Regional Features of the Relationship between Daily Heat-Stroke Mortality and Temperature in Different Climate Zones in Japan

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Abstract

Relationships between daily heat-stroke mortality and temperature were statistically analyzed using Vital Statistics data for 1999 to 2016, with attention to regional differences related to different climate zones. An analysis based on data categorized for each prefecture has revealed that the daily heat-stroke mortality depends not only on daily temperature but also on the summer mean temperature in a way that a prefecture in a cooler summer climate tends to show a higher mortality for a specified value of daily temperature, implying the effect of acclimatization. Additionally, daily heat-stroke mortality is found to be higher for cases of higher temperature on preceding few days to a week, apparently due to accumulated heat stress, but is lower for cases of higher temperature a few weeks ago, presumably due to acclimatization. As for relative humidity, the mortality on a day of higher humidity tends to be higher for a specified value of daily maximum temperature, but lower for a specified value of daily mean temperature. It is also shown that heat-stroke mortality tends to be high on a day of low wind speed and long sunshine hours.

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1. Introduction

Heat stroke is strongly related to air temperature. The relationship between daily temperature (maximum or mean) and ambulance transports due to heat stroke has been documented for Tokyo (Tamura et al. 1995), Tokyo and two Chinese cities (Ando et al. 1996), Tokyo and Chiba City (Hoshi et al. 2007), Yamanashi Prefecture (Akatsuka et al. 2016), and eleven cities in Japan (Japan Meteorological Agency 2018). Yokoyama and Fukuoaka (2006) examined heat-stroke transports for the Tokyo Metropolis and 41 cities in Japan for July to September in four years. These studies indicate an increase of heat-stroke transports with temperature, whereas the relationship between temperature and heat stroke is different according to regions. In some studies, heat stroke was found to occur at lower temperature in northern regions than in other regions (Yokoyama and Fukuoaka 2006; Japan Meteorological Agency 2018).

As for mortality, Hoshi et al. (2016) analyzed the dependence of heat-stroke mortality rate on Wet Bulb Globe Temperature (WBGT) in seven large cities in Japan over 13 years (1995−2007). They showed that heat-stroke mortality in two cities in northern Japan (Sapporo and Sendai) starts to increase at a lower temperature than in other five cities in the southern regions, implying lower tolerance of the dwellers in cooler climates to heat load. However, more detailed climatological features of heat-stroke mortality over the country including the dependence on regions, ages, and meteorological quantities other than temperature still remain unclear.

Fujibe et al. (2018; hereafter F18) examined the relationship between heat-stroke mortality and temperature over the country using the Vital Statistics data for 16 years (1999−2014). They categorized the data in prefecture and month, and showed that heat-stroke mortality was dependent on temperature in different ways according to age groups. They also showed a tendency of higher mortality in July than in August if the monthly mean temperature is equal, implying an effect of acclimatization to high temperature.

The aim of the present study is to find statistical relationships concerning the dependence of daily heat-stroke mortality on daily temperature and climatic mean temperature, from a viewpoint of their regional features. Analysis is also made on the dependence of mortality on humidity, wind speed and sunshine hours, which are believed to affect the occurrence of heat stroke.

2. Data and procedure of analysis

2.1 Heat-stroke mortality

Data of heat-stroke mortality were obtained from the Vital Statistics provided by the Ministry of Health, Labour and Welfare of Japan (MHLW) for 1999 to 2016, with the International Classification of Diseases (ICD) code X30. They are the same as those used by F18, who made a series of analysis using data reduced to annually and monthly values, except that the period is two years longer in the present study. The mortality of an age category k (in five-year intervals) in prefecture i and year n is defined by

\[ m_{kin} = d_{kin}/p_{kin}, \]

where \( m_{kin} \), \( d_{kin} \), and \( p_{kin} \) are mortality rate, number of deaths, and population, respectively. For an age group that spans over more than one age category, age adjustment was made on the basis of the population of the whole country in the 2015 National Census, in the same way as made by F18 who used the 2010 Census data. Figure 1 shows the map of Japan, with all 47 prefectures.

As shown by F18, more than 80% of heat-stroke deaths occur in July and August in Japan. The following analysis was made for the four months from June to September in order to capture the dependence of heat-stroke mortality on a wide range of daily temperature. According to the adjusted data, the daily mortality averaged over these four months for the whole country is 0.0037 × 10−2, which is denoted by \( M_0 \) in this article.

2.2 Surface air temperature

Analysis of surface air temperature was made using data of the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency (JMA). The data have a resolution of 0.1°C. In the same way as in F18, the “temperature of the prefecture” was defined as the average over stations in lower elevation (below 200m or the 60th percentile among stations) in order to represent the temperature in populated areas in each prefecture. The number of stations used for analysis is 629, which is smaller than 631 in F18 due to the difference in the analysis periods that affect data availability.

The temperature of each prefecture was used for two purposes. One is to give the climate of each prefecture, and the other is to give the daily heat load in the prefecture. For the former purpose, the average of daily maximum temperature in July and August for 1999 to 2016 was used. The maximum temperature is defined from hourly data, because continuous records (actually one-minute average temperature recorded every ten seconds) are available

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only for limited stations or periods, so that it is lower than that obtained from continuous records by about 0.4 K on the average (Fujibe 2004). However, this difference is not essential for the subsequent analysis. Hereafter it will be denoted by \( \delta T_{\text{max}} \). In the same way, \( \delta T_{\text{mean}} \) was defined by the average of daily mean temperature. For the latter purpose, the daily maximum and mean temperatures of each day, hereafter denoted by \( T_{\text{max}} \) and \( T_{\text{mean}} \), respectively, were used. It is to be noted that \( T_{\text{max}} \) and \( T_{\text{mean}} \) have different meanings from those in F18, who used \( T_{\text{max}} \) and \( T_{\text{mean}} \) in the meaning of \( \langle T_{\text{max}} \rangle \) and \( \langle T_{\text{mean}} \rangle \) in this article.

### 2.3 Other quantities

Among the 629 stations used for temperature analysis, relative humidity data were available at 137 stations that were classified as synoptic stations in the observational network of the JMA. The data of daily minimum humidity (\( H_{\text{min}} \)) based on continuous records with a resolution of 1% were used, and its value for each prefecture was defined in the same way as done for temperature. However, many synoptic stations are located in cities, so that relative humidity can have negative bias due to urban effects. The analysis was therefore based on the deviation from the average value defined as \( \delta H_{\text{min}} = H_{\text{min}} - \langle H_{\text{min}} \rangle \), where \( \langle H_{\text{min}} \rangle \) is the average of \( H_{\text{min}} \) for July to August from 1999 to 2016. For the sake of comparison, analysis based on daily mean humidity (\( H_{\text{mean}} \)) was made as well.

For surface wind speed, the AMeDAS data with a resolution of 1 m s\(^{-1}\) were used. On the basis of hourly data, the daily maximum wind speed (\( U_{\text{max}} \)) was defined. Since surface wind speed is sensitive to the anemometer height and environmental conditions, wind speed data at each station was normalized as \( U_{\text{max}}/\langle U_{\text{max}} \rangle \), where \( \langle U_{\text{max}} \rangle \) is the average of \( U_{\text{max}} \) for July to August from 1999 to 2016. Then the normalized wind speed for each prefecture was obtained by averaging over stations as done for temperature. Analysis using daily mean wind speed (\( U_{\text{mean}} \)) was also made by normalizing it as \( U_{\text{mean}}/\langle U_{\text{mean}} \rangle \), where \( \langle U_{\text{mean}} \rangle \) is defined in the same way as \( \langle U_{\text{max}} \rangle \).

For sunshine duration, AMeDAS data with a resolution of 0.1 hour were used and analyzed in a way similar to other quantities.

### 3. Regional difference in the relationship between daily heat-stroke mortality and temperature

For each prefecture, an average mortality in each 1°C range of \( T_{\text{max}} \) was calculated. Figure 2 shows the dependence of mortality on \( T_{\text{max}} \), for three prefectures of Aomori, Ibaraki, and Osaka, which are in a cool, middle, and hot climate zones in Honshu, as an example of the difference of heat-related mortality according to regional climate. Each graph has an approximately linear dependence on \( T_{\text{max}} \) with a logarithmic scale for mortality, indicating that mortality increases with \( T_{\text{max}} \) in an exponential way, whereas the three graphs are vertically apart from each other, indicating that mortality differs according to prefectures for a fixed value of \( T_{\text{max}} \).

In Fig. 3a, mortality in each prefecture for each of three \( T_{\text{max}} \) ranges of 30–31°C, 28–29°C, and 26–27°C is plotted with \( \langle T_{\text{max}} \rangle \) as the x-axis. It can be seen that mortality decreases with \( \langle T_{\text{max}} \rangle \). Thus mortality tends to be higher in prefectures in a cooler climate than in the middle and hot climate zones in Honshu.

The results described in Figs. 2 and 3a imply a linear dependence of the logarithm of mortality on \( \langle T_{\text{max}} \rangle \) and \( T_{\text{max}} \). In an attempt to quantify this dependence, a linear regression was applied with \( a, b, \) and \( c \) as least-squares coefficients in the form

\[
\log M_k = a \cdot \langle T_{\text{max}} \rangle + b \cdot T_{\text{max}} + c \rightarrow \min.,
\]

where \( M_k \) is the average mortality of prefecture \( k \) for the \( i \)-th

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No. | Prefecture | Population (× 10⁴) |
---|------------|--------------------|
1  | Hokkaido   | 5.382              |
2  | Aomori     | 1.208              |
3  | Iwate      | 1.280              |
4  | Miyagi     | 2.314              |
5  | Akita      | 1.025              |
6  | Yamagata   | 1.124              |
7  | Hokkaido   | 1.914              |
8  | Ibaraki    | 2.917              |
9  | Tochigi    | 1.074              |
10 | Gunma      | 1.073              |
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**Fig. 1.** Topography of East Asia, with shading for areas above 1,000 m from the mean sea level (upper left), and prefectures of Japan (center). The list of prefectures with their population in 2015 is shown on the right-hand side.

**Fig. 2.** Heat stroke mortality in each 1°C interval of daily maximum temperature (\( T_{\text{max}} \)) for three prefectures. The value of \( \langle T_{\text{max}} \rangle \) for each prefecture is shown in brackets.

**Fig. 3a.** Mortality in each prefecture for each of three \( T_{\text{max}} \) ranges of 30–31°C, 28–29°C, and 26–27°C is plotted with \( \langle T_{\text{max}} \rangle \) as the x-axis.
dependence of $T_{\text{max}}$ that was inversely proportional to the confidence range of each $T_{\text{max}}$ for prefecture $k$ was less than 10. The weight $w_k$ was assigned to be proportional to the population of prefecture $k$ in 2015, in order that a more populated prefecture could have a larger weight. The summation was made over the 45 prefectures other than Hokkaido and Okinawa, and for temperature intervals of 20–21°C and above. The reason for excluding Hokkaido and Okinawa is that the two prefectures have highly different climates from others, so the regression applied without them is expected to rather represent the features from Honshu to Kyushu. For comparison, however, the results of analysis including Hokkaido and Okinawa are shown in Supplement 1, together with the results of analysis in which invalid $M_k$ values were avoided by way of regional averaging.

Table 1 shows the number of valid data and the values of $a$ and $b$ obtained from the analysis for all the ages, ages less than 60, and ages of 80 years and over. The result for all ages indicates an increase of $\ln M$ by 0.40 for a 1°C increment of $T_{\text{max}}$ but a decrease of $-0.28$ for a 1°C increment of $(\text{of } T_{\text{max}})$. Thus the positive dependence of $M$ on $T_{\text{max}}$ is largely offset by a negative dependence on $(\text{of } T_{\text{max}})$. The situation is qualitatively similar for ages of $<60$ years old and $\geq 80$ years old, although the group of $\geq 80$ years old shows a stronger dependence of $M$ on $(\text{of } T_{\text{max}})$ than the group of $<60$ years old.

In addition to $T_{\text{max}}$ and $(\text{of } T_{\text{max}})$, heat-stroke mortality can depend on temperature on preceding days. In order to examine this dependence, an analysis was made on the relationship between the following two quantities. One is the ratio of the observed mortality $M$ and the calculated mortality $M_\text{c}$, which is based on observed temperature and the regression coefficients obtained from Eq.(1). The other is the difference of $M_\text{c}$ on the target day and the $n$-th preceding day, hereafter denoted by $\Delta T_{\text{max}}^{(n)}$. Figure 4 shows the dependence of $M/M_\text{c}$ on $\Delta T_{\text{max}}^{(n)}$ for $n = 1, 4, 7$ and 18. The analysis for Fig. 4 was made for cases in which $M_\text{c}$ was not smaller than $M_k$ (defined in 2.1). In the analysis, the value of $M/M_\text{c}$ for a 1°C interval of $\Delta T_{\text{max}}^{(n)}$ was obtained for each prefecture, and then the average value of $\ln(M/M_\text{c})$ over the 45 prefectures (except Hokkaido and Okinawa) was calculated with weights proportional to the population of the prefectures. The rate of change of $\ln(M/M_\text{c})$ with $\Delta T_{\text{max}}^{(n)}$ evaluated from linear regression, using a weight that was inversely proportional to the confidence range of each $\ln(M/M_\text{c})$ value, is also shown in Fig. 4 in brackets. It can be seen that $M/M_\text{c}$ increases with $\Delta T_{\text{max}}^{(n)}$, with a lower rate for a larger value of $n$. This fact indicates that heat-stroke mortality is positively related to temperature of previous few days to a week. For $n > 10$, $M/M_\text{c}$ does not have a significant correlation with $\Delta T_{\text{max}}^{(n)}$ (not shown). For $n > 15$, however, $M/M_\text{c}$ has a weak negative correlation with $\Delta T_{\text{max}}^{(n)}$ as seen from the case of $n = 18$. In other words, heat stroke mortality tends to be higher if temperature is lower a few weeks ago.

The main features of the results described so far are basically unchanged if daily mean temperature ($T_{\text{mean}}$) is used instead of $T_{\text{max}}$ as shown in Supplement 2. For the dependence of $M/M_\text{c}$ on relative humidity, however, there is a marked difference between the result of an analysis based on $T_{\text{max}}$ and that using $T_{\text{mean}}$. Figure 5a shows the average values of $M/M_\text{c}$ for each category of deviation in daily minimum humidity ($\delta H_\text{min}$; see 2.3) with a 5% interval. The two graphs in Fig. 5a correspond to an analysis based on $T_{\text{max}}$ and that using $T_{\text{mean}}$. The analysis based on $T_{\text{max}}$ shows an increase of $M/M_\text{c}$ with $\delta H_\text{min}$, indicating that heat-stroke mortality is higher on days of higher minimum humidity if $T_{\text{max}}$ is fixed. On the other hand, the analysis based on $T_{\text{mean}}$ shows a decrease of $\ln(M/M_\text{c})$ with $\delta H_\text{min}$. This indicates that heat-stroke mortality is higher on days of lower minimum humidity if $T_{\text{mean}}$ is given. The dependence on humidity deviation becomes less obvious if daily mean humidity ($H_\text{mean}$) is used instead of $H_\text{min}$, although the dependence of $\ln(M/M_\text{c})$ on $\delta H_\text{mean}$ is positive and negative according to analyses based on $T_{\text{max}}$ and $T_{\text{mean}}$, respectively (0.053 ± 0.067/5% and $-0.031 ± 0.074/5%)$.

Figure 5b shows the relationship between $M/M_\text{c}$ and normalized daily maximum wind speed ($U_{\text{mean}}/(U_{\text{max}})$) categorized with an interval of 0.2. For both the analyses based on $T_{\text{max}}$ and $T_{\text{mean}}$, $\ln(M/M_\text{c})$ tends to be lower for higher wind speed. A similar result was obtained if daily mean wind speed ($U_{\text{mean}}$) is used. The dependence of $\ln(M/M_\text{c})$ on $U_{\text{mean}}/(U_{\text{max}})$ is $-0.066 ± 0.053$ and $-0.139 ± 0.064$, respectively, for a 0.2 increment of $U_{\text{mean}}/(U_{\text{max}})$.

Figure 5c shows the relationship between $M/M_\text{c}$ and daily sunshine hours. For the analyses based on $T_{\text{max}}$, $\ln(M/M_\text{c})$ is slightly negative for moderate sunshine, while it increases for sunshine over 10 hours. For the analyses based on $T_{\text{mean}}$, $\ln(M/M_\text{c})$ increases monotonically with sunshine hours.

### 4. Discussion

The present study has revealed that heat-stroke mortality depends not only on the daily temperature but also on the seasonal mean temperature, namely the summer climate of the prefecture, implying that the threat of summer heat load is largely offset by acclimatization. The results are qualitatively in agreement with previous findings that heat stroke transports and mortality for a specified daily temperature tend to be larger and higher in regions where summer mean temperature is lower (Yokoyama and Fukushima 2006; Hoshi et al. 2016; Japan Meteorological Agency 2018).
Fig. 5. Relationship between M/M\text{c} and (a) \(\delta H_{\text{min}}\), (b) \(U_{\text{max}}/(U_{\text{min}})\), and (c) sunshine hours obtained from analyses based on daily maximum temperature (\(T_{\text{max}}\)) and daily mean temperature (\(T_{\text{mean}}\)). The rate of change of \(\ln(M/M\text{c})\) with each quantity is shown in brackets.

whereas our results have evaluated the dependence of mortality on daily and summer mean temperatures quantitatively.

Our analysis has revealed that low temperature of a few weeks ago tends to aggravate heat-stroke casualty. This fact also implies the effect of acclimatization to hotness, and agrees with the seasonal feature that heat-stroke mortality is higher in early summer than in late summer (F18). On a shorter time scale, however, the heat of preceding few days to a week aggravates heat-stroke casualty, in consistency with previous finding that heat-related mortality (not limited to heat stroke deaths) is positively related to hot days with a lag of a few to several days (Hajat et al. 2002; Luber and McGeehin 2008; Anderson and Bell 2009; Honda et al. 2014). Thus heat stroke mortality appears to be worsened by hotness persistent for a few to several days due to accumulated heat stress, although it is alleviated by hotness on a time scale of few weeks and more as a result of acclimatization.

Our analysis has also detected the effect of humidity on heat-stroke mortality. It is interesting, however, that the mortality on a day of higher humidity tends to be higher for a specified value of \(T_{\text{max}}\), but lower for a specified value of \(T_{\text{mean}}\). The latter feature, which is contradictory to the general understanding that high humidity will increase heat-related casualty (Luber and McGeehin 2008; Zhang et al. 2014), can be interpretable by lower daytime temperature on a wetter day for a specified daily mean temperature.

As for the effect of wind speed, the tendency of lower mortality on a day of higher wind speed implies a relieving effect of wind by reducing human heat load and enhancing ventilation in buildings. On the other hand, the high mortality on a day of long sunshine hours implies an aggravating effect of sunshine even for a fixed value of \(T_{\text{max}}\), although it is more evident for a fixed value of \(T_{\text{mean}}\) for which longer sunshine hours mean higher daytime temperature.

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Supplements

Supplement 1: Comparison of the results of regression analysis in Eq.(1) with different ways of application.

Supplement 2: Results of analysis based on daily mean temperature.

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