with a distributed lag non-linear model to estimate pooled non-linear lag-response relationships associated with extreme temperatures on mortality.
Results: The relative risk of mortality increased during heat extremes in all decades, with a declining trend over time. The mortality risk was higher during cold extremes for the entire study period, with a dispersed pattern across decades. Meta-analysis showed that both heat and cold extremes increased the risk of mortality. Cold effects were delayed and lasted for several days, whereas heat effects appeared quickly and did not last long.
Conclusions: Our study provides quantitative evidence that extreme heat and low temperatures were significantly and non-linearly associated with the increased risk of mortality with substantial variation. Our results suggest that timely preventative measures are important for extreme high temperatures, whereas several days' protection should be provided for extreme low temperatures.

1. Introduction

The impact of heat and cold extremes on mortality represents a global public health issue (Costello et al., 2009; McMichael et al., 2008; Analitis et al., 2008; Baccini et al., 2008). Exposure to extreme heat and low temperatures is associated with substantial increases in morbidity and mortality (Kovats and Hajat, 2008; Basu, 2009; McMichael et al., 2008), and the frequency, intensity, and duration of extreme heat events are projected to increase due to climate change (IPCC, 2012). The associations between daily temperature and mortality are generally non-linear U-, V-, or J-shaped (Huang et al., 2011), and mortality increases with hotter and colder temperatures (McMichael et al., 2008; Analitis et al., 2008). Warm temperatures increase mortality in the elderly (Rocklov et al., 2011; Baccini et al., 2008; Hajat et al., 2007; O'Neill et al., 2003); however, excess mortality is elevated in all age groups during heat waves (Rey et al., 2007). Low temperatures also increase mortality, and the effects are more apparent in middle-aged and younger populations (Rocklov et al., 2011; Analitis et al., 2008; Hajat et al., 2007; O'Neill et al., 2003). Although these findings help to explain extreme temperature-related mortality, associations can differ substantially by location (Hajat and Kosatky, 2010). Moreover, these associations may not be adequate to describe more local mortality.

Several studies have explored the effects of extreme temperatures on human physiology and performance (Kovats and Hajat, 2008). Social, environmental, behavioral, technological, infrastructural, and biophysical adaptations can affect a population's vulnerability to heat and cold (Stafoggia et al., 2006). Several studies have reported reduced short-term mortality due to extreme temperatures in areas where the population has adapted to highly variable ambient temperatures (Carson et al., 2006; Davis et al., 2003). However, the relationships between temperature and mortality can be affected by demographic changes, variations in susceptibility factors, and the degree of adaptation to the local environment (Astrom et al., 2013).

In the present study, we examined the variation in the effects of extreme heat and low temperatures on mortality in Fukuoka, Japan, during the period 1973–2012. To our knowledge, this is the

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Abbreviations: CI, confidence interval; ICD, *International Classification of Diseases*; REM, relative effect modification; RR, relative risk

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first report to quantify the impact of extreme heat and low temperatures on mortality in Japan by characterizing vulnerable subgroups and identifying effect modifiers.

2. Methods

2.1. Data sources

We obtained the daily numbers of deaths from all causes in Fukuoka, Japan (Supplementary data, Fig. S1), during the period of 1973–2012 (Table 1). In this study, we used all-cause daily mortality, excluding any deaths from external causes (based on the *International Classification of Diseases* (*ICD*), 10th revision (ICD-10), codes V01-Y98; the *ICD*, 9th revision, codes 800 and above, and the *ICD*, 8th revision, codes 800 and above). In Japan, residency and death registration is required under the Family Registration Law and is believed to be complete across the country.

We obtained data on the daily mean temperatures in Fukuoka Prefecture from the Japan Meteorological Agency (Table 2). Heat extremes were defined as days on which the 2-day moving average of the mean temperature was above the 98th percentile (30.0 °C) for the entire period (1973–2012). Cold extremes were defined as days on which the 26-day moving average of the mean temperature was below the 2nd percentile (5.0 °C). These lags are suitable for describing effects related to short-term variability in heat and low temperature, considering mortality displacement (Astrom et al., 2013; Anderson and Bell, 2009; Guo et al., 2011; Gasparrini and Armstrong, 2013). Using the same criteria for the heat and cold extremes over the study period might not account for increasing temperature over time or acclimatization over decades. Additionally, this approach could lead to bias in earlier decades because we might be estimating mortality at a more extreme temperature (Astrom et al., 2013). To overcome this problem, we also investigated temperature extremes occurring within each decade using the same percentiles and lags for heat and cold extremes as defined above.

2.2. Statistical analysis

We examined the relationship between extreme hot and low temperatures and mortality using Poisson regression models allowing overdispersion (McCullagh and Nelder, 1989). To account for the seasonality of mortality that was not directly due to the weather, the model included Fourier terms up to the sixth harmonic for each year. Fourier terms can be used to recreate any periodic signal, such as a consistent seasonal pattern, using a linear combination of sine and cosine waves of varying wavelengths (Stolwijk et al., 1999). The number of harmonics defines the lowest wavelength reproduced (i.e., the level of seasonal adjustment), with six harmonics corresponding to a wavelength of 60 days. The day of the week was included in the model as a categorical explanatory variable. Public holidays were included in the model as binary variables. Indicator variables for the years under study were incorporated into the model to allow for long-term trends and interannual variations. To allow for autocorrelations, an autoregressive term of the first order was incorporated into the models (Brumback et al., 2000). Plots of the model residuals, predicted and observed time-series plots, and the partial autocorrelation function of the residuals (Supplementary data, Fig. S2) suggested that the adjustment for seasonal trends was adequate. For the sensitivity analysis, we also estimated the relationships between extreme temperature and mortality using different degrees of seasonal control (3rd and 12th harmonics).

In summary, the models were of the following form:

$$\begin{aligned}\log[E(Y)] = {} & \alpha + \text{heat} + \text{heat} \times \text{decade} + \text{cold} \\ & + \text{cold} \times \text{decade} + \text{dow} + \text{holiday} + \text{year} \\ & + \text{time}(\text{Fourier, 6 harmonics/year}),\end{aligned}$$

where *E(Y)* is the expected daily mortality count, heat represents the indicator variables for heat extremes, cold represents the indicator variables for cold extremes, decade represents the indicator for the decade, dow is the indicator for the day of the week, holiday is the indicator variables for public holidays, year is the indicator variables for the year, and Fourier represents Fourier (trigonometric) terms.

Model 1 was computed using cut-off temperatures for temperature extremes defined for the entire period of investigation, 1973–2012, whereas for model 2, the cut-off temperatures for temperature extremes were defined within each decade. Thus, model 2 was assumed to adapt to the potentially increasing temperatures and considered the changes in temperature extremes over time. As gender and age have been shown to modify susceptibility (Kovats and Hajat, 2008; Basu, 2009), we used stratified models to investigate the differences in vulnerability to extreme temperatures by gender and four age categories (0–14, 15–64, 65–79, and 80+ years). Effect modification was tested and reported as the relative effect modification (REM) index, which is calculated as the ratio between the specific relative risk (RR) and the RR from the reference category (Stafoggia et al., 2006).

We also examined temperature-morbidity curves and lag effects in more detail using two-stage analyses; multivariate meta-analysis with distributed lag non-linear model (Le Tertre et al., 2006; Armstrong, 2006; Gasparrini and Armstrong, 2013; Guo et al., 2014). In the first stage, a Poisson regression allowing overdispersion with distributed lag non-linear model was used to estimate the decade-specific temperature-mortality relation. Distributed lag non-linear models were fit to the mortality data with a 5-df natural cubic spline for the temperature-mortality relation and 4-df natural cubic spline for lag effect. In the second stage, a multivariate meta-analysis was used to pool the four sets of decade-specific non-linear and delayed effects of temperature. The multivariate meta-analyses were fitted using a random effects model by maximum likelihood. More details of this approach have been published previously (Le Tertre et al., 2006; Armstrong, 2006; Gasparrini and Armstrong, 2013; Guo et al., 2014).

In summary, the distributed lag non-linear models were of the form:

Table 1
Daily mortality counts and the mortality distribution by age.

Decade	No. of daily deaths						Percent distribution of deaths by age			
	Minimum	25th percentile	Median	75th percentile	Maximum	Total	0–14	15–64	65–79	80+
1973–1982	32	62	70	78	134	258,651	2.8	27.7	41.6	27.9
1983–1992	43	72	81	90	131	296,469	1.3	24.3	36.6	37.7
1993–2002	56	84	93	104	196	346,723	0.8	18.9	35.9	44.4
2003–2012	64	101	113	125	171	414,075	0.4	13.9	31.4	54.4