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Time Variation of Thermal Environment in Seoul and Daegu during the Heat Wave in 2018

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ABSTRACT

In this study, a comparison of characteristics of temporal changes in temperature, discomfort index (DI), and wet bulb globe temperature (WBGT) between Seoul and Daegu during the 2018 heat wave was conducted. Both Seoul and Daegu showed high temperatures exceeding the heat wave warning level (33°C) from 11:00 to 19:00. However, the time slot when the highest daily temperature was observed differed between the two regions; it was around 14:00 for Daegu and around 16:00 for Seoul. There was also a significant difference in the time slot when the WBGT value exceeded the severe warning level (28°C or higher) in the two regions; it was from 09:00 to 18:00 for Daegu and from 11:00 to 20:00 for Seoul. The time slot when the highest value was observed was 14:00 for Daegu and 15:00 for Seoul. These data indicate that the time slot when the thermal environment of the heatwave warning level was observed later in Seoul than in Daegu, but the duration in Seoul was longer than in Daegu. Likewise, the time-period when the highest level of the high-temperature thermal environment was observed was 2∼3 h later in Seoul than in Daegu. The DI value at which more than 80% of the people felt discomfort due to high temperatures was observed from 09:00 to 22:00 in both regions, while the highest DI value at which all people felt discomfort due to high temperatures was observed only in Seoul from 14:00 to 18:00. The difference in the thermal environment between the two regions is believed to be mainly because there is a substantially higher artificial structure density in Seoul than in Daegu; therefore, the urban heat capacity is much higher in Seoul than in Daegu.

Key words : Heat wave, Discomfort index, WBGT, Heat capacity

1. Introduction

Global warming and urbanization are the two main causes of heat waves, so heat waves can be alleviated only by reducing these two factors. The industrial revolution began as the energy required for human production activities was acquired from fossil fuels. Fossil fuels contributed to the increase in the population on earth from a mere 300 million at the beginning of the industrial revolution to 7.8 billion today. Fossil fuels have also brought affluent lifestyles to humanity, but the carbon dioxide generated in return has brought global warming, which aggravated heat waves [1-3].

Another cause of heat waves is urbanization. The effect of urban heat islands on the rising temperatures in the large cities is known to be much greater than that of global warming. The biggest culprit of urban heat islands is the disappearance of soil and green space as a result of the increase in asphalt roads and buildings. Artificial structures absorb and store more solar energy during the day, which is an increase in heat capacity. As the heat capacity increases, the surface and air temperatures in cit-

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ies are consistently higher than those in the suburbs [4].

The heat waves in Korea are also becoming far more severe due to climate change; in the summer of 2018, in particular, Korea experienced the most severe heat wave since 1973, when the national meteorological observation network was established. In the summer of 2018, both the highest and lowest daily temperatures were the highest and all-time highs were recorded in all heat wave indices, including the number of days with heat waves and tropical nights. According to the data released by the Korea Meteorological Administration in September 2018, there were 31.4 days nationwide that year when severe heat warnings were issued because the highest daytime temperature exceeded 33°C, exceeding the record set in 1994 (29.7 days), which was the highest since the start of weather observation. The number of days with tropical nights, which is defined as a day with a minimum daily temperature of 25°C or higher, was 17.7 days, which was also more than the record set in 1994 (17.4 days). The sunlight conditions, which greatly influence the bodily heat sensation index for people working outdoors, were also the highest levels in history. The daylight hours reached 695 hours, the longest ever, exceeding the record set in 1994 (680 hours). In addition, the so-called super-high temperature of 38°C or higher was more frequently observed. The highest daily temperature of 40°C or higher, which had previously been recorded only once in Daegu, in 1942, was also observed on August 1 at as many as five meteorological stations, including Hongcheon (41.0°C) in Gangwon-do. On August 14, when the summer's high temperatures have usually started to decline, the late heat wave of over 40°C continued in Uiseong, Gyeongbuk (40.3°C).

In this study, the temporal changes in the thermal environment during the period of continuous heat wave in 2018 were compared for Seoul and Daegu using the differences in the temporal changes not only in temperature but also in the discomfort index (DI) and the wet bulb global temperature (WBGT). Based on the results of the comparative analysis, this study aimed to characterize thermal environments of the two regions at each time point and identify the causes of regional variations.

2. Research Content and Methods

In this study, the differences in mean temperature, DI, and WBGT during the period in 2018 when severe heat warnings were consecutively issued in Seoul and Daegu (July 18∼August 8) were analyzed and the two regions compared. The meteorological data used were values measured by the Korea Meteorological Administration (Seoul) and Daegu Regional Meteorological Administration. Equation (1) was used to calculate the DI according to Nakamura and Kitamura [5]. The value calculated using this equation is known to be similar to the bodily heat sensation in Celsius. Table 1 shows the bodily heat sensation perceived by humans according to the DI value.

$$DI = T_d - 0.55 \times (1 - 0.01 \times RH) \times (T_d - 14.5) \quad (1)$$

Here, temperature T_d indicates the dry bulb temperature (°C) and RH indicates the relative humidity (%). In the present study, the DI was calculated using the temperature and humidity at each time point according to Equation (3). The DI follows the categories listed in Table 1.

The WBGT is an index proposed by Yaglou and Minard [6] for the purpose of defining limits for military training under high-temperature conditions. Currently, it is widely used as a thermal environmental index by various organizations, such as the Occupational Safety and Health Administration (OSHA), US and domestic military training centers, and the Meteorological Administrations in Japan, Australia, and Hong Kong. It is also a standard index (ISO 7243) recognized by the International Organization for Standardization (ISO) for evaluating thermal stress on workers due to high temperatures in outdoor working environments. The equation for calculating the WBGT is as follows.

If globe temperature (T_g) observation data are available,

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a \quad (2)$$

If globe temperature (T_g) observation data are not available,

$$WBGT = 0.735T_a + 0.0374RH + 0.00292T_aRH + 7.619SR - 4.557SR^2 - 0.0572W_S - 4.064 \quad (3)$$

Here, T_w, T_g, and T_d indicate wet bulb temperature (°C), globe temperature (°C), and dry bulb temperature (°C), respectively. RH, SR, and W_s indicate relative humidity (%), solar radiation (W/m^2), and wind speed (m/s), respectively. Although globe temperature observation data are required to calculate the WBGT, no such data are available in the weather stations located in major cities in Korea because globe temperature (T_g) is not measured there. Therefore, in the present study, the WBGT was calculated using Equation (3). Table 2 shows the bodily heat sensation perceived by humans corresponding to WBGT values.

Table 1. Discomfort index (DI) and bodily sensations, American case

Stage	DI Value (°C)	DI Value (°F)	Description and precautions
Very High	≥29	≥85	Everyone experiences discomfort
High	29～27	84～80	93% of people feel discomfort
Medium	27～24	80～75	50% of people feel discomfort
Low	24～21	75～70	10% of people feel discomfort

Source: Nakamura and Kitamura, 1987.

Table 2. Warning criteria for hyperthermia prevention from the Ministry of Environment (MOE) in Japan

Stage	Criteria, wet bulb globe temperature (WBGT) value
Nearly safe	<21
Warning	21～25
Alert	25～28
Severe alert	28～31
Danger	≥31

3. Research Results and Discussion

3.1 Time variations of air temperature and relative humidity

Figs. 1 and 2 show the distributions of mean temperature and relative humidity over time in Seoul and Daegu during the consecutive days with heat waves in 2018 (July 18～August 8). As shown in the figures, high temperatures at heat wave warning levels (above 33°C) continued from 11:00 to 19:00 in both regions. During the late-night to early morning hours, temperatures were higher in Seoul than in Daegu, but at other times, temperatures were slightly higher in Daegu than in Seoul. From sunrise to around noon, the rate of temperature increase was faster in Daegu than in Seoul. The time period with the highest daily temperature in Seoul was around 16:00, which was about 1 to 2 hours later than in Daegu. From 22:00 to sunrise, the rate of temperature decline was much slower in Seoul than in Daegu. This temporal difference in temperature between Seoul and Daegu can be attributed to the fact that the density of artificial structures in the city is much higher in Seoul than in Daegu. An and Kim [1], Kim et al. [7], and Oke and Maxwell [8] pointed out in their studies on the phenomenon of urban heat islands that the heat capacity increases in cities with a higher density of artificial structures, which is consistent with the characteristics of Seoul observed in this study comparing temporal changes in temperature between Seoul and Daegu.

Yamajoe et al. [9] also conducted meteorological observations in Tokyo and surrounding suburban areas and confirmed that the rate of temperature increase from sunrise to noon was slower in the city than the suburbs and the time period when the highest daily temperature was observed was later in the city than in the suburbs. The authors pointed out that the high heat capacity of the downtown area caused the discrepancies.

Looking into the distribution of the relative humidity over time (Fig. 2), the relative humidity in Daegu was high, about 80% at sunrise, but declined thereafter to less than 50% from 10:00 to 20:00. On the other hand, the relative humidity in Seoul exceeded 50% except for the time period when the temperature was the highest (12:00 to 17:00). The difference in the relative humidity between the two regions during the hours of 13:00～23:00 was about 10%. Considering that the temperature distribution was 2°C higher in Seoul than in Daegu from dawn to early morning and that the temperature in Daegu was slightly higher than in Seoul at other times (Fig. 1), the absolute humidity (g/kg) was thought to be higher in Seoul than in Daegu. This is presumed to be due to the fact that the inflow of water vapor blowing along the edge of the North Pacific high which dominated the Korean peninsula in 2018 was more prominent in Seoul than in Daegu.

During the daytime, the temperature was slightly lower in Seoul than in Daegu, but the relative humidity was about 10% higher in Seoul so that the bodily heat sensation was higher in Seoul than in Daegu.

3.2 Time variations of DI and WBGT

Figs. 3 and 4 show the distributions of the mean DI and solar radiation over time in Seoul and Daegu during the consecutive days of heat wave in 2018 (July 18 to August 8). When the distribution of the DI over time was compared between the two regions, the values were almost the same during the hours of 7:00～11:00, but at other times, Seoul showed higher values than Daegu. During the hours of 14:00～17:00, in particular, the DI value exceeded 29 in Seoul, which corresponds to the highest rating at which everyone feels severe discomfort due to high temperatures. The highest DI value during the day was observed at 14:00 in Daegu and at 17:00 in Seoul. The DI of 27 or higher, at which more than 93% of people feel discomfort due to high temperatures, was observed during the hours of 09:00～23:00 in Seoul and 09:00～21:00 in Daegu, indicating that both regions were exposed to severe discomfort due to

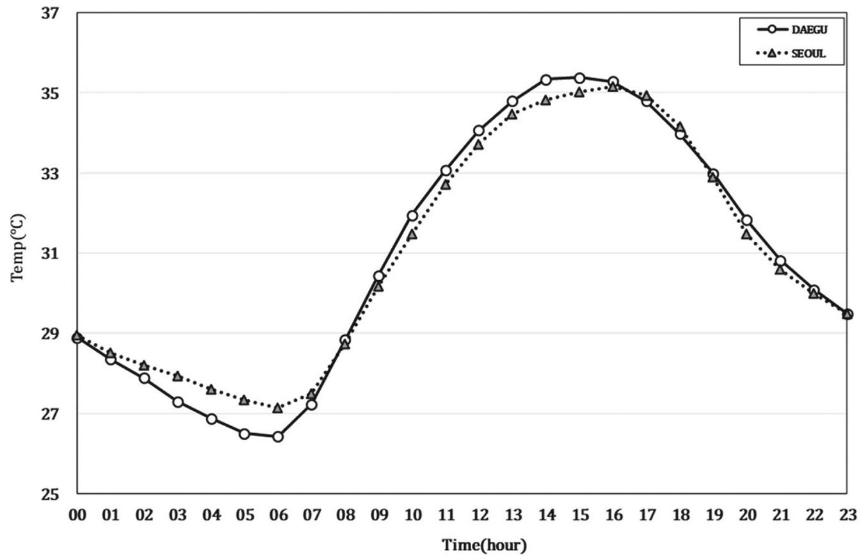

Fig. 1. Variation in air temperature (°C) over time in Daegu and Seoul during the 2018 heat wave period (July 18～August 8).

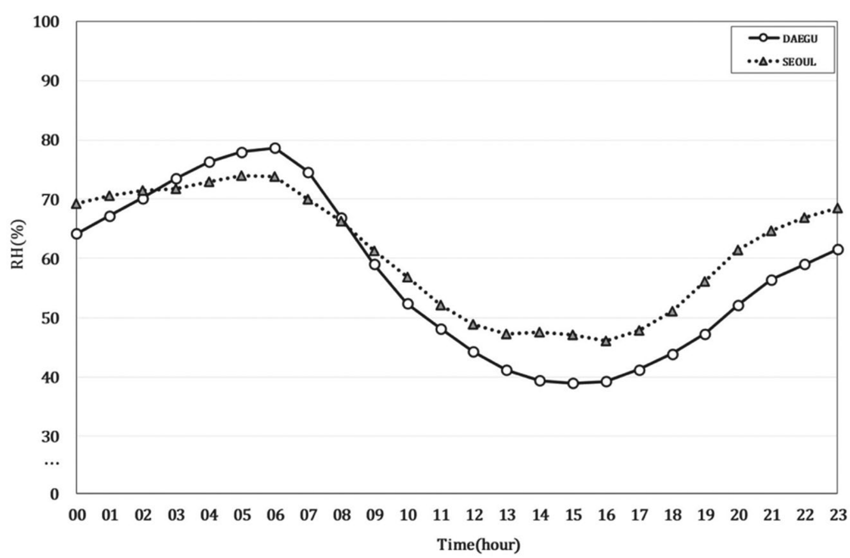

Fig. 2. Variation in relative humidity (%) over time in Daegu and Seoul during the 2018 heat wave period (July 18～August 8).

high temperatures throughout the day, excluding midnight to the morning hours.

Temperature, humidity, solar radiation, and wind speed are known to be the most important meteorological factors used to indicate the bodily heat sensation perceived by humans. As can be seen from Equation (3), by using these meteorological factors, the WBGT is an index that can well represent high-temperature environments that people who are active outdoors may experience. In addition, solar radiation plays a significant role in outdoor thermal environments in summer. For this reason, the mean solar radiation values over time are presented in Fig. 4. Solar radiation was higher in Daegu than in Seoul from sunrise to around 15:00. However, from then until sunset, it was higher in Seoul than in Daegu. The meteorological element that has the greatest effect on solar radiation in the same season is cloudiness. Therefore, the mean cloudiness data of Seoul and Daegu over time during this period were calculated and are presented in Fig. 5. In Daegu, solar radiation was highest at 12:00, when it was estimated to be about 2.6MJ/m^2 per hour, which is equivalent to about 720W/m^2. In Seoul, solar radiation was

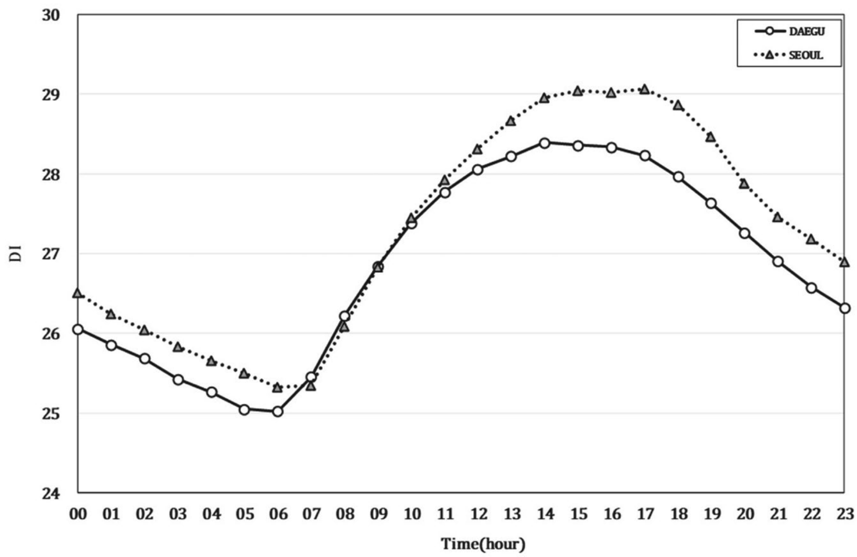

Fig. 3. Variation in the discomfort index (DI) over time in Daegu and Seoul during the 2018 heat wave period (July 18∼August 8).

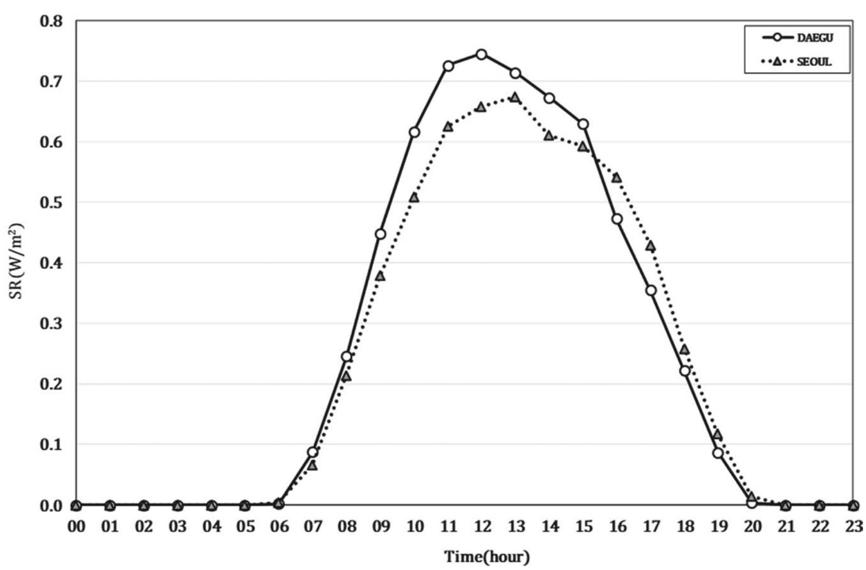

Fig. 4. Variation in solar radiation (W/m^2) over time in Daegu and Seoul during the 2018 heat wave period (July 18∼August 8).

highest at 13:00, when it was estimated to be about 2.45MJ/m^2 per hour, which is equivalent to about 680W/m^2.

Fig. 6 shows the distribution of the mean WBGT over time. As with the DI, both regions showed similar WBGT values during the hours of 07:00∼11:00, but at other times, Seoul showed higher values than Daegu. During the hours of 14:00∼16:00, in particular, in Seoul, the WBGT value exceeded 31, which is the highest level (danger) at which outdoor activities should be stopped unless there is a special reason. The WBGT of 28 or higher, which is the level at which strict warnings are issued for outdoor activities, was observed between 09:00 and 18:00 in Daegu, and in Seoul the duration was extended by one hour. This indicates that both Seoul and Daegu were exposed to levels of high-temperature thermal environments at which all outdoor activities should be prohibited throughout the daytime. The highest WBGT of the day was observed at 14:00 in Daegu and at 15:00 in Seoul.

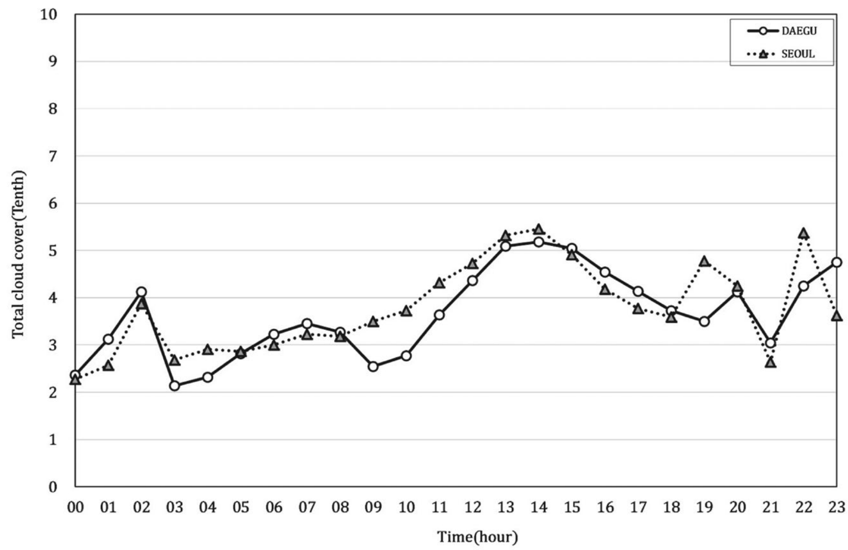

Fig. 5. Variation in cloudiness over time in Daegu and Seoul during the 2018 heat wave period (July 18～August 8).

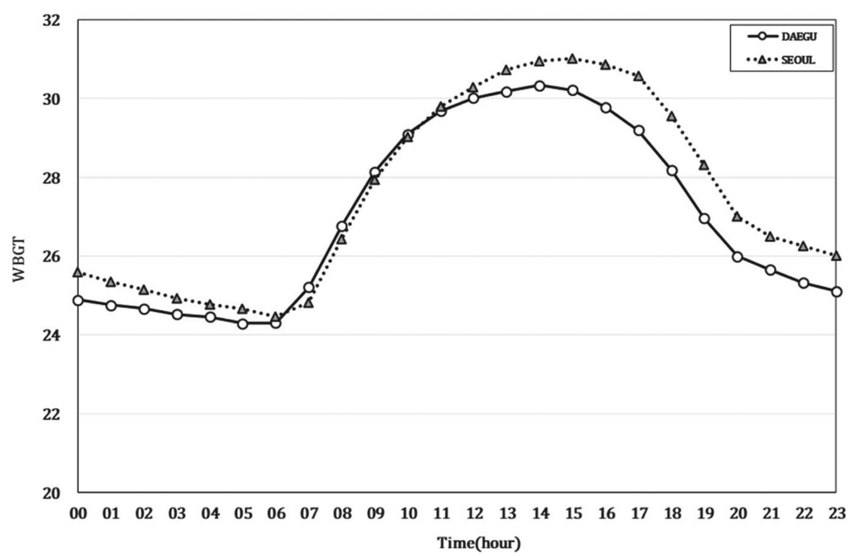

Fig. 6. Variation in wet bulb globe temperature (WBGT) over time in Daegu and Seoul during the 2018 heat wave period (July 18～August 8).

4. Conclusion

This study investigated and analyzed the regional differences between Seoul and Daegu during the heat waves lasting 21 days (July 18 to August 8) in 2018, when consecutive heat wave warnings were issued across the country. That year was recorded as the year when the most severe heat wave was experienced in the history of Korea's meteorological observations. The following conclusions were reached.

First, while the temperature was generally higher in Daegu than in Seoul during the day, it was higher in Seoul than in Daegu at night. The highest daily temperature was observed around 14:00 in Daegu and around 16:00 in Seoul. During the morning, after sunrise, the rate of temperature increase was faster in Daegu than in Seoul. These characteristics can be attributed to the high heat capacity of Seoul as the density of artificial structures in Seoul is much higher than in Daegu. High temperatures in cities are further promoted by the urban heat island phenomenon; in particular, increases in night temperatures are greatly affected by the increase in heat capacity, which depends on the density of artificial structures in the city [8,10].

Second, when the bodily heat sensation in Seoul and Daegu during the day was investigated using the DI, which can well represent the level of indoor high-temperature thermal environments, and the WBGT, which can well represent the level of outdoor high-temperature thermal environments, it was found that the level of high-temperature thermal environments was similar from sunrise to noon, but in the afternoon, Seoul showed more severe levels than Daegu. The meteorological factor that was likely to directly cause this difference is a decrease in cloudiness during the afternoon hours in Seoul. However, the reason why the cloudiness was low in Seoul during the afternoon hours requires further investigation.

Third, in order to reduce human casualties, in the event of future heatwaves like the one in 2018, it is recommended to produce high-temperature information that can better express the outdoor high-temperature environments, such as the WBGT, rather than the bodily heat sensation that is dependent on temperature and humidity and to implement labor regulatory policies accordingly.

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