

Evaluation of some indices for urban heat stress found in the regional scale of Western Japan

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1. Introduction

In Japan, a high heat stress often causes a human heat disorder in summer. Although the Japanese public organizations and related associations recommend a use of the wet-bulb globe temperature (WBGT) index (Yaglou and Minard, 1957) to prevent human heat disorders, this index is difficult to be measured by ourselves and observation sites are very few in Japanese urban regions. Hence, other simple index is better to evaluate or predict the heat disorder risk in urban area. This concept is probably common in urban region worldwide. In the present study, simple indices of urban heat stress were compared with each other whether those can be applied as a heat hazard indicator for some large urban regions in western Japan.

2. Study regions and used index

Big urban cities (Osaka, Kyoto, Kobe, Okayama, Hiroshima, Fukuoka, and Kumamoto) in western Japan were chosen to compare the air temperature, the modified discomfort index (MDI; Moran et al., 1998), and the environmental stress index (ESI; Moran et al., 2001). The MDI can be calculated by the air temperature and relative humidity, while the ESI can be calculated by those and the solar radiation:

$$MDI = 0.3 T_a + 0.75 T_w \quad (1)$$

and

$$ESI = 0.63 T_a - 0.03 RH + 0.002 SR + 0.0054 T_a RH - 0.073 (0.1 + SR)^{-1}. \quad (2)$$

Here, T_a is a dry-bulb temperature ($^{\circ}C$), T_w is a wet-bulb temperature ($^{\circ}C$), RH is a relative humidity (%), and SR is a global solar radiation (W/m^2). In particular, the ESI has shown good responses to human physiological parameters (Moran et al., 2003). In the present study, their index values were analyzed for 50 days of extremely hot (heat wave) period in the 2013 summer season, using the meteorological hourly data (temperature, humidity, and pressure) provided by the Japan Meteorological Agency.

Locations of the aforementioned cities are plotted in Fig. 1. In the study, seven cities in western Japan were chosen as big urban cities (with population of about 0.7-2.6 million) which are the ordinance-designated city. Consecutive meteorological data measured by the Japan Meteorological Agency were used for analysis of the hourly air temperature, MDI, and ESI in each city. The hourly WBGT data are measured by the Japanese Ministry of Environment in Osaka, Hiroshima, and Fukuoka City of western Japan. As extremely hot (heat wave) days, an analysis period was chosen between July 5 and August 23 in 2013.

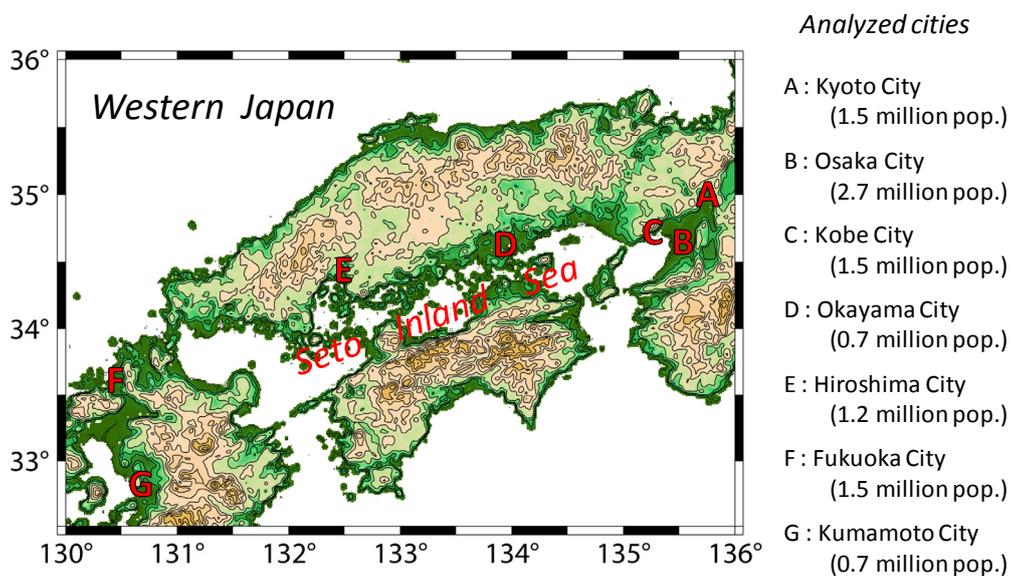


Fig. 1 Locations of analyzed cities in the present study.

3. Alternative indices to WBGT

Moran et al. (1998) and (2001) indicated that the MDI and ESI indices can be alternative to the WBGT index in several countries. Figure 2 shows the MDI and ESI biases against the WBGT value in Osaka City. The WBGT index can be estimated from the following equation:

$$\text{WBGT} = 0.1 T_a + 0.7 T_w + 0.2 T_g. \quad (3)$$

Here, T_g is the globe temperature which is difficult to measure because of requirement of special measurement, a globe thermometer. In Japan, heat stress levels are categorized as “warning” for $\text{WBGT} < 25 \text{ }^\circ\text{C}$, “Alert” for $25 \text{ }^\circ\text{C} \leq \text{WBGT} < 28 \text{ }^\circ\text{C}$, “Severe alert” for $28 \text{ }^\circ\text{C} \leq \text{WBGT} < 31 \text{ }^\circ\text{C}$, and “Danger” for $\text{WBGT} \geq 31 \text{ }^\circ\text{C}$ (the Japanese Society of Biometeorology). The figure revealed that the ESI had a good correspondence with the WBGT as smaller variance than the MDI. However, the following relationship between the ESI and WBGT was produced in this study.

$$\text{ESI} = \text{WBGT} + 1. \quad (4)$$

The same result was also obtained from analysis of the Hiroshima and Fukuoka City data.

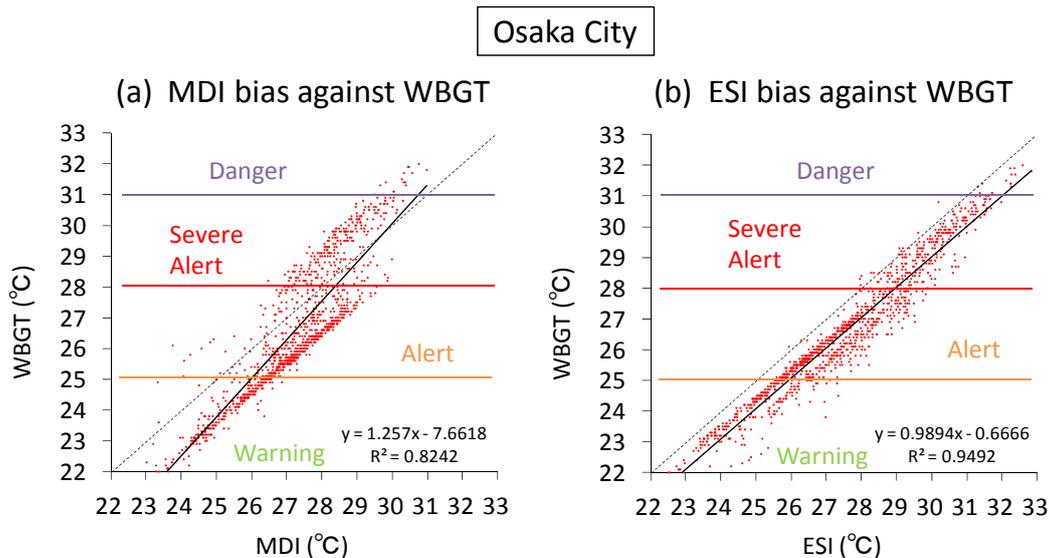


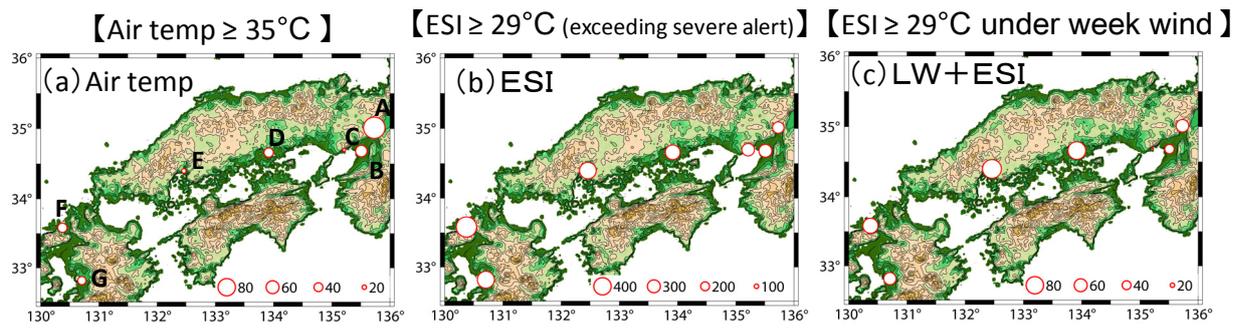
Fig. 2 Biases of MDI and ESI against WBGT in Osaka City. The hourly data was chosen from the period of July 5-August 23, 2013.

4. Regional difference in temperature and indices

Figure 3 indicates the distributions of the number of recorded hours in (a) high air temperature ($\geq 35 \text{ }^\circ\text{C}$), (b) exceeding severe alert level ($\text{ESI} \geq 29 \text{ }^\circ\text{C}$), and (c) exceeding severe alert level under weak wind condition ($\text{ESI} \geq 29 \text{ }^\circ\text{C}$ at less than 1.0 m/s). In many days, Osaka City (about 2.6 million population), which is the biggest urban region in western Japan, recorded very high air temperature of $35\text{-}37 \text{ }^\circ\text{C}$ during daytime. Kyoto City is located inland from the coastal Osaka City and also encountered most frequently the high temperature condition (Osaka and Kyoto are 53 and 98 hr, respectively). Because Kyoto is located at an inland basin and low altitude, the air temperature is easy to be exposed to extremely high conditions. On the other hand, the ESI calculated in Osaka and Kyoto City were lower than those in other cities for many days. These were attributed to the urban dryer atmosphere (lower specific humidity) in Osaka and inland dryer atmosphere in Kyoto. Conversely, the ESI in west regions of western Japan tended to be higher than those in Osaka and Kyoto City; high ESI conditions exceeding severe alert level were observed for 466 hr and 387 hr in Fukuoka and Kumamoto City, respectively. Figures 3a and b revealed that the high air temperature appeared for longer hours towards east regions while high heat stress appeared for longer hours towards west regions.

However, the ESI does not consider wind conditions which affect human heat stress. Weaker wind and higher ESI urban regions will suffer from a higher risk of heat disorder. The number of hours in the $\text{ESI} \geq 29 \text{ }^\circ\text{C}$ at less than 1.0 m/s (Fig. 3c) increased in Okayama and Hiroshima City which are located at the center region of western Japan rather than the eastern (Kyoto and Osaka) and western (Fukuoka and Kumamoto) regions; this high heat stress conditions were recorded as 86 hr and 81 hr in Hiroshima and Okayama City, respectively, which corresponded to be almost twice as frequent as hours in Osaka City. On the central sea called as the Seto Inland Sea (see Fig. 1), daytime sea breezes tend to be weaker than other open seas, and clear calm conditions frequently appear at the stage of land and sea breeze changes. This is the reason why high heat stress hours were found in Okayama and Hiroshima City.

High risk condition of Heat disorder



The size of circle : the number of record (hr)

<p>A. Kyoto City 98hr</p> <p>B. Osaka City 53hr</p> <p>F. Fukuoka City 43hr</p> <p>D. Okayama City 42hr</p> <p>G. Kumamoto City 38hr</p> <p>E. Hiroshima City 20hr</p> <p>C. Kobe City 13hr</p>	<p>F. 466hr</p> <p>G. 387hr</p> <p>E. 379hr</p> <p>D. 336hr</p> <p>C. 292hr</p> <p>A. 263hr</p>	<p>E. 86hr</p> <p>D. 81hr</p> <p>F. 69hr</p> <p>G. 56hr</p> <p>A. 58hr</p> <p>B. 42hr</p> <p>C. 7hr</p>
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Fig. 3 Hourly frequency distributions of (a) high air temperature ($\geq 35\text{ }^\circ\text{C}$), (b) exceeding severe alert level ($\text{ESI} \geq 29\text{ }^\circ\text{C}$), and (c) exceeding severe alert level under weak wind condition ($\text{ESI} \geq 29\text{ }^\circ\text{C}$ at less than 1.0 m/s). The hourly data was chosen from the period of July 5-August 23, 2013.

5. Heat disorder risk

The usefulness of the aforementioned temperature and indices as a heat disorder risk was evaluated using daily heat disorder patients transported by ambulance. The transported patient data were referred from the 2013 report of the National Institute for Environmental Studies (<http://www.nies.go.jp/health/HeatStroke/spot/2013/index.html>). For example, relationships between heat disorder incidence and daily maximum air temperature, WBGT, and ESI in Osaka City are shown in Fig. 4. Here, the heat disorder incidence represents the number of heat disorder patients transported by ambulance per 100,000 population. The results revealed that the daily maximum temperature demonstrated a heat disorder risk (i.e., increase of heat disorder patients) with the best fitted linear (Fig. 4a). Its regression line indicated the increase of patients when exceeding 32-33 °C in the daily maximum temperature. However, both WBGT and ESI more scattered for heat disorder risk. In particular, the danger level days (enclosed by square) presented a large difference in heat disorder incidence among days for the WBGT and ESI. This result reveals that the heat disorder incidence (i.e., heat disorder risk) in whole urban scale (e.g., city) can be better explained by daily maximum temperature than heat stress indices such as WBGT, MDI, and ESI. Day-to-day air temperature strongly affects day-to-day human heat stress from which all people suffers.

Because heat stress indices include other meteorological parameters such as humidity and radiation, those parameters are probably affected by the local environment. For instance, the heterogeneity of solar radiation is remarkable on urban canyon and will induce a larger difference in heat index values by location. Therefore, heat stress indices should be generally used for human active places (local places).

6. Summary

Alternative heat stress indices to the WBGT index were discussed for the Japanese hot environment. The WBGT is often used for evaluating a heat disorder risk during the Japanese summer season. The result showed that the ESI can be applied as a heat stress index, which is easily calculated from meteorological parameters observed at the JMA and AMeDAS stations. In this study, a relationship equation of $\text{ESI} = \text{WBGT} + 1\text{ }^\circ\text{C}$ was obtained.

Next, regional differences in heat stress were examined using the ESI and compared with those in high air temperature. It was analyzed for seven big cities in western Japan: Kyoto, Osaka, Kobe, Okayama, Hiroshima, Fukuoka, and Kumamoto City located at low altitude plains. While high temperature conditions were found towards east regions (Kyoto and Osaka City), high heat stress conditions were found towards west regions (Fukuoka and Kumamoto City). However, if a limitation of weak wind were added to high heat stress conditions

(the high ESI), a high risk of heat disorder appeared on plains in the central Seto Inland Sea (Okayama and Hiroshima City). This result was attributed with weaker sea breezes and longer calm hours than other regions.

Finally, the analysis of relationship between the indices and heat disorder incidence suggested that the daily maximum temperature was sufficiently available for prediction of the outdoor heat disorder risk in a whole city scale.

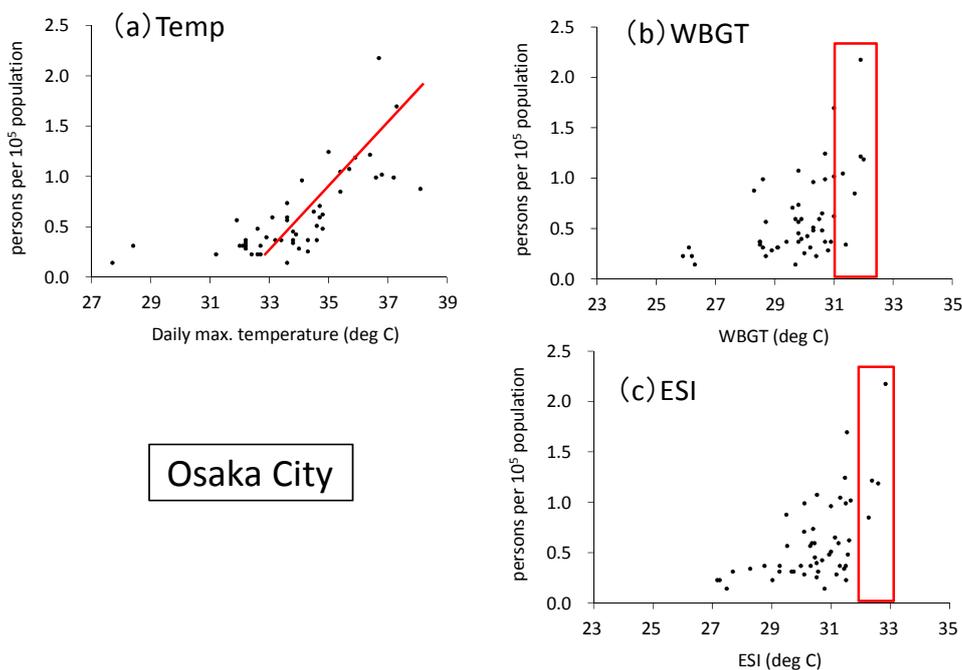


Fig. 4 Relationships between heat disorder incidence and daily maximum (a) air temperature, (b) WBGT, and (c) ESI in Osaka City. The daily data was chosen from the period of July 5-August 23, 2013.

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