Determination of Optimum Daily Maximum Temperature Using Climate Data

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Abstract

Objective: The relation between daily maximum temperature and mortality rate has a V-shaped pattern; the mortality rate is lowest at a certain temperature, that is, optimum temperature (OT), and the mortality rate increases when the temperature becomes higher or lower than OT. OT is associated with climate, but the relation between OT and long-term average temperature, which is a frequently used index of climate, had an outlier (Okinawa) even in Japan alone. Our objective is to determine the best climate index for OT estimation.

Methods: We obtained death certificate data, meteorological data and population data for Japan from relevant government ministries. All the data obtained were from 1972 to 1995 except for Okinawa's mortality data (1973 to 1995). Using smoothing spline with the degree of freedom fixed to 6, we computed the OTs for 47 prefectures in Japan. These OTs were exhaustively compared with percentiles of daily maximum, average, and minimum temperatures, along with the long-term average temperature.

Results: Among the candidates of the best climate index, 80 and 85 percentiles of daily maximum temperatures (Tmax80 and Tmax85) showed the highest correlation coefficient with OT ($R > 0.9$, much higher than the R for the long-term average temperature, i.e., 0.63), and the regression models using Tmax80 and Tmax85 best regressed the OT, that is, the difference between the observed OT and the expected OT was smallest when Tmax80 or Tmax85 was used. Unlike previously used average of daily mean temperature, Tmax80 and Tmax85 made Okinawa a nonoutlier. This characteristic is desirable because Okinawa's being an outlier is due to its maritime climate and the capacity to accommodate a different type of climate may expand the applicability of OT estimation method to wider regions in the world. A direct comparison of OT with Tmax75 to Tmax90 revealed that the difference is smallest for the percentile between Tmax80 and Tmax85.

Conclusion: We considered that a daily maximum temperature between Tmax80 and Tmax85 is the best climate index for estimating OT in Japan.

Key words: global warming, climate, optimum daily maximum temperature, mortality, Japan

Introduction

Many reports have confirmed that daily temperature level (either average or maximum) and mortality rate have a V-shaped relation, that is, mortality rate is lowest at a certain

temperature (optimum temperature=OT) and it becomes higher when the temperature becomes higher or lower than OT (1–4). It is important to be able to estimate OT, because it is essential for estimating the future health impact of global warming, although we also need to know other characteristics, such as the extent to which mortality rate is higher than the mortality rate at OT when the temperature is higher than OT, or the extent of the contribution of “mortality displacement”; the contribution is reported to depend on population characteristics (5).

Curriero et al. (4) and our group (6) have demonstrated that the relation is associated with climate. However, nobody has ever succeeded in finding the climate index that best

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Fig. 1 Relation between long-term average temperature and optimum temperature (OT).

estimates OT. For example, Patz et al. (7) stated that OT is closely associated with mean temperature. However, even in Japan alone, the OT-mean temperature relation has an outlier (Fig. 1). In this paper, we report the optimum climate index that best predicts the OT level in Japan.

Methods

Materials

All the data obtained were from 1972 to 1995, except for Okinawa's mortality data, which were from 1973 to 1995. Death certificate data including the date of death and date of birth from 1972 to 1995 were obtained from the Ministry of Health and Welfare with special permission. The corresponding meteorological data were obtained from Japan Meteorological Agency. Population data were obtained from the office of the Prime Minister.

Basic measures

There are 47 prefectures in Japan from Hokkaido to Okinawa. For each prefecture, we computed daily mortality rate using the person-time method (8). Briefly, mortality rate was defined as the number of deaths on a certain day divided by the product of 1 day and midyear population (For convenience, the rates were multiplied by 100 000 000). Unlike our previous studies (2, 6), we did not stratify the population by age or sex, because the results of this study will be used in global models that include many developing countries. In most developing countries, it is impossible to obtain age-specific mortality rates. Fortunately, however, the V-shaped relation pattern is mainly determined by the older population (1, 2 for example), and including the younger population may not change the OT level substantially.

As an exposure variable, we used the daily maximum temperature of the capital city of a prefecture. When the data for a capital city was not available, we used the data for the closest city.

As the candidates of the best climate index, we examined quantiles of the daily minimum, average, and maximum temperatures of the capital city (or the city with available data

Fig. 2 Two smoothing spline curves for Iwate prefecture. (a) Degree of freedom (df)=6; (b) Df is computed using a generalized cross-validation (GCV) method (df=26.0).

Fig. 3 Comparison of optimum daily maximum temperature (OT) levels obtained using two different degrees of freedom, namely, 6 and 10.

closest to the capital city) of each prefecture, along with the long-term average temperature.

Statistical methods

First, we examined the distribution of the basic measures described above using boxplots (In all the boxplots in this paper, a thick midline in a box indicates median, both sides of the box indicates lower and upper quartiles, and each whisker indicates 1.5 times the interquartile range or the maximum value, whichever is smaller.). After observing the distributions of mortality data, we examined the impact of the marked outlier (due to Hanshin-Awaji earthquake disaster in 1995) by comparing the situations with and without the outliers.

For obtaining OTs, we first calculated smoothing spline curves with degrees of freedom determined using generalized cross-validation (GCV) (9) to obtain OTs for the prefectures. GCV, however, yielded very large degrees of freedom for some

prefectures, and resulted in two or more minimal points that were close to each other. For the relation between temperature and mortality rate, however, there should only be one minimum point, that is, an OT. Thus, after we examined the spline curves that were computed with some fixed degrees of freedom, we decided to fix the degree of freedom to six. The reason for selecting a rather low degree of freedom is that GCV has a tendency of “undersmoothing,” particularly in cases of small sample sizes (9). The right panel of Fig. 2 shows a typical problematic example of GCV undersmoothing as an example. Detailed analysis on this issue can be found in another report (10). As shown in Fig. 3, the OT level did not substantially fluctuate when we changed the degree of freedom from 6 to 10. Thus, even when a different degree of freedom, such as 8 or 10, is selected, the difference in the results may be small.

Next, we compared the OTs with the quantiles of daily minimum, average, and maximum temperatures for the 47 prefectures, along with the long-term average temperature. In comparing with the indices, we first observed correlation coefficients. We then computed the difference between the observed OT and the expected OT; the expected OT was based on a linear regression line that predicted the OT using a percentile of daily maximum temperature. For comparison, we also obtained the expected OT using the long-term average temperature. In regressing the OT using the long-term average temperature, we did two calculations, that is, with and without Okinawa, since Okinawa was an outlier, as shown in Fig. 1. Then, we predicted

all 47 prefectures using both “with” and “without” Okinawa models. On the basis of the low values of the correlation coefficients shown below, we decided not to use daily minimum and average temperatures as the predictors for OT.

For some indices that had high correlation coefficients with the OT, we computed differences between the values of OT and those of the indices, to examine the ability of the indices to directly predict the OT.

We used R 2.5.0 (11) for all the analyses.

Results

Figure 4 shows the boxplots of the daily minimum, average, and maximum temperatures. Basically, a smaller prefecture number indicates a higher latitude, that is, cold climate. Prefecture 20 (Nagano) is an exception; it is cooler than what the prefecture number indicates, because its altitude is high. It is obvious that prefecture 47, Okinawa, has quite different distributions from other prefectures: Okinawa’s median values of daily minimum and average temperatures were higher than the upper quartiles of most of the other prefectures, and Okinawa’s lower quartile values of daily minimum and average temperatures were higher than the median values of most of the other prefectures. As for daily maximum temperature, Okinawa’s highest value was lower than those of many other prefectures, whereas Okinawa’s lowest value was much higher than those of the other prefectures. Except for Okinawa, all the prefectures

Fig. 4 Distribution of daily minimum, average, and maximum temperatures for 47 prefectures (1972–1995).

Fig. 5 Distribution of daily number of deaths (right panel) and mortality rate (left panel) for 47 prefectures. Mortality rate was multiplied with 100 000 000 for convenience.

Fig. 6 Figure 5 was rescaled such that the differences among the prefectures other than Hyogo prefecture can easily be evaluated.

have the range from sub-zero minimum temperature and over-thirty maximum temperature, regardless of the latitude.

Figure 5 shows the boxplots of the daily number of deaths and the mortality rate for each prefecture. Prefecture 28 (Hyogo) had a prominent outlier in each of the panel. We re-scaled Fig. 5 such that the differences among the other prefectures were expanded, and showed it as Fig. 6. On the left panel, the prefectures 13, 14, 23, 28, 29, and 40 showed large number of deaths, whereas on the right panel, the pattern was opposite; these prefectures showed lower mortality rates.

As described in the Methods section, we examined the impact of the earthquake disaster on the OT calculation. Figure 7 shows the spline curve with and without the outlier due to the earthquake. Because the earthquake occurred in January, the low temperature area was affected, but the OT (and the mortality rate at OT) was almost identical. Since the outlier due to the effect of the earthquake disaster appeared negligible in calculating OT, we decided to use Hyogo data as these were.

Table 1 shows the correlation coefficients between OT and the quantiles of daily minimum, average, and maximum temperatures. Although the correlation coefficients were significant at the 0.0001 level in most of the cases, the percentiles of daily minimum and average temperatures showed low correlation coefficients. Only from 50 to 90 percentiles of daily maximum temperature (Tmax50 to Tmax90) showed a correlation coefficient greater than 0.85. Unlike these higher percentiles of daily maximum temperature, the long-term average temperature had a much lower correlation coefficient, that is, 0.63.

Figure 8 shows the distribution of the difference between the observed and expected values of OT when the long-term average temperature was used as a predictor. The range of the difference was larger than 5°C even when Okinawa was included in the regression model.

Figure 9 shows the distribution of the difference between the observed and expected values of OT when the percentiles of

daily maximum temperature were used as predictors. Tmax80 and Tmax85 had the narrowest range, that is, <3.6°C. Even Tmax20 had a narrower range than the long-term average temperature.

Figure 10 shows the relation of OT with 80 and 85 percentiles of the daily maximum temperature (Tmax80 and

Table 1 Correlation coefficient between optimum temperature (OT) and quantiles of daily minimum, average, and maximum temperatures and long-term average temperature

Percentile	Daily minimum temperature	Daily average temperature	Daily maximum temperature
0	0.57	0.51	0.57
5	0.55	0.65	0.71
10	0.55	0.66	0.72
15	0.55	0.66	0.74
20	0.57	0.67	0.75
25	0.58	0.68	0.77
30	0.60	0.69	0.78
35	0.61	0.70	0.80
40	0.62	0.71	0.81
45	0.63	0.73	0.83
50	0.64	0.75	0.85
55	0.66	0.76	0.87
60	0.67	0.77	0.89
65	0.68	0.78	0.89
70	0.71	0.79	0.90
75	0.74	0.81	0.91
80	0.77	0.82	0.91
85	0.78	0.83	0.91
90	0.76	0.83	0.89
95	0.73	0.82	0.83
100	0.52	0.39	0.35

Long-term average temperature: 0.63

Note: All the p-values for the above correlation coefficients, including that for the long-term average temperature, were less than 0.0001, except for the following: 0.0002 for Tmin100, 0.0003 for Tave000, 0.0064 for Tave100, and 0.0168 for Tmax100.

Fig. 7 Spline curves of relation between daily maximum temperature and mortality rate, with (solid line) and without (dotted line) outlier, that is, the earthquake-related extremely high mortality.

Fig. 8 Observed and expected OTs. The expected OT was based on the regression lines that regress OT using long-term average temperature, with and without Okinawa.

Fig. 9 Observed and expected OTs. The expected OT was based on the regression lines that regress OT using the quantiles of daily maximum temperature.

Tmax85) for the 47 prefectures. Unlike in Fig. 1, there was no prominent outlier. The dotted lines show the lines where $OT = Tmax80$ and $OT = Tmax85$. The solid lines are the regression lines expressed as $OT = 0.88 \cdot Tmax80 + 4.1$ for Tmax80 and $OT = 0.89 \cdot Tmax85 + 2.4$ for Tmax85.

On the basis of the close relation of Tmax80 and Tmax85 to OT, we examined the distribution of the difference between OT and some selected percentiles of daily maximum temperature (Fig. 11). The median values of the differences for Tmax80 and Tmax85 were close to zero (-0.81 and 0.67 , respectively), and the differences between the lower and upper quartiles for Tmax80 and Tmax85 were 1.75 and 1.30 , respectively. The median values of the differences for Tmax75 and Tmax90 were more than $2^\circ C$.

Discussion

Basic measures

As shown in Fig. 4, Okinawa had temperature distributions quite different from the other prefectures; Okinawa has a maritime climate. This different climatic characteristic may have made Okinawa an outlier in Fig. 1. In this sense, it is desirable for the climate index for OT prediction to be able to make Okinawa a nonoutlier.

The prefectures with a larger number of deaths were those with mega cities, such as Tokyo (#13), Yokohama (#14), Nagoya (#23), Osaka (#27), Kobe (#28), and Kitakyushu (#40). The mortality rates for these prefectures were relatively low, because these prefectures' proportion of older subjects was low (data not shown).

Best predictor

The results of both correlation analysis and the evaluation of the observed-expected difference showed that the previously used long-term average temperature is not a good index for predicting OT; the correlation coefficient was 0.63 , and the

Fig. 10 Relation between 80 and 85 percentiles of daily maximum temperature (Tmax80 and Tmax85) and optimum temperature. The solid lines are regression lines and the dotted lines are the lines with equal abscissas and ordinates.

Fig. 11 Difference between OT and selected percentiles of daily maximum temperature, that is, Tmax75 to Tmax90.

observed-expected difference was larger than 5°C. The percentiles of daily minimum and average temperatures were not good, either. Instead, the higher percentiles of daily maximum temperature showed a good correlation, as shown in Table 1. Among them, Tmax80 and Tmax85 had the narrowest range of difference between the observed OT and the predicted OT (<3.6°C). Also, as shown in Fig. 10, both Tmax80 and Tmax85 made Okinawa a nonoutlier. This characteristic suggests that we can accommodate areas with maritime climate using Tmax80 and Tmax85 in predicting OT. With these reasons, Tmax80 and Tmax85 can be regarded as superior to long-term average temperature.

As for the ability for direct prediction, Tmax85 may be slightly better than Tmax80 from Fig. 11. However, these two indices had some offsets; the best index with the offset being closest to zero appeared to be between Tmax80 and Tmax85. This offset may be dependent on how we compute the OT: Figure 3 showed a very high correlation, but it also showed that there is an offset; OT with df=10 is slightly higher than OT with df=6. This suggests that the best index for the OT with df=10 may be the higher percentile of daily maximum temperature than that for the OT with df=6. Actually, when we used GCV in determining the degree of freedom, Tmax85 had a much smaller offset than Tmax80 or Tmax90 (data not shown). We need to explore other areas in the world to determine which, among the higher percentiles of daily maximum temperature, has the smallest offset.

Our group used Tmax85 to predict OT in estimating the impact of global warming, assuming that the relation is applicable to all the countries in the world (12). This estimation is the first step for more sophisticated estimations; we need to obtain a risk estimate for daily maximum temperature that is higher than OT and we need to further investigate the effect of mortality displacement.

Comparison with other studies

Curriero et al. (4) reported that the “minimum mortality temperature,” which corresponds to OT in this study, is associated with latitude; however, they did not show any statistical test results. Latitude is not a good climate index from other viewpoints either: not only latitude, but also altitude affects the climate; there are areas with identical latitude and altitude whose climates are different.

Keatinge et al. (13) attempted to assess heat-related mortalities in relation to climate within Europe. They used “3°C band of minimum mortality” for elderly (65–74 years of age), which corresponds to our OT, and examined the relation with summer (May to August) mean temperature. The P-value for the relation between mean summer temperature and 3°C band of minimum mortality was 0.027, and the largest difference between the mean summer temperature and the closer side of the 3°C band was 2.4°C (in London). The index used here, summer mean temperature, may be closer to higher percentiles of daily maximum temperature than to long-term average temperature, because both higher percentiles of daily maximum temperature and summer mean temperature are much higher than annual mean temperature.

These two reports showed the quantitative relation of OT

with climate factor, but their primary intention was not to predict OT with the climate factor, and there was no evaluation of the predicting ability. Note that, in Keatinge et al.’s report (13), “number of days per year warmer than upper limit of minimum mortality band” was shown for 7 cities. The average of the number of days was 38.3 days, which is about 10% of the year. Although they used daily average temperature, daily average temperature and daily maximum temperature have a good correlation coefficient, and this upper limit of the minimum mortality band is considered to be close to Tmax90, that is, the midpoint of the minimum mortality band would be around Tmax85 (the average difference between Tmax90 and Tmax85 was 1.7°C in Japan). If this speculation is correct, our finding would also be applicable to Europe, although further analysis is necessary to determine whether Tmax85 (or Tmax80) can be used to predict OT better than mean summer temperature in Europe.

Adaptation to climate

Although the regression line is not exactly $OT = Tmax85$ or $OT = Tmax80$, it is obvious that the adaptation to climate is not targeted to long-term average temperature, but it appeared that it is targeted to a certain higher percentile of daily maximum temperature (Tmax80–Tmax85 in Japan). This phenomenon is supported by the above report: Keatinge et al. (13) stated that “Populations in Europe have adjusted successfully to mean summer temperatures.” This can be a clue for understanding the mechanism of adaptation to climate. Also, since a warming trend has been observed, we may be able to evaluate how fast we adapt to the changing climate, by evaluating the changing climate index and OT.

Limitations

The limitation of this study is that this study is restricted to Japan. Although Japan covers a wide range of climate, from subtropical to subfrigid zones, differences in ethnicity and culture may alter the relation between temperature and mortality rate. Another problem is the applicability of this study to developing countries, aside from the ethnicity and cultural difference problems. We used a nonstratified all-cause mortality rate, because this is the only type of data available for developing countries. However, mortality rates for younger age groups in developing countries may be much higher than those for younger age groups in developed countries, and the OT level for older age groups may not be similar to that for all ages combined. We are now in the process of ascertaining whether the other regions have a similar relation. The results will be reported in separate articles. In addition to the problem of the applicability of this study to developing countries as mentioned above, many developing countries are located in the tropical zone, and the response to heat stress may be different from the response in midlatitude countries.

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