Numerical Simulations of Summer Mesoscale Heat-Stress around the Seto Inland Sea, Japan

Yukitaka OHASHI

Faculty of Biosphere-Geosphere Science, Okayama University of Science, Okayama, Japan

Susumu SHIMADA¹

Graduate School of Engineering, Gifu University, Gifu, Japan

and

Teruo OHSAWA

Graduate School of Maritime Sciences, Kobe University, Kobe, Japan

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Abstract

We simulated mesoscale distributions of summertime human heat stress around the Seto Inland Sea in western Japan, using a mesoscale numerical model: WRF-ARW at 2 km horizontal resolution. In this study, the Heat Index, which indicates the real human-felt temperature, was adopted as a heat-hazard index that can represent mesoscale spatial distributions of human heat stress. Our simulations specified regions of undesirably high daytime Heat Index around the Seto Inland Sea for the year 2007, an extremely hot summer. Although the daytime high surface air temperature in the Osaka Plain was the most prominent of the calculation domain (at 1400 JST, August air temperature means of 33–35 °C), high Heat Index regions were broadly found in other land areas around the Seto Inland Sea in addition to the Osaka Plain: the Tokushima, Okayama, Sanuki, and Nakatsu Plains (at 1400 JST, August Heat Index means of 37–39 °C). Daytime differences between air temperature and Heat Index were large in the four previously mentioned plains (excluding the Osaka Plain), showing a difference of 5–7 °C in our simulation. The large differences were caused by the difference of relative humidity in the region. Hence, residents in these plains should carefully avoid high heat stress, because they may feel hotter than the actual air temperature.

To discuss mechanisms increasing the mesoscale Heat Index, sensitivity experiments for mountains and sea surface temperature were conducted. They revealed that those factors worked selectively in the above regions. The existence of mountains induced thermal effects due to a valley-like terrain, and higher sea surface temperature produced warm and moist air transports from the sea. Daytime local circulations, which were topographically and thermally driven, were important for both factors. These mountain and high sea surface temperature influences produced increases of Heat Index of 1–2 °C in the aforementioned four regions.

Keywords heat stress; heat index; mesoscale simulation; the Seto Inland Sea

Corresponding author: Yukitaka Ohashi, Editorial Office,
Faculty of Biosphere-Geosphere Science, Okayama
University of Science, 1-1, Ridai-cho, Kita-ku, Okayama
700-0005, Japan

E-mail: ohashi@big.ous.ac.jp

¹Present affiliation: National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

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1. Introduction

In recent times, the number of hyperthermic patients reported during summertime has gradually increased throughout Japan. Although the number of heatstroke deaths was around 200 people per year in the second half of the '90s, this number exceeded 400 people after the year 2000 and eventually reached 1,731 people in

Fig. 1. August climatological mean values (1981–2010) of the daily maximum temperature at meteorological stations of the Japan Meteorological Agency (JMA) throughout the islands of Japan.

2010, according to the Ministry of Health, Labour and Welfare, Japan. Such increases in hyperthermia-related deaths, which are regarded as a social problem in Japan, are caused mainly by the following two factors: the number of elderly people, who tend to have low resilience against the summertime environment because of declining thermoregulation of their bodies (e.g., Kenney and Munce 2003), increases every year; and the surface air temperature (AT) or magnitude of the heat stress index increases every year because of global warming and the urban heat island effect (e.g., Fujibe 2009). Therefore it is expected that hyperthermia-related mortality will continue to increase in the future. Because it is believed that global warming and the urban heat island will be exacerbated in the future (e.g., Alcoforado and Andrade 2008), numerical evaluations of mesoscale heat stress and its hazards, such as those conducted in this study, will be expected frequently. In fact, a mesoscale analysis of the heat hazard is published daily for human health in European countries and the U.S.

Summers in Japan are very hot and humid because of the North Pacific High (NPH). Hence, a southerly flow can form easily over western Japan (WJ), which is located in the western part of the NPH. In fact, our analysis of meteorological station data from the Japan Meteorological Agency (JMA) elucidated that the

August climatological mean values of daily maximum AT recorded in cities in WJ are notably higher than those in cities in eastern Japan (Fig. 1). Consequently, summer atmospheric conditions that are uncomfortable for inhabitants are more frequent in WJ. Air humidity is a significant factor that affects human heat stress and has thus been incorporated into many heat indices: the Temperature-Humidity Index (originally Thom 1958), which was once called the “Discomfort Index,” the Humidex (Masterson and Richardson 1979), which has often been utilized in Canada as the hot and humid perceived temperature used in the weather forecast routines, and the Wet-Bulb Globe Temperature (WBGT; Yaglou and Minard 1957), which is broadly used to evaluate the risk of hyperthermia under a solar heat load in Japan. Therefore, regional human discomfort is not always consistent with AT. From a mesoscale perspective, this condition of discomfort may be caused by local geography and morphology, such as the distribution of coasts, mountains, plains, and urban areas. Thus, AT and humidity are more important elements than solar radiation. A mesoscale meteorological model has often been utilized for the prediction of regional and continental human heat stress evaluations (e.g., Segal and Mahrer 1979; Segal and Pielke 1981; Jendritzky et al. 2001).

Our study attempts to elucidate atmospheric thermal

Fig. 2. Map of western Japan and calculation domain. Calculation domain (solid-enclosed area) is depicted in the right-sided figure. The left-sided figure is a topographical map of the dashed-enclosed area shown in the right-sided figure.

discomfort and its formation mechanism in WJ from a mesoscale meteorological point of view. As mentioned before, not only urban heat islands but also geographical distributions of mountains, plains, and seas possibly affect a human heat stress as a regional scale. Therefore, we focus on mountain- and sea-scale effects that are spatially larger than those at the urban scale. This is achieved by simulating a heat stress index using a numerical meteorological model. In this study, the August period in 2007 is selected for the analysis. This summer season was well known for its record number of extremely hot days throughout Japan.

2. Numerical model

We used a mesoscale meteorological model, the Weather Research & Forecasting (WRF) model (ARW, Ver. 3.0.1.1), developed by National Center for Atmospheric Research (NCAR). The WRF is a numerical model composed of fluid-dynamics equations with a fully compressible fluid and non-hydrostatic equilibrium. Model physics schemes chosen for radiation, cloud microphysics, planetary boundary-layer, and land surface are the Dudhia shortwave (Dudhia 1989) and the Rapid Radiative Transfer Model (RRTM) longwave (Mlawer et al. 1997) schemes, the WRF Single-Moment 6-class (WSM6) scheme (Hong et al. 2004), the Mellor-Yamada-Janjic (MYJ) turbu-

lent kinetic energy parameterization (Janjic 1990), and the Noah Land Surface Model (Noah-LSM) (Chen and Dudhia 2001), respectively.

A calculation domain of 700 km (west–east) $\times$ 600 km (north–south) was assigned to WJ, as shown in Fig. 2. This domain includes the entire Seto Inland Sea (SIS) region, which is composed of the Kinki, Chugoku, Shikoku, and Kyushu regions surrounding it. The terrain altitude within the domain and the meteorological station locations described hereafter are also indicated in Fig. 2. A 2-km grid interval was adopted as the horizontal spatial resolution in our calculations. Initial and boundary conditions for the model atmosphere, sea surface temperature (SST), and soil properties were input from 10 km $\times$ 10 km resolution mesoscale objective analysis data provided by the JMA, 0.05° $\times$ 0.05° New Generation Sea Surface Temperature data for Open Ocean (NGSST-O) provided by Tohoku University, and final analysis data with 1° $\times$ 1° resolution provided by the National Center for Environmental Prediction (NCEP), respectively.

The topography and land-use input data were modified from the WRF default data. In this study, terrain elevation and land-use type distributions were produced from 50-m meshed data provided by the Geospatial Information Authority of Japan (GSI), and 100-m meshed data (developed in 2006) from

the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), respectively. These data were used as the terrain data input into the WRF model after they had been averaged as 2-km meshed data. In this study, urban canopy and anthropogenic heat effects were not included in the simulations, because it is difficult to determine the urban structure parameters (e.g., building height and fraction) peculiar to each urban city.

Our simulation period was 0000 UTC 31 July to 0000 UTC 1 September for the year 2007. The calculated output data for August within this period are analyzed here.

3. Heat stress index

In our study, the Heat Index (HI) was adopted to analyze the mesoscale heat stress distribution:

$$HI = -8.784695 + 1.61139411T + 2.338549H - 0.14611605T \cdot H - 1.2308094 \times 10^{-2} T^2 - 1.6424828 \times 10^{-2} H^2 + 2.211732 \times 10^{-3} T^2 H + 7.2546 \times 10^{-4} T \cdot H^2 - 3.582 \times 10^{-6} T^2 H^2. \quad (1)$$

Here, T ($^{\circ}\text{C}$) and H (%) indicate AT and relative humidity (RH), respectively. This index is produced by multiple regression analysis with AT and RH as explanatory variables (Rothfus 1990; Blazejczyk et al. 2012). It originates from Steadman's apparent temperature (Steadman 1979), which is the human-felt temperature derived from heat budget calculations between the human body and the atmosphere under the assumed conditions. In Eq. (1), HI becomes more sensitive to RH as AT rises above 26–27 $^{\circ}\text{C}$. This property produces a large difference between the human-felt temperature and the AT under daytime high-AT conditions.

HI has been popularly utilized instead of the Temperature-Humidity Index and is published in the United States (e.g., NOAA National Weather Service) as a measure of the heat hazard for human health. Thresholds of the HI (in $^{\circ}\text{C}$) can be related to human sensation as follows: 27–31 $^{\circ}\text{C}$ corresponds to “caution,” 32–40 $^{\circ}\text{C}$ to “extreme caution,” 41–53 $^{\circ}\text{C}$ to “danger,” and 54 $^{\circ}\text{C}$ and higher to “extreme danger.” These values can be regarded as real human-felt temperatures in shade. If a human is exposed to full sunlight, HI could increase by up to 8–9 $^{\circ}\text{C}$ (NOAA National Weather Service 2013). NOAA National Weather Service initiates alerts when HI is expected to exceed 41–43 $^{\circ}\text{C}$ (depending on local climate) for at least two consecutive days. HI values above 41 $^{\circ}\text{C}$ correspond to the level that may cause increasingly severe heat disorders with continued exposure or physical activity.

As illustrated in Eq. (1), HI does not include direct influences of solar and infrared radiation, and wind flows. Although these meteorological factors have strong heterogeneity in time and space that changes at microscales, AT and humidity are more strongly dominated by mesoscale meteorological conditions. Therefore, instead of using a heat stress index that includes solar effects (such as WBGT) which has generally been used for evaluating the local thermal load to the human body and activities (e.g., Parsons 2006; Asayama 2009), this study analyzed HI, which is preferred for considering mesoscale and shady conditions.

In our analyses, results at 1400 JST are often indicated as the time at which the daily maximum temperature is likely to be found.

4. Results

4.1 Model validations

The simulated AT and HI were quantitatively compared with those observed by the 34 JMA meteorological station sites indicated in Fig. 3. Figure 4 indicates the relationships between the observed and calculated HIs along with the ATs. In a comparison of monthly mean values at 1400 JST (Figs. 4a and 4b), the correlation between the observed and calculated HI values was lower than that between the AT values. In particular, a positive mean bias of 1.1 $^{\circ}\text{C}$ was found for the HI values, indicating that calculated values were larger than observed ones. This lower reproducibility of HI is because RH, which is not so high reproducibility as AT, is contained in the calculation of HI. However, high correlations were obtained for both AT and HI on extremely hot days (clear-sky conditions covered with NPH). For instance, at 1400 JST 16 August (Figs. 4c and 4d), the correlation coefficients between simulated and observed values were 0.82 for AT and 0.74 for HI, both of which were found to be statistically significant, at the significance level of 1% ($p < 0.01$). Further, the mean biases of AT and HI tended to be small, -0.08 $^{\circ}\text{C}$ and $+0.7$ $^{\circ}\text{C}$, respectively. The Spearman's rank correlation coefficients calculated for the 34 sites were 0.78 ($p < 0.01$) for AT and 0.34 ($p < 0.05$) for HI for the monthly mean of August, but were 0.81 ($p < 0.01$) for AT and 0.66 ($p < 0.01$) for HI for 16 August.

In addition, the calculated daily maximum AT was compared with that obtained using the Automated Meteorological Data Acquisition System (AMeDAS) by JMA for 128 sites (Fig. 4e). A high correlation between the calculated and observed values was found even when the number of sites used for comparison was increased.

Figure 5 shows the regional AT and HI comparisons

Meteorological stations

Pacific Ocean (PO) side

Station No.	Station name
1	Nobeoka
2	Sukumo
3	Shimizu
4	Kochi
5	Murotomisaki
6	Shionomisaki

Seto Inland Sea (SIS) side

Station No.	Station name
7	Shimonoseki
8	Oita
9	Uwajima
10	Matsuyama
11	Hiroshima
12	Kure
13	Fukuyama
14	Okayama
15	Takamatsu
16	Tokushima
17	Himeji
18	Sumoto
19	Kobe
20	Osaka
21	Wakayama

【Analysis domain】

Japan Sea (JS) side

Station No.	Station name
22	Hagi
23	Hamada
24	Matsue
25	Sakai
26	Yonago
27	Tottori
28	Maizuru

Inland (IN) area

Station No.	Station name
29	Hita
30	Yamaguchi
31	Tsuyama
32	Toyoooka
33	Kyoto
34	Nara

Fig. 3. Map of western Japan showing the analysis domain in our study and the locations of the JMA meteorological stations. Shaded areas denote the distribution of urban land use. Contours within the analysis domain show terrain elevation.

between observed and calculated values at 1400 JST in August 2007. Here, the regions used for comparison were divided into the Pacific Ocean (PO) side, the SIS side, the Japan Sea (JS) side, and the inland (IN) area. ATs observed in the SIS side and IN area tended to be higher than those of the other regions, and this was well reproduced by the model calculation. On the other hand, HI distributions revealed that both observed and simulated HIs at many stations near the seashore of the SIS were higher than those of the other regions; Osaka, Okayama, and Takamatsu were particularly remarkable examples. It should be noted that higher HIs appeared in the SIS side compared to the IN area; this relation was reproduced by both observations and simulations.

Artificial modifications of the atmosphere, such as urban buildings and anthropogenic heat, are inferred in some large cities, such as Kyoto, Osaka, and Kobe, within our analyzed areas in WJ. Terui et al. (2009) revealed a 0.6 °C impact of anthropogenic heat on

daytime AT in the downtown area of Osaka from results of their numerical simulation. Also, Kikegawa et al. (2011) suggested an AT increase of 0.9 °C at an office district due to additional anthropogenic heat from a comparison between weekday and weekend observations of AT. On the other hand, urban canopy effects in the WRF were analyzed in detail by Kusaka et al. (2012). They broadly compared ATs between urban canopy and slab surface conditions on the Kanto Plain in Japan. As a result, not only in megacity Tokyo but also in medium-city Kumagaya, existence of urban canopy decreased the daytime AT by more than 1 °C because of the large thermal inertia of buildings. Consequently, the two aforementioned effects on AT cancel each other out. In fact, observed AT and HI in the aforementioned urban sites were not particularly higher than the calculated ones, and this tendency was the same as that found at the other sites. Therefore, it was speculated that urban anthropogenic

Fig. 4. Scatter diagrams between the observed and calculated values for (a) monthly mean air temperature (AT) and (b) Heat Index (HI) at 1400 JST in August 2007; (c) AT and (d) HI at 1400 JST 16 August 2007; and (e) daily maximum AT in August 2007.

Fig. 5. Comparisons between observed and calculated values at each station of (a) monthly mean AT and (b) HI for 1400 JST, August 2007.

heat and canopy effects did not alter the results of the mesoscale HI distributions. Conversely, in evaluations of AT and HI during nighttime, urban canopy model needs to probably be included in simulations for the following reasons: the impact of anthropogenic heat on AT becomes larger because of the thermally stabilized

atmosphere, sensible heat supply from the surface to the atmosphere last longer due to larger thermal inertia, and surface radiative cooling is reduced by the trapping of longwave radiation within street canyons (e.g., Martilli 2002; Kusaka and Kimura 2004; Salamanca et al. 2011).

(a) Mousho-bi ($\geq 35^{\circ}\text{C}$) Aug '07 (b) Danger HI ($\geq 41^{\circ}\text{C}$) days Aug '07

(c) Daytime AT (14JST) Aug '07

(d) Daytime HI (14JST) Aug '07

Fig. 6. Calculated spatial distributions of (a) the number of Mousho-bi days (daily maximum AT $\geq 35^{\circ}\text{C}$), (b) the number of danger HI days (daily maximum HI $\geq 41^{\circ}\text{C}$), (c) monthly mean daytime AT (1400 JST), and (d) monthly mean daytime HI (1400 JST), all for August 2007. Regions of A–E in (b) indicate those of especially high HI: region A, the Osaka Plain; B, the Tokushima Plain; C, the Okayama Plain; D, the Sanuki Plain; and E, the Nakatsu Plain.

4.2 Mesoscale distribution of heat stress

In Japan, a day on which a daily maximum AT of 35°C or more is recorded is called a “Mousho-bi” day in Japanese (defined by JMA): an extremely hot day in English. Figures 6a and 6b show calculated distributions of the number of Mousho-bi days and dangerous HI ($\geq 41^{\circ}\text{C}$) days for August 2007. On the Osaka Plain, more than half of the days of the month were Mousho-bi days, and this number was the largest

of simulated domain. This enlargement of Mousho-bi extended broadly from Osaka to Kyoto. In addition, a large number of Mousho-bi days, in excess of 10, occurred at and around Okayama and Takamatsu. On the contrary, the largest number (about 5) of dangerous HI days was found across broad areas, which include the Okayama Plain including Okayama (region C in Fig. 6b) and the Sanuki Plain including Takamatsu (region D) of the SIS side, as well as the Osaka Plain

including Osaka and Kyoto (region A). The features of this distribution differed from that of Mousho-bi. In addition to these areas, the Nakatsu Plain (region E) and the Tokushima Plain including Tokushima (region B) had a higher number of dangerous HI days than the surrounding areas.

In Fig. 6c, the monthly mean AT distribution at 1400 JST is shown as the daytime summer climatology. The AT tended to be high in the plains located more toward the eastern part of SIS. This distribution was similar to that of the Mousho-bi distribution. In particular, inlands of the Osaka Plain, which includes Kyoto, had the highest monthly mean AT, higher than 34 °C. Although the monthly mean HI at 1400 JST (Fig. 6d) was also higher for plains adjacent to the SIS, high HI was prominent on the plains including Okayama and Takamatsu but not on the plain including Osaka and Kyoto.

4.3 Temperature and humidity effects on the heat index

Inconsistencies between spatial distributions of AT and HI were represented in Fig. 6. As can be seen in Eq. (1), HI is determined by both AT and RH and thus can be regarded as a nearly actual human-felt temperature. Figure 7 indicates the difference between AT and HI ($HI - AT$) simulated at 1400 JST as the August 2007 mean. On the Osaka Plain (region A), where daytime AT was the highest and where the most Mousho-bi days were counted, HI was larger than AT mostly by 3–4 °C. On the other hand, regions of B, C, and D including Tokushima, Okayama, Fukuyama, and Takamatsu, with the highest HI of the calculation domain generally had a 5–6 °C difference between HI and AT. This large difference implies that residents may feel hotter than they would feel under the actual AT and suffer a large heat stress compared with residents of the Osaka Plain (region A). However, the difference between HI and AT was most notable in region E, which includes the Nakatsu Plain, with a magnitude of 6–7 °C because the monthly mean AT in this region was 2–5 °C lower than that of the other four regions.

These differences between AT and HI could also be induced by a regional difference of RH. Figure 8 shows the spatial distribution of the monthly mean surface RH at 1400 JST for August 2007: it reveals a higher RH in western regions. Figure 9 shows response curves of HI to both AT and RH. Here, the simulated values at 1400 JST in regions A–E are plotted. Relation curves between AT, RH, and HI in the figure show that as AT in the existing atmospheric condition becomes higher, HI becomes sensitive to RH. This physical

Fig. 7. Simulated monthly mean spatial distributions of HI minus AT (i.e., difference between the actual felt temperature and air temperature) at 1400 JST in August 2007. The regions of A–E are the same as in Fig. 6b.

Fig. 8. Simulated monthly mean spatial distributions of relative humidity (RH) at 1400 JST in August 2007.

Fig. 9. Scatter plots of simulated HI and AT at 1400 JST in regions A–E and relation curves between HI and AT for constant values of RH (40–70%). The plotted data are extracted for the areas as follows: A, around 135.3°–135.7° long. and 34.6°–34.9° lat.; B, around 134.2°–134.5° long. and 34.0°–34.15° lat.; C, around 133.7°–134.2° long. and 34.3°–34.7° lat.; D, around 133.8°–134.2° long. and 34.2°–34.35° lat.; and E, around 131.0°–131.4° long. and 33.5°–33.7° lat.

process depends on the principle that the endothermic action of evaporation from the human body is easily controlled by RH conditions under higher AT because a day with higher daily maximum AT has an increased saturation vapor pressure in the atmosphere. Hence, HI simulated in more eastern regions (especially region A) with lower RH was close to AT, and that simulated in western regions (especially region E) with higher RH tended to separate from AT (differences from the line $HI = AT$ drawn in Fig. 9).

Relations among HI, AT, and RH simulated in each region are also denoted in Fig. 9. It can be seen that HIs estimated in regions B, C, D, and E became comparable to that in region A because of higher RH in the other regions. This arose from the fact that the higher AT and lower RH in region A, including Osaka and Kyoto, was induced by a broadly drier urban extent with large sensible heat supply from the surface.

4.4 SST and topography effects on mesoscale heat stress

A mesoscale heterogeneity of heat stress hazard

was found in land areas around the SIS. Accordingly, to clarify what determined the mesoscale regional contrast, we conducted additional case runs via some sensitivity experiments (Fig. 10 and Table 1). CASE NO had a spatially constant SST of 27 °C and no mountains throughout the model domain, which means calculations were based only on flat terrain distributions (i.e., zero elevation) of land and sea, but CASE MNT had real undulating mountains added to the case of CASE NO. Henceforth, the previous real run is referred to as CASE REAL. Additionally, two case runs were simulated for the period of August 2007, the same as CASE REAL. The assigned SST of 27 °C in CASE NO and CASE MNT was used because it was nearly the lowest value of SST within the domain of CASE REAL.

Figure 11 provides surface spatial distributions of HI differences between CASE REAL and CASE NO and between CASE REAL and CASE MNT; however, the figure was drawn only for land areas where HI in CASE REAL was higher than that in CASE NO or CASE MNT. The difference between CASE REAL and CASE NO (Fig. 11a) indicates that mountains and SST heterogeneity increased HI in the areas with many danger days and the higher values found in Figs. 6b and 6d. These areas were on plains which are unaffected by the model elevation rising from CASE NO to the actual terrains, CASE REAL (on the other hand, decreases of HI in inland mountain areas were caused by the elevation rising). In particular, the increase was broadly prominent in region C, including Okayama, in which HI increased by about 2 °C. On the other hand, a comparison between CASE REAL and CASE MNT (Fig. 11b) suggests that the high SST causes HI in seashore areas and plains to increase. Then, sea breezes blew in seashore areas from the neighboring sea, as seen in Fig. 12 (for CASE REAL), which probably involved a heat transport from the high SST. The aforementioned particularly high HI in region C was influenced by the higher SST of SIS. The relationship between mesoscale winds and high HI will be discussed later.

Figure 13 shows variations of HI in the three cases and the components of AT and RH at representative points (region A: $X = 294$, $Y = 195$; B: $X = 237$, $Y = 154$; C: $X = 211$, $Y = 184$; D: $X = 222$, $Y = 165$; and E: $X = 89$, $Y = 127$) within the five regions indicated in Fig. 6b. These grid values were confirmed to differ little from the surrounding those. Here, it should be noted that the HIs in region A (Fig. 13a) and regions B and E (Figs. 13b and 13e) in CASE NO were the highest (37.2 °C) and the lowest (36.6 °C), respectively, of

Fig. 10. Configurations of the sensitivity experiment. (a) CASE NO with flat terrain and constant SST, (b) CASE MNT with real mountains and constant SST, (c) CASE REAL with real mountains and real SST. As an example, the SST distributions shown in (c) are monthly averaged at 1400 JST in August 2007.

Table 1. List of sensitivity experiments in the present study.

Case name	SST	Land height	Land and sea
CASE NO	Fixed uniformly 27 °C	Zero elevation	Real distribution
CASE MNT	Fixed uniformly 27 °C	Real elevation	Real distribution
CASE REAL	Real SST distribution	Real elevation	Real distribution

Fig. 11. Horizontal distributions of HI difference between (a) CASE REAL and CASE NO (REAL minus NO) and (b) CASE REAL and CASE MNT (REAL minus MNT) at 1400 JST in August 2007. The figure was drawn only for land areas where HI in CASE REAL was higher than that in CASE NO or CASE MNT. The regions of A–E in (a) are the same as in Fig. 6b.

CASE REAL (14JST) Aug 2007

Fig. 12. Simulated monthly mean horizontal distributions of horizontal wind vectors at the surface in CASE REAL at 1400 JST in August 2007.

all the regions. In experiments of CASE NO, the HI distribution has no influences from mountains and SST heterogeneity. The former highest HI in region A was due to a large sensible heat supply from the extended urban surface on the Osaka Plain, and the latter lowest HI in region E was due to a suppression of the AT increase because the region is adjacent to the nearby sea. The presence of mountains obviously increased AT and conversely decreased RH in the four regions other than E (i.e., from variation between CASE NO and CASE MNT in Figs. 13a–d). As shown in Figs. 14a (difference of AT) and 14b (difference of RH) that represent the surface distribution, this phenomenon appeared broadly, including the surroundings of each region. In addition, the vapor mixing ratio (MR) in CASE MNT fell by more than 0.3 g/kg relative to that in CASE NO (Fig. 14c) (On the other hand, the MR reduced more greatly in inland mountain areas because of the model elevation rising from CASE NO to CASE MNT).

The above features imply the existence of higher potential temperature and downward dry-air inflows from the upper atmosphere due to daytime valley circulations. Valley-like topographies having plains of different scales (denoted by the dotted squares in Fig. 14a), which include regions A, B, C, and D, can develop these daytime local circulations. The vertical advection of potential temperature (i.e., $-w \times \partial\theta/\partial z$; where w is vertical wind speed and θ is potential temperature) at the SIS, for instance, around regions C and D in CASE REAL was compared with that in

CASE NO (Fig. 15). This figure reveals that in CASE REAL positive temperature advection was remarkable in the lower layer below a height of about 1 km. This positive value was produced by the coexistence of downward air motion along with the upper high potential temperature. As a result, AT around regions C and D increased easily in CASE REAL compared with that in CASE NO. Such a daytime development of local circulations probably arises from the circumstance that the terrain within the dotted square including regions C and D, which is drawn in Fig. 14a, is shaped like one large basin or valley having the SIS and the plains on both-sides (i.e., the Okayama and Sanuki Plains) at the bottom. The thermal effect of the local circulations can be estimated as an increase in HI of 0.7 °C at region C from the difference between CASE MNT and CASE NO in Fig. 13c.

On the other hand, meteorological variations from CASE MNT to CASE REAL represent the influence of the higher SST, which resulted in increases of AT, particularly in regions C and E (Figs. 13c and 13e). From the distribution of the AT difference illustrated in Fig. 14d, the existence of an increase in AT of 0.3–0.6 °C in CASE REAL is obvious around region C. Kasuya and Kawamura (2011) pointed out that sea breezes seemed to hardly suppress the rising AT on coastal areas of the SIS, and this tendency was different from that of the JS and PO sides. Hence, our experimental result agrees with their conclusion. However, no coastal areas, including region C, had decreases of RH, even if AT increased there, as can be seen in Fig. 14e (RH difference between CASE REAL and CASE MNT). This lack of a decrease in RH was caused by sea-breeze inflows of moist air (i.e., higher MR) from the sea (Fig. 14f). The high MR in the eastern part of SIS, which includes region C, especially tended to extend inland. It is suggested that the latent heat flux supplied from the sea to the overlying atmosphere is large toward the eastern SIS because of the higher AT than that on the western SIS, as discerned from the AT distribution in Fig. 14d.

We also calculated the temporally accumulated amounts (MJ/m^2) of latent heat flux supplied from the surface, LH_g , and within the atmospheric column to a height of 2 km, LH_c (Ohashi and Kida 2004). These quantities were integrated from 0600 to 1400 JST as the monthly mean. Figure 16 represents the relationship between LH_g and LH_c at representative points within the five regions. Values of LH_g in regions A and C were extremely small because the selected grids were in urban land use. However, LH_c , which indicates latent heat storage within the atmospheric boundary layer, at

Fig. 13. Relationships among AT, RH, and HI at grids of the region (a) A ($X = 294$, $Y = 195$), (b) B ($X = 237$, $Y = 154$), (c) C ($X = 211$, $Y = 184$), (d) D ($X = 222$, $Y = 165$), and (e) E ($X = 89$, $Y = 127$) at 1400 JST in August 2007. These locations are denoted in the lower right map.

region C was significantly larger than that at region A and comparable to that at region D. This result implies the existence of the aforementioned transport of moist air from the sea by daytime sea breezes around region C. On the other hand, region A, which is surrounded by mountains, strongly experiences a downward transport of the upper dry air by developed valley circula-

tions during daytime, as indicated by Ohashi and Kida (2004). This effect can also contribute to the decrease of LH_c in region A.

5. Summary

For the recent excessively hot summer climate in Japan, we simulated the mesoscale distribution of the

Fig. 14. Horizontal distributions of (a) (d) AT, (b) (e) RH, and (c) (f) MR differences between the (a) (b) (c) CASE MNT and CASE NO and the (d) (e) (f) CASE REAL and CASE MNT at 1400 JST in August 2007. Regions of A–E in (a) are the same as in Fig. 6b.

human heat stress occurring on land areas around the Seto Inland Sea (SIS) in western Japan and then examined its spatial heterogeneity and formative mechanisms by using a mesoscale numerical model.

The Heat Index (HI), which can be regarded as the actual human-felt temperature, was selected as an index that can represent the human heat hazard at the mesoscale. Then, we specified five regions (the Osaka, Tokushima, Okayama, Sanuki, and Nakatsu Plains) where undesirably high daytime HI (at 1400 JST; August HI means of 37–39 °C) were found around the SIS in the year 2007, representing an extremely hot summer, in which the number of days with a “danger” HI rank of above 41 °C increased. However, the spatial distribution of high HI differed from that of surface air temperature (AT). Simulated Mousho-bi days (days having a daily maximum AT of 35 °C or more) appeared most frequently on the Osaka Plain, where the August mean daytime AT at 1400 JST was 33–35 °C.

Daytime differences between HI and AT were large on all the aforementioned plains except the Osaka Plain, which showed differences of 5–7 °C in our simulation. The difference between HI and AT was caused by the different relative humidity in regions. Hence, residents in these plains may feel hotter than the actual AT and suffer from higher heat stress.

As the main geographical factors that could influence mesoscale HI, effects of mountains and sea surface temperature (SST), which have a larger scale compared to urban areas, were examined by sensitivity experiments. The results revealed that mountains and SST increased the daytime HI in some regions through thermal effects induced by valley-like terrain and warm and moist air transports from the sea, respectively. These were related to the development of daytime local circulations (i.e., sea breezes or valley winds) attributable to topographic sources. From the experimental results, increases of 1–2 °C in HI were confirmed in the

Fig. 15. Vertical advections of potential temperature at the location of $X = 220$ and $Y = 172$ (a star marked in the lower right map of Fig. 13) in CASE REAL and CASE NO. The figure is an August mean at 1400 JST.

mentioned four regions (except the Osaka Plain). In particular, high HI found broadly in the Okayama Plain was produced by superposition of both these mechanisms. Therefore, not only megacities as Osaka but also such a region with high HI requires measures to monitor the heat hazard and prevent human heat-strokes.

Thus, it was found that outdoor heat stress during summer in Japan was affected by both mesoscale geography and local factors. It is anticipated that heat wave encounters will increase over Japan in the future and that this will trigger heat disorders and sleep disturbance in many inhabitants (e.g., Nakano and Matsueda 2012). Hence, mesoscale evaluations and predictions of human heat indices will be required to help the society and the general public.

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Fig. 16. Relationship between the temporally accumulated amounts of latent heat flux supplied from the surface (LH_g) and that within the atmospheric column to the height of 2 km (LH_c). These quantities were integrated from 0600 to 1400 JST as the monthly mean of the representative grids (same as in Fig. 13) in the five regions.

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