A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP493.

Heat-Related Mortality in Japan after the 2011 Fukushima Disaster: An Analysis of Potential Influence of Reduced Electricity Consumption

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Background: In March 2011, the Great East Japan Earthquake devastated several power stations and caused severe electricity shortages. This accident was followed by the implementation of policies to reduce summer electricity consumption in the affected areas, for example, by limiting air-conditioning (AC) use. This provided a natural experimental scenario to investigate if these policies were associated with an increase in heat-related mortality.

Objectives: We examined whether the reduced electricity consumption in warm season modified heat-related mortality from 2008 to 2012.

Methods: We conducted prefecture-specific interrupted time-series (ITS) analyses to compare temperature–mortality associations before and after the earthquake, and used meta-analysis to generate combined effect estimates for the most affected and less affected areas (prefectures with $>10\%$ or $\leq 10\%$ reductions in electricity consumption, respectively). We then examined whether the temperature–mortality association in Tokyo, one of the most affected areas, was modified by the percent reduction in electricity consumption relative to expected consumption for comparable days before the earthquake.

Results: Contrary to expectations, we estimated a 5–9% reduction in all-cause heat-related mortality after the earthquake in the 15 prefectures with the greatest reduction in electricity consumption, and little change in the other prefectures. However, the percent reduction in observed vs. expected daily electricity consumption after the earthquake did not significantly modify daily heat-related mortality in Tokyo.

Conclusions: In the prefectures with the greatest reductions in electricity consumption, heat-related mortality decreased rather than increased following the Great East Japan Earthquake. Additional research is needed to determine whether this finding holds for other populations and regions, and to clarify its implications for policies to reduce the consequences of climate change on health. https://doi.org/10.1289/EHP493

Introduction

High ambient temperatures increase deaths, and heat-related mortality is expected to increase with climate change (WHO 2014). Although an association between ambient heat and mortality has been observed consistently around the world (Gasparrini et al. 2015b; Guo et al. 2014), estimated risks vary among locations (Anderson and Bell 2009; Chung et al. 2015; Curriero et al. 2002; Guo et al. 2014) and over time (Bobb et al. 2014; Boeckmann and Rohn 2014; Carson et al. 2006; Gasparrini et al. 2015a; Todd and Valleron 2015). Several potential modifiers, such as population density, the proportion of older people, income level, green space, housing, and air-conditioning (AC), have been proposed to explain spatial and temporal heterogeneity in heat-related mortality and morbidity (Hajat and Kosatky 2010; Hondula and Barnett 2014; Loughnan et al. 2015; Madrigano et al. 2015). AC is assumed to be an effective means of reducing heat-related mortality (Medina-Ramón and Schwartz 2007; Ostro et al. 2010; Semenza et al. 1996; Rogot et al. 1992). An analysis of data from 11 eastern U.S. cities (1973–1994) indicated that the association between ambient heat and mortality was stronger for cities that had a lower proportion of homes with AC, even after adjusting for potential confounders (Curriero et al. 2002). However, although increasing access to AC has been recommended as a key intervention to prevent heat-related deaths (CDC 1996; Semenza 1999; Semenza et al. 1999), there is uncertainty about whether to include AC in adaptation planning for future climate change. Two recent studies reported that heat-related mortality in U.S. cities declined over several decades (for 1962–2006 and 1987–2005, respectively), and both found that the declines could not be explained by increases in the prevalence of AC alone (Bobb et al. 2014; Nordio et al. 2015). Increased power consumption as a consequence of increasing AC use poses a threat to electricity grids and could contribute to urban heat islands and greenhouse gas emissions that promote climate change (Lundgren and Kjellstrom 2013). It has been estimated that worldwide AC use consumes about 1 trillion kilowatt hours of electricity annually and that AC-associated electrical consumption could increase tenfold by 2050 (Dahl 2013).

In March 2011, a great earthquake and tsunami struck eastern Japan and devastated several nuclear and thermal power stations, including the Fukushima nuclear power plant, resulting in severe electricity shortages, especially in the Tokyo metropolitan area. In May 2011, the government announced the implementation of an energy-saving strategy for the summer peak demand months (July–September). The demand reduction target was set at 15% of the 2010 summer level in the areas served by the Tohoku Electric Power Company and Tokyo Electric Power Company (TEPCO) (Ministry of Economy, Trade and Industry 2012). While these targets were voluntary for households, the target was mandatory for large industries consuming more than 500 kW in these areas (Ministry of Economy, Trade and Industry 2012). In the Tokyo metropolitan area (served by TEPCO), 53% of household electricity consumption during the summer peak hours of 2010 was attributed to AC use (Ministry of Economy, Trade and Industry 2012). To reduce this consumption, a public information campaign was implemented through mass media and the Internet to introduce power-saving protocols, such as setting AC temperatures to 28°C and using electric fans instead of AC as much as

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Supplemental Material is available online (https://doi.org/10.1289/EHP493).

The authors declare they have no actual or potential competing financial interests.

Received 11 May 2016; Revised 7 March 2017; Accepted 13 March 2017; Published 6 July 2017.

possible. However, there were concerns that this power-saving policy might cause increases in heat-related illnesses, particularly among older people (Kondo et al. 2011). According to a survey conducted in February 2011, before the great earthquake, the average prevalence of AC in households with the elderly in eight major cities in Japan was 78.2% (90.6% in Tokyo), with only 3.4% reporting that they never used AC during daytime, and 73.2% reporting AC use when room temperatures were ≤28°C (Kondo et al. 2013).

The reduction in AC use following the great earthquake in Japan can be regarded as a natural experiment that may illustrate what would occur if societies were required to reduce their electricity consumption in order to reduce global greenhouse gas emissions (Craig et al. 2012). It has been estimated that a mitigation strategy to conserve energy through the active promotion of household behavioral changes could reduce U.S. household greenhouse gas emissions by approximately 20% (Dietz et al. 2009). However, the potential effect of electricity conservation on heat-related illnesses during the summer has not been examined in detail.

We hypothesized that the power-saving policy implemented after the great earthquake in Japan may have affected the association between heat and mortality, and that effects would have been more pronounced in areas with the greatest reduction in electricity consumption. We examined this hypothesis using two approaches. First, to estimate the total impact of the power-saving policy on heat-related mortality, we conducted prefecture-specific interrupted time-series (ITS) analyses and compared summary effect estimates (generated using meta-analysis) for the most affected prefectures (i.e., those with the greatest reduction in electricity consumption) with those for less affected prefectures (Figure 1). Second, we examined whether daily heat-related mortality in Tokyo was modified by the percent reduction in daily electricity consumption after the earthquake relative to expected consumption based on electricity consumption before the earthquake.

Methods

Mortality and Weather Data

Prefecture-specific daily mortality data for deaths in 2008–2012 during 1 May–30 September (hereafter referred to as the warm season) were obtained from the Ministry of Health, Labour and Welfare, including deaths from all causes, and from cardiovascular and respiratory diseases specifically, and deaths among people of all ages and among those ≥65 y of age. Daily mean temperature (°C) data measured at a single monitoring site in the capital city of each prefecture were obtained from the Japan Meteorological Agency for the same period. When there was no monitoring site in the capital city (two prefectures), we used temperatures measured at the site closest to the capital city of the prefecture.

Electricity Consumption Data: Interrupted Time-Series Analysis

For the ITS analysis, we used data reported by (Federation of Electric Power Companies of Japan 2011) to estimate the proportion of power use in June–September 2011 for each prefecture compared with average power use in the same prefectures in 2007–2010 (see Table S1). For prefectures served by more than one electric power company, we chose a company serving the capital city of the prefecture. We then classified each prefecture into one of two groups defined *a priori* as the most affected

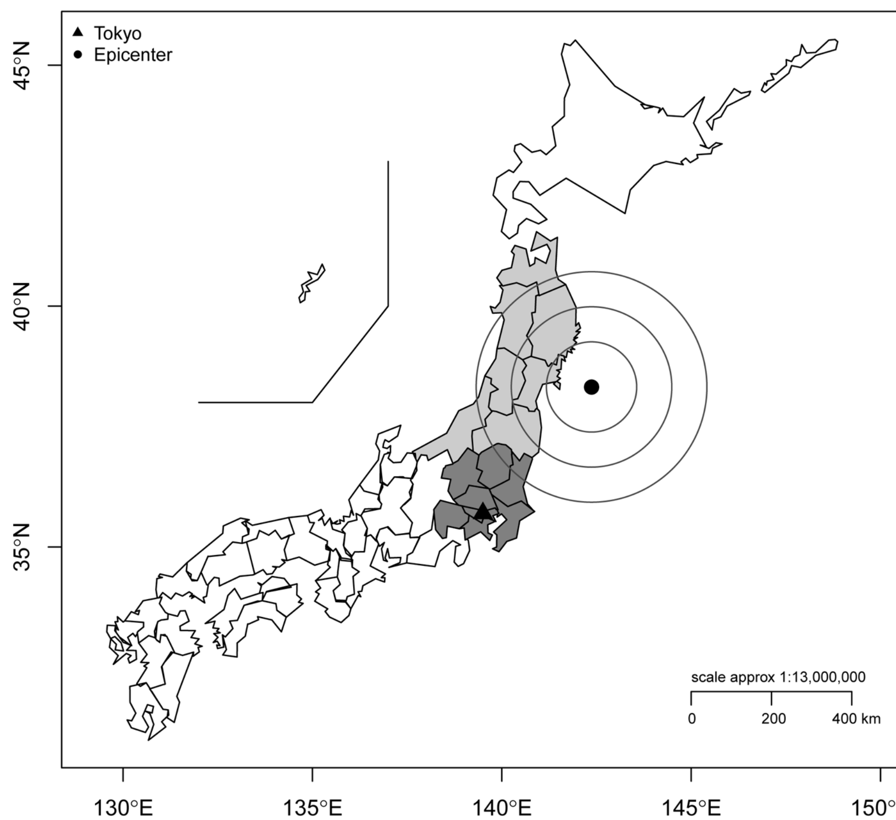

Figure 1. Prefectures less affected (white) and most affected (dark and light gray) by the Great East Japan Earthquake from the epicenter at 38.322°N 142.369°E (circle) that occurred on 11 March 2011. The prefectures including Tokyo (triangle) served by the Tokyo Electric Power Company (TEPCO) are highlighted in dark gray.

(>10% reduction in power consumption in 2011 compared with average consumption before the earthquake, $n=15$) and less affected (≤10% reduction in power consumption, $n=32$).

Electricity Consumption Data: Daily Electricity Consumption Analysis

We collected hourly total electricity consumption data ($kW \times 10^4$) for households and the industrial/commercial sectors in 2008–2012 in the eight metropolitan prefectures served by TEPCO (Tokyo Electric Power Company 2017), which operates the Fukushima nuclear power plant and supplies almost all of Tokyo's electrical power (Figure 1). This area accounts for more than half of the 15 prefectures classified as most affected based on a >10% reduction in power use following the earthquake (Table S1).

Next, we calculated daily mean consumption of the electricity data and derived a continuous variable representing the temperature-adjusted electricity reduction (%) as a possible modifier of heat-related mortality in Tokyo following the great earthquake. First, we estimated expected electricity consumption during the warm season (May–September) based on a regression model of 2008–2010 data with an indicator term for the day of week or national holiday (eight categories), mean daily temperature [natural cubic spline with 3 degrees of freedom (df)], and day in season (natural cubic spline with 4 df per y). The model allowed us to estimate what electricity consumption would have been in the TEPCO service area on each day following the earthquake if the earthquake had not occurred. Next, we calculated the percentage difference between the observed and expected electricity consumption and restricted the percentage to zero for all days before the earthquake, which we refer to as the percent reduction of (warm season) electricity consumption.

Statistical Analyses

We applied a Poisson regression with an overdispersion parameter and a distributed lag nonlinear model (DLNM) (Gasparrini 2011) for the temperature term for two analytical approaches: the ITS and daily electricity consumption analyses. In addition, we stratified analyses according to cause of death (all cause, cardiovascular, or respiratory) and by age (all ages and ≥65 y).

Interrupted time-series analysis. The DLNM for the ITS was specified as

$$Y_i \sim Poisson\,(\mu_i)$$

$$\log(\mu_i) = \alpha + cross.basis_i + cross.basis_i \times i.period_i + covariates_i \quad [1]$$

where Y_i is the number of deaths on day i, α is the intercept, $cross.basis_i$ is a bivariate spline of mean temperature covering lags 0 to 10, and $i.period_i$ indicates the period before or after the great earthquake. For the cross-basis function, which describes the shape and lag structure of the temperature–mortality association, we used a quadratic B-spline with a knot at the 75th percentile for mean temperature. The lag was specified using a natural cubic spline with two equally spaced knots in the log scale. The $covariates_i$ for day i comprised a categorical variable indicating the day of week or national holiday, date (linear term), and an interaction between day in season (a natural cubic spline of consecutive numbers representing 1 May to 30 September during each year, with 4 df per y) and year (a categorical variable). For each prefecture, we used DLNM to characterize the association between heat and mortality by estimating cumulative relative risks (RRs) over a 0- to 10-d lag for mortality associated with heat (defined *a priori* as the daily mean temperature corresponding to the 95th or 99th percentile of daily mean temperatures for the prefecture during May–September in 2008–2012), compared with a prefecture-specific reference temperature corresponding to the 50th percentile of daily mean temperatures during the same period of May–September (see Table S1 for daily mean temperature distribution for each prefecture). We estimated prefecture-specific RRs for heat and mortality before and after the great earthquake, and estimated the ratio of the RRs (RRRs) to estimate the difference in the heat–mortality association between the two periods of time.

We used fixed effects meta-analysis (Higgins et al. 2003) to combine the prefecture-specific RRs or RRRs into summary RRs or RRRs for the less affected (≤10% reduction in electricity consumption) and most affected (>10% reduction) prefectures by cause of deaths and age. The I^2 statistics for heterogeneity of the summary RRRs in all ages were estimated at 0.0% except the summary RRRs for respiratory mortality associated with heat for the 95th percentile of mean temperature (13.2% in less affected and 22.3% in most affected prefectures). In addition, maximum values of the I^2 statistics were 33.9% and 24.2% for the summary RRs in all ages before and after the earthquake, respectively, and there was no strong evidence of heterogeneity for each meta-analysis (all of $p < 0.05$ by test for heterogeneity). The I^2 statistics for older people (≥65 y) were 0.0–37.9%. To compare the summary RRs and RRRs for the less affected and most affected prefectures, we used random effects meta-regression with an indicator term to categorize prefectures as most or less affected (Sharp 1998).

Daily electricity consumption analysis. In the ITS analysis, we used DLNM to estimate cumulative RRs (0- to 10-d lags) for mortality associated with heat (defined as the 95th or 99th percentile of daily mean temperature in Tokyo during May–September, or 30.1 and 31.1°C, respectively) compared with the 50th percentile of daily mean temperature (24.4°C) with adjustment for day of the week or holiday, date, and day in season (natural cubic spline with 4 df/year) × year. However, instead of evaluating modification of the heat–mortality association by time period (pre- or postearthquake), we evaluated modification by the estimated percentage difference in observed vs. expected daily electricity consumption following the earthquake. Specifically, we modeled a linear interaction term between the cross-basis function (based on temperature and mortality data for Tokyo) and the 4-d moving average of estimated percent reduction in observed vs. expected electricity consumption in the TEPCO service area (which includes Tokyo). To characterize the effect of reduced electricity consumption on the association between heat and mortality in Tokyo, we used the fitted DLNM to derive cumulative RRs of heat-related mortality with a 0% (no reduction), 10%, or 20% reduction in the 4-d moving average electricity consumption. Significance of the effect modification was determined by using F-tests to compare the fit of models with and without the linear interaction between the temperature–mortality association and the percent reduction in electricity consumption.

Sensitivity Analyses

Previous studies reported a significant increase in cardiovascular deaths (CVDs) in the earthquake-affected Tohoku areas 1 mo after the earthquake (from 11 March to the first week of April 2011) (Kitamura et al. 2013; Kiyohara et al. 2015; Niiyama et al. 2014; Takegami et al. 2015). Therefore, to determine whether the sudden increase in CVDs after the great earthquake might have reduced the size of the population susceptible to heat in the subsequent period, we repeated the analysis comparing prefecture-specific RRs for heat and mortality before and after the earthquake after excluding data from 2011. Because air pollutants have been linked to daily mortality, we collected additional data on particulate matter, nitrogen dioxide, sulfur dioxide, and ozone to examine if their inclusion in the model influenced the estimates of heat–mortality association (see Table S3). We also performed several sensitivity analyses to evaluate the influence of different DLNM specifications using data from Tokyo. Specifically, we evaluated the effect of changing: the degree of piecewise polynomials for the mean temperature B-spline (2–5), the degrees of freedom for the natural cubic spline of day in season (1–8 df/y), the single knot placement for the mean temperature B-spline (from the 75th percentile to the 65th–85th percentiles); the reference temperature (from the 50th percentile to the 40th–60th percentiles), the number of lag days (from 0–21 d), and the number of internal knots for the mean temperature B-spline (1–4 knots). In addition, we generated deviance residuals from the final DLNM and applied partial autocorrelation function on the residuals.

All the analyses were conducted using R (version 3.1.2; R Foundation for Statistical Computing) with packages dlnm and splines and STATA with packages metan and metareg (version 13.1; StataCorp). The statistical significance level (α) was 0.05.

Results

Recorded Deaths and Temperature Regions in Japan

There were 2,229,021 recorded deaths in Japan during May–September in 2008–2012 (3,002.6 deaths per day on average). The proportion of deaths among people ≥ 65 y ranged from 78.2% to 88.8% across the 47 prefectures (see Table S1). The number of deaths from all causes increased slightly over the study period all prefectures, as illustrated in Figure S1 for Tokyo. Daily mean temperatures during May–September ranged from 19.7°C (Hokkaido in the north) to 28.3°C (Okinawa in the south) in the study period (see Table S1).

Analyses Comparing Heat-Related Mortality before and after the Earthquake between the Most and Less Affected Prefectures

The changes in heat-related mortality following the introduction of the power-saving policy were different in the less affected and most affected areas. In the most affected areas, prefecture-specific RRRs comparing cumulative heat-related all-cause mortality (0- to 10-d lags) before and after the great earthquake indicated that the estimated risk of mortality associated with the 95th vs. 50th percentile of daily mean temperature decreased for 13 of the 15 prefectures (Figure 2A). Corresponding summary RRs (for all of the most affected prefectures combined by meta-analysis) also decreased, from 1.08 [95% confidence interval (CI): 1.05, 1.11] to 1.02 (95% CI: 1.00, 1.05), resulting in a 5% decrease in the estimated risk of heat-related all-cause mortality (RRR = 0.95; 95% CI: 0.92, 0.99) (Table 1, Figure 2A). Estimates for all-cause mortality associated with heat at the 99th vs. 50th percentiles suggested a 9% decrease in heat-related mortality following the earthquake in the most affected prefectures (RRR = 0.91; 95% CI: 0.86, 0.96) (Table 1, Figure S2). In contrast, estimates for the less affected prefectures showed no consistent pattern in prefecture-specific RRRs comparing heat-related mortality before and after the earthquake (Figure 2B, Figure S2), and summary RRRs for all of the less affected prefectures combined were close to the null (e.g., RRR for the 95th percentile = 1.01; 95% CI: 0.98, 1.04) (Table 1). In addition, the temporal changes (RRRs) were significantly different between the most affected and less affected areas ($p = 0.020$ for 95th percentiles) (Table 1). For cardiovascular mortality, summary RRs decreased in both the most affected and less affected prefectures, but RRRs comparing heat-related mortality before and after the earthquake were close to the null (Table 1). For respiratory mortality, summary RRRs indicated nonsignificant decreases in heat-related mortality for the most affected prefectures, while RRRs for the less affected prefectures suggested an increase in heat-related mortality after the earthquake, which was significant for the 99th vs. 50th percentiles of daily mean temperature (RRR = 1.15, 95% CI: 1.03, 1.29) (Table 1). Similar patterns were observed for people aged 65 y and over (see Table S2). The prefecture-specific RRs and RRRs for all-cause mortality associated with daily mean temperature are shown in Figure S3.

Potential Modification of Heat-Related Mortality in Tokyo by Temperature-Adjusted Electricity Consumption

The daily mean electricity consumption in the TEPCO service area immediately dropped after the great earthquake (Figure S1C), and average daily electricity consumption during May–September in the area decreased by 9.85% between 2008–2010 and 2011–2012. In general, daily consumption was lower after the earthquake than on pre-earthquake days with the same daily mean temperature (Figure 3A). The difference between observed electricity consumption after the earthquake and expected consumption (based on a model of pre-earthquake electricity consumption in relation to daily mean temperature, day of the week or holiday, and date) was greater on days with high vs. moderate temperatures (Figure 3B). However, we found no evidence that heat-related mortality in Tokyo was modified by the percent reduction in daily electricity consumption in the TEPCO area. The 95% CIs for the stratified cumulative RRs for all-cause mortality overlapped considerably (Figure 3C), and the linear interaction between the percent reduction and the temperature–mortality association was not significant ($p = 0.8$). All-cause heat-related mortality also did not appear to be modified by the percent reduction in electricity consumption when we altered the number of lag days (e.g., as shown in Figure 3D for stratified RRs for all-cause mortality when the daily mean temperature in Tokyo was 30.1 vs. 24.4°C).

In subgroups classified by cause of death, the RRs for both cardiovascular and respiratory mortality also changed very little as the percent reduction increased from 0% to 10% and 20% (Figure 4). Regardless of the percent reduction, the RRs of cardiovascular mortality associated with heat were higher than the RRs of respiratory mortality that were almost close to the null. Similar patterns were observed for people aged 65 y and over (see Figure S4).

Sensitivity Analyses

The sensitivity analyses, excluding the 2011 period, showed consistent results despite wider 95% CIs due to the lower power of a smaller sample (see Figure S5), indicating the findings in our study were unlikely to be influenced by the sudden rise of CVDs after the earthquake against a concern that it might result in a spurious negative association between heat and mortality following the earthquake. Results from other sensitivity analyses were generally consistent with primary analyses, with none of the analyses indicating an increase in heat-related deaths after the earthquake (see Table S3, Figures S6 and S7). Model diagnosis also revealed nothing untoward (see Figure S6).

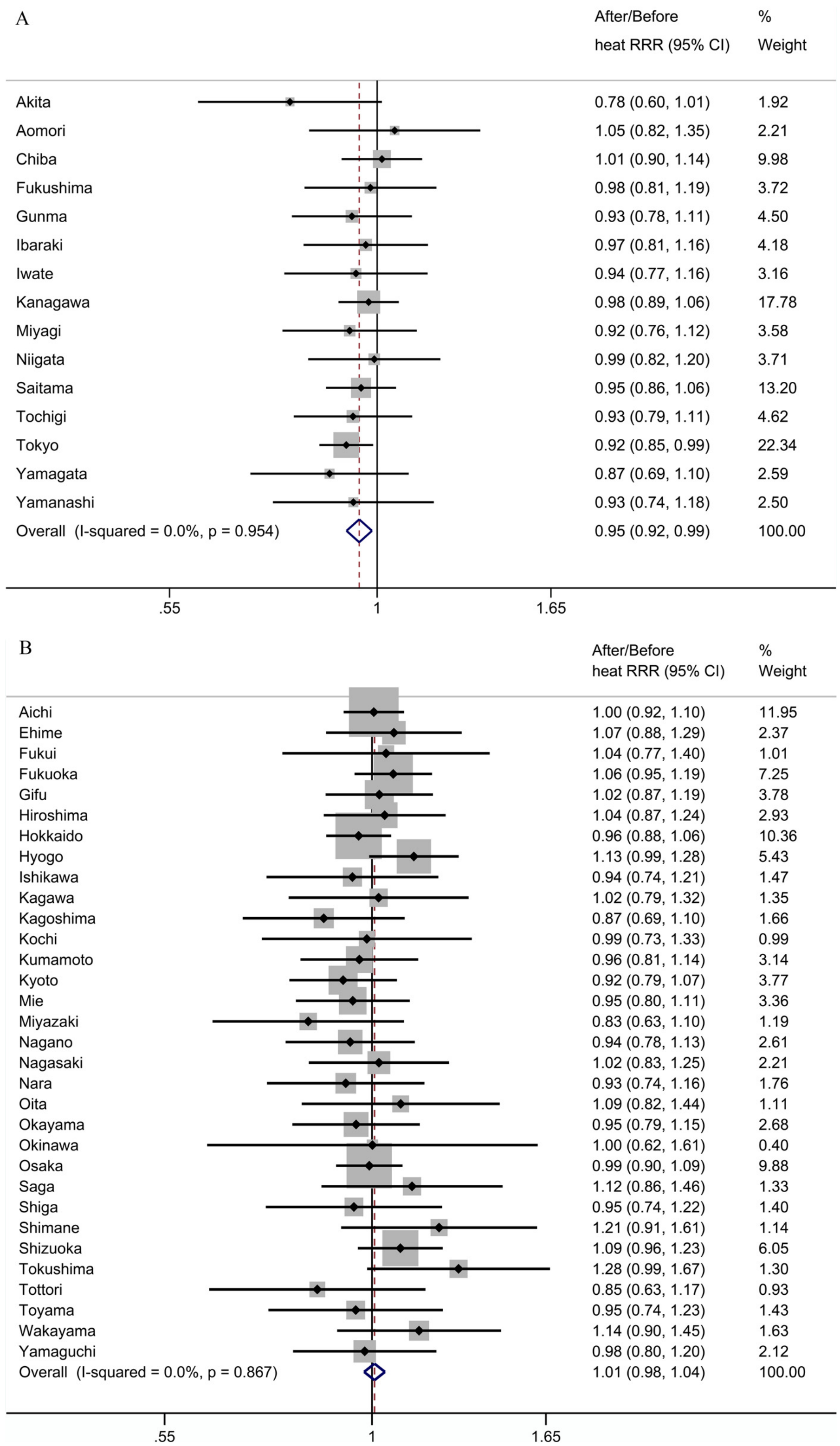

Figure 2. Forest plots for prefecture-specific ratio of relative risks (RRRs) for all-cause mortality associated with heat (the 95th percentile of daily mean temperature during May–September for prefecture specific shown in Table S1) compared with the 50th percentile of the temperature over 0–10 lag days after to before the earthquake and 95% confidence intervals (CIs) based on the distributed lag nonlinear model (DLNM) adjusted for day of week or holiday, date, and day in season (natural cubic spline with 4 df/y) × year. The periods for before and after correspond to 2008–2010 and 2011–2012, respectively. A fixed effect meta-analysis was used to estimate the summary RRRs in (*A*) most affected and (*B*) less affected areas.

Discussion

Despite the concern that large reductions in electricity consumption might have an adverse effect on heat-related mortality, we did not find any evidence for this in Japan after the great earthquake. Rather, our estimates suggest that in prefectures with the greatest reduction in electricity consumption, the risk of mortality due to heat decreased after the great earthquake (e.g., the summary RRR for all-cause mortality in all ages associated with

Table 1. Mean cumulative relative risks and ratio of relative risks with 95% confidence intervals (CIs) in less affected and most affected areas for all ages.

Heat[a]	Cause of death	Area	RR[b] before	RR[b] after	RRR[c] after/before	p-Value[d]
95%	All-cause	Less	1.02 (1.00, 1.04)	1.04 (1.01, 1.06)	1.01 (0.98, 1.04)	0.020
		Most	1.08 (1.05, 1.11)	1.02 (1.00, 1.05)	0.95 (0.92, 0.99)	
	Cardiovascular	Less	1.05 (1.01, 1.09)	1.04 (1.00, 1.09)	0.99 (0.94, 1.05)	0.954
		Most	1.09 (1.04, 1.15)	1.07 (1.02, 1.12)	0.99 (0.93, 1.06)	
	Respiratory	Less	1.00 (0.95, 1.05)	1.07 (1.01, 1.13)	1.07 (0.99, 1.15)	0.155
		Most	1.07 (1.00, 1.15)	1.05 (0.99, 1.12)	0.97 (0.89, 1.06)	
99%	All-cause	Less	1.05 (1.02, 1.08)	1.07 (1.04, 1.11)	1.03 (0.98, 1.08)	0.001
		Most	1.17 (1.12, 1.22)	1.06 (1.02, 1.09)	0.91 (0.86, 0.96)	
	Cardiovascular	Less	1.09 (1.04, 1.16)	1.09 (1.02, 1.17)	1.00 (0.92, 1.10)	0.381
		Most	1.23 (1.14, 1.34)	1.14 (1.07, 1.22)	0.94 (0.85, 1.05)	
	Respiratory	Less	0.99 (0.93, 1.07)	1.15 (1.06, 1.25)	1.15 (1.03, 1.29)	0.043
		Most	1.17 (1.05, 1.30)	1.13 (1.03, 1.23)	0.94 (0.82, 1.09)	

[a]The 95th and 99th percentiles of daily mean temperature during May–September were defined using prefecture-specific temperature distributions (Table S1). Cumulative relative risks (RRs[b]) and ratio of relative risks (RRRs[c]) for mortality associated with heat compared with the 50th percentile of temperature during May–September were estimated by a distributed lag nonlinear model over 0–10 lag days, adjusted for day of week or holiday, date, and day in season (natural cubic spline with 4 df/y) $\times$ year. The periods for before and after correspond to 2008–2010 and 2011–2012, respectively. A fixed effect meta-analysis was used to combine the prefecture-specific RRs or RRRs in less affected and most affected areas with a range of I^2 statistics, 0.0–33.9%, suggesting no evidence of heterogeneity (all of $p < 0.05$ by test for heterogeneity). The most affected prefectures are the 15 prefectures that reduced electricity consumption by $>10\%$ following the earthquake (reported by electric power companies; Table S1) and the less affected prefectures are the remaining 32 prefectures, specifically listed in Figure 2. [d]Random effects meta-regression was used to test the difference of RRs or RRRs between most affected and less affected areas.

heat at the 95th percentile of daily mean temperature = 0.95, 95% CI: 0.92, 0.99), while there was little change in heat-related mortality in the less affected prefectures. In the second analysis, daily heat-related mortality in Tokyo was not significantly modified by the percent reduction in observed vs. expected electricity consumption after the earthquake (relative to consumption on comparable days before the earthquake).

Air-Conditioning Prevalence and Heat-Related Mortality

Several studies conducted in the United States reported that heat-related mortality was lower in areas with high AC prevalence compared with other areas (Anderson and Bell 2009; Curriero et al. 2002; Medina-Ramón and Schwartz 2007; Ostro et al. 2010). In addition, studies from multiple countries have reported that communities with high income levels, which may be a proxy indicator of AC ownership or the extent of AC use, have lower heat-related morbidity and mortality than less affluent communities (Gronlund 2014; Hondula and Barnett 2014). Although a higher prevalence of AC may reduce heat-related mortality by reducing exposure to ambient heat, other factors may also reduce susceptibility to ambient heat, such as advances in medical care, housing technology, heat warning advisories, and other public health interventions (Bobb et al. 2014). Because increased power consumption as a consequence of increasing AC use could contribute to urban heat islands and greenhouse gas emissions that promote climate change (Lundgren and Kjellstrom 2013), it should be balanced to include those factors with AC use in adaptation planning for future climate change.

Reduced Electricity Consumption, Households vs. Business Sectors

Although summer electricity consumption declined after the earthquake because of reduced consumption by industry and commercial sectors as well as households, household consumption was substantially reduced. For example, compared with consumption during July–September 2010, temperature-adjusted electricity consumption during July–September 2011 was reduced by 11% and 18% among households in the TEPCO and Tohoku service areas, respectively, while it was by only 4% in the Kansai Electric Power Company area (around Osaka in western Japan) (Kimura and Nishio 2013). A survey of the households in the TEPCO service area reported that 30% achieved the government target of a 15% reduction in electricity use, and 17% achieved reductions of 25% or more (Murakoshi et al. 2012). The most common electricity conservation measures implemented by households during the summer of 2011 in the TEPCO service area involved behavioral changes, specifically, setting AC to higher temperatures and reducing the hours of AC use at night (reported by 69% and 66% of households, respectively) (Nishio and Ofuji 2012). In contrast, only 4% of households installed more energy-efficient AC units, which suggests that behavioral changes, rather than technological measures, were a primary reason for the reductions in household electricity consumption. Nishio and Ofuji (2012) reported that in the summer of 2011, the average daily duration of household AC use in the TEPCO service area decreased by 25% (to 6.4 h), while AC temperature settings were increased by 1.2°C (to 27.4°C), resulting in estimated reductions in electricity demand of 2.6% and 0.7%, respectively. Overall, the authors estimated that measures related to AC use accounted for approximately 40% of the total reduction in household electricity demand in the TEPCO service area (Nishio and Ofuji 2012). In addition, household summer electricity consumption was greater when the head of the household was in their 50s (10.6%) or 60s (10.5%) and lowest when the head of the household was in their 20s (3.5%) or 30s (5.9%) (Nishio and Ofuji 2012).

Factors Influencing Decreased Relative Risk of Heat-Associated Mortality

The apparent reduction in heat-related mortality after the earthquake (based on the ITS analysis) was unexpected and may indicate that factors other than electricity consumption and AC use played an important role. Increased awareness of how to prevent heat-related illness, which was promoted by public information campaigns implemented along with the energy-saving campaigns (Japanese Society of Biometeorology 2011), may have reduced the potential elevated risk of heat effects associated with reduced summer electricity consumption. These campaigns provided detailed information about how to avoid risks of heat in both business (e.g., wearing casual attire, shifting a working schedule, and gathering together at a cool place) and household (e.g., drinking enough water, wearing a hat when going out, and placing rattan/bamboo blinds and curtains on windows to reduce sunlight inside the house) settings. It is possible that the campaign increased awareness of methods to reduce risks associated with ambient heat, particularly in the most affected areas.

Evidence of a long-term decline in heat-related mortality has been reported for Japan (Gasparrini et al. 2015a), with the

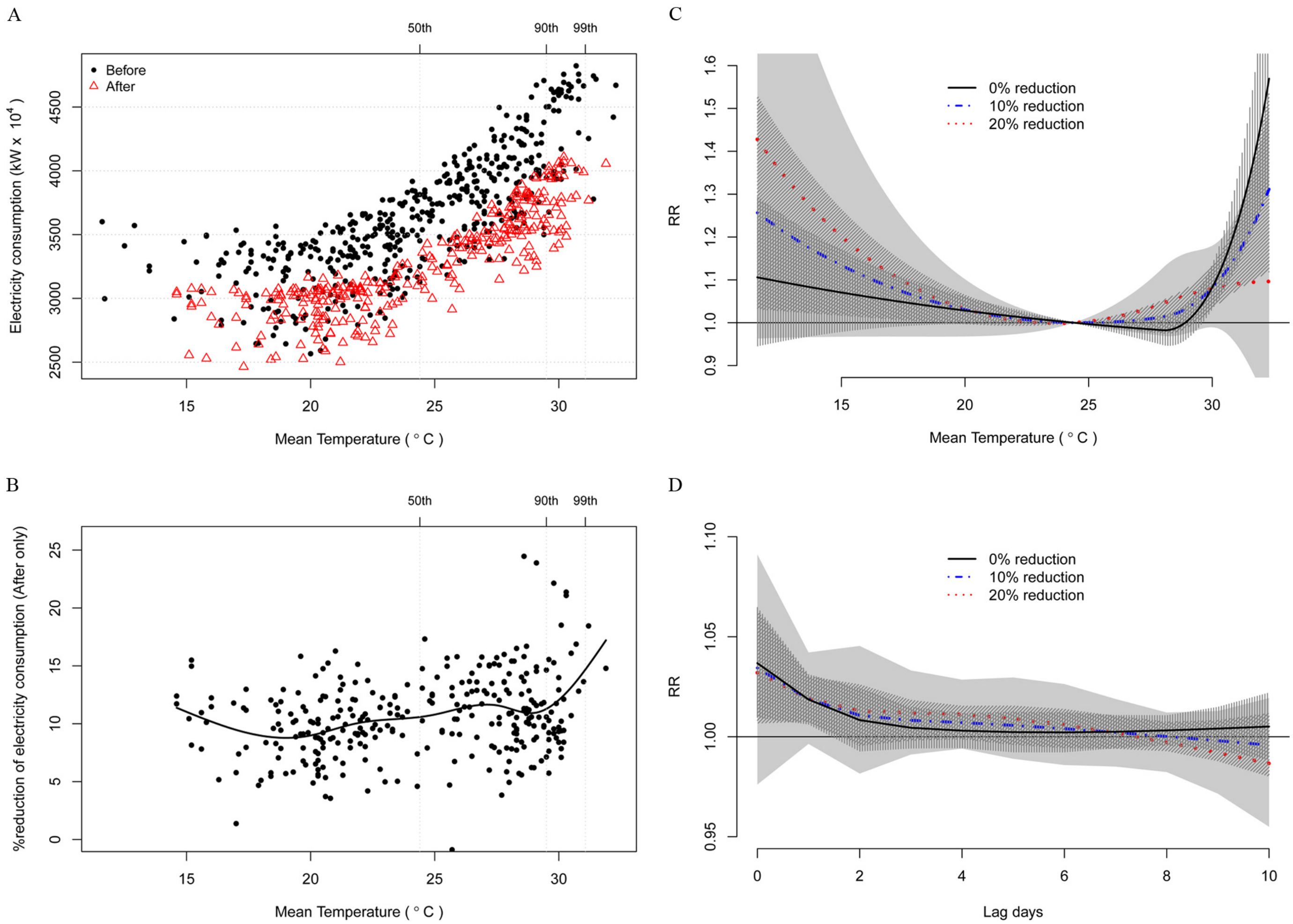

Figure 3. (*A*) Daily electricity consumption during May–September (warm seasons) before (2008–2010) and after (2011–2012) the great earthquake in the prefectures served by the Tokyo Electric Power Company (TEPCO), against daily mean temperature in Tokyo. (*B*) Percent reduction of (warm season) electricity consumption indicating the estimated percentage difference in observed vs. expected daily electricity consumption following the earthquake from the model adjusted for day of week or holiday, daily mean temperature, and day in season against daily mean temperature in Tokyo. The smoothing line was applied by a natural cubic spline with 6 degrees of freedom (df). The numbers at the top of the panels (*A*) and (*B*) indicate 50th (24.4°C), 90th (30.1°C), and 99th (31.1°C) percentiles of daily mean temperature during May–September in 2008–2012 in Tokyo. (*C*) Cumulative relative risks (RRs) for all-cause mortality associated with mean temperature in warm seasons compared with the 50th percentile of the temperatures over 0–10 lag days in Tokyo by the percent reduction in observed vs. expected electricity consumption in TEPCO service area. (*D*) Lag-response curves of the RRs for the 95th percentile of mean temperatures in warm seasons in Tokyo compared with the 50th percentile of the temperatures by the percent reduction in observed vs. expected electricity consumption in the TEPCO area. The gray areas in panels (*C*) and (*D*) indicate 95% confidence intervals (CIs) (for 0% reduction (vertical patterns), 10% reduction (diagonal patterns), and 20% reduction (filled in gray).

estimated mean RR for the 99th percentile of mean temperature compared with the minimum mortality percentile decreasing from 1.16 in 1993 to 1.06 in 2006 by DLNM (Gasparrini et al. 2015a). However, the nationwide long-term decline would be unlikely to fully explain the estimated large decline in heat-related mortality over the 5-y study period in the most affected prefectures.

Advantages and Limitations of the Study

To our knowledge, this is the first study to examine the impact of a large-scale power-saving policy on heat-related mortality. The unique situation after the Great East Japan Earthquake allowed us to evaluate the impact of reduced summer electricity consumption on heat-related mortality with a low likelihood of confounding by other factors that might contribute to temporal changes in this (e.g., adaptation to heat, urbanization, and social infrastructure such as healthcare and housing) because these factors would have changed little over the short study period.

Nonetheless, our study has several limitations. First, for our daily electricity consumption analysis, we used combined electricity consumption data from the household and industry sectors because separate electricity consumption data for households were not available. Although the industry/commercial sectors and households were both reported to have substantially reduced electricity consumption, complex changes in people's behavior in terms of electricity reduction made it difficult to determine which sector was more likely to have contributed to the measured effect of reduced electricity consumption on heat-related mortality. Our findings could be interpreted as the association between heat-related mortality and collective reduction of electricity use in all industry/commercial and household sectors in the society. Second, we used inconsistent geographical boundaries for the electricity consumption and mortality data in the daily electricity consumption analysis. The boundary of electricity consumption data served by TEPCO (Tokyo metropolitan area) surrounds and is larger than the area (Tokyo) to which the mortality data applies (Figure 1, Table S1). Also, although some spatial auto-

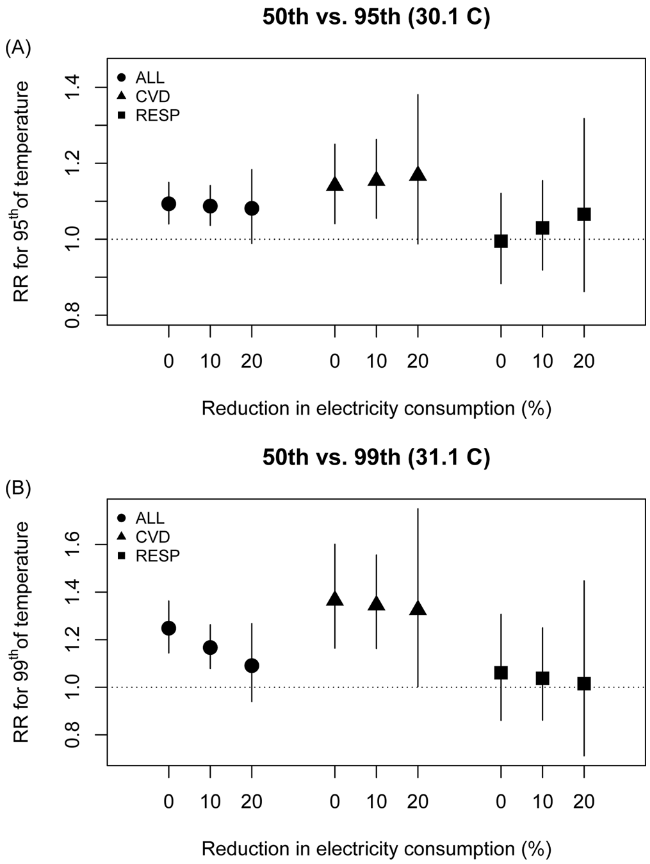

Figure 4. Cumulative relative risks for all-cause (ALL), cardiovascular (CVD), and respiratory (RESP) mortality for all ages associated with heat at the 95th (*A*) or 99th (*B*) percentiles of daily mean temperature during May–September in Tokyo (30.1°C or 31.1°C, respectively), compared with those for the 50th percentile of the temperature (24.4°C) over 0–10 lag days, stratified by the estimated percent reduction in electricity consumption (i.e., the difference between observed and expected consumption after the earthquake based on a model adjusted for temperature, day of week or holiday, and day in season using daily electricity consumption in the TEPCO service area that includes Tokyo).

correlation is possible, our meta-analysis assumed independence of prefecture-specific heat–mortality RRs or RRRs within the most affected and less affected prefecture groups.

We do not know if our findings are generalizable to other populations, including populations in different climates, populations with a lower prevalence of household AC, or populations with different housing or construction standards, demographic characteristics, cultural norms, or other characteristics that might influence susceptibility to ambient heat (Stafoggia et al. 2006). In Japan, the prevalence of AC-owning households is high (e.g., 93.0% in Tokyo in 2014) (Statistics Bureau 2014), suggesting that a large proportion of people in this study area would have easy access to and controlled use of AC. Further studies will be required to confirm our findings and clarify potential mechanisms for the apparent reduction in heat-related mortality following the great earthquake and determine whether our findings apply to other populations and settings.

Conclusions

Contrary to expectations, we did not find an increase in heat-related mortality following reductions in electricity consumption after the great earthquake in Japan. Instead, we found evidence of a decrease in heat-related all-cause mortality in the 15 prefectures that had the highest reductions in electricity use (>10%), though a second analysis of heat-related mortality in Tokyo did not indicate modification of the association by the magnitude of the reduction in daily electricity consumption (relative to expected consumption based on days before the earthquake). The reduced heat-related mortality following the earthquake may have been influenced by increased awareness of measures to prevent heat-related illnesses promoted by public information campaigns that provided detailed information on how to avoid risks of heat in both business and household settings. Our findings may not be generalizable to populations with a lower prevalence of AC. Future studies to evaluate effective compromises between electricity conservation and public health interventions are needed to understand how to limit the risks of heat-related morbidity and mortality as ambient temperatures increase with climate change.

Acknowledgments

We thank M. Ono for his valuable comments on the preliminary draft. This study was supported by the Environment Research and Technology Development Fund (S-10 and S-14) of the Ministry of the Environment, Japan, and by the School of Tropical Medicine and Global Health, Nagasaki University, Japan. A.G. was supported by the Medical Research Council, UK (Grant ID: MR/M022625/1 and G1002296). B.A. was supported by the National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Environmental Change. Y.K. was supported by the JSPS KAKENHI Grant Number JP16K19773, Japan.

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