Academic Article

Spatiotemporal Evaluation of Thermal Environment in Kumamoto City Urban Districts

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ABSTRACT

To investigate the thermal environment in urban districts, moving meteorological observations were performed in the location of Kumamoto City. The observations were carried out eight times in 2012 and 2013. In this paper, the result of August 8 was used to evaluate the spatiotemporal characteristics of the areas. When conducting the observations, two instruments were used and the results' error caused by differences between observation times and instruments were reviewed. The instruments were calibrated and observation times adjusted to remove differences. Then, the results were able to show the thermal environment of the districts with the allowable margin of error. In addition, some unique areas were categorized into hot zones and cool zones for each measurement time. In conclusion, it is suggested that this investigation method is useful to evaluate the thermal environment of urban districts in time and space.

Key Words : Urban district, Heat environment, Moving meteorological observation, Air conditioning load

1. Introduction

In urban areas of Japan, the thermal environment becomes extreme particularly in summer. Therefore, negative health effects on the local residents, such as heat stroke, increase. In addition, the air conditioning load of buildings and energy consumption increase. It is necessary to reduce energy consumption and carbon dioxide emissions. Previously, the authors had studied the thermal environment of Kumamoto City urban districts, and considered its influence on local air conditioning load of buildings [(1)]. In the study, the results of investigations in 2011 and 2012 were compared and showed strong similarities [(2)]. The analysis, however, was limited to three arcades in the center of Kumamoto City. In addition, there was a problem of not being able to evaluate the reliability of the movement observation sufficiently. The observation method of using hand-held *WBGT* measurement devices at different points in the area is somewhat unreliable due to the time lag between recordings. In this report, the improvement of observation values using two measuring instruments was performed using the moving temperature measurement method. In addition, the results of all points under observation were shown and considered next to the present conditions of the summer thermal environment of the central districts of Kumamoto City.

2. Thermal environment survey in urban districts of Kumamoto City

The observations were carried out from 2012 through 2013 as shown in Table 1. The observation times were 9:00, 12:00, 15:00 and 18:00. Fig.1 shows the observation points. Several shopping arcades were included in these observation points. Temperature, relative humidity, *WBGT* and globe temperature were observed using mobile measuring instrument (Kyoto electronics industry, *WBGT*-113) [(3)]. Operation of the measuring instruments was in accordance with the reference manual. For instance, the influence of solar radiation on the globe temperature was considered, as such the instruments were kept in the shade during transit. *WBGT* is an index to express the degree of risk of heat stroke. In this report, the characteristics of the central districts of Kumamoto City were examined using observation results of August 8. A meteorological measuring system was installed near the point of B9 to observe the standard values; however, the observation data were not provided because of the mismanagement of the instrument. Therefore, the Automated Meteorological Data Acquisition System (AMeDAS) data were used for a comparison of all points in this study. Thus, the information related to wind velocity and direction was not used, and the local wind system such as land and sea breeze were not mentioned because the area was not so large and the influence of these on air temperature distribution was considered to be limitted.

Table 1 Observation period (2012 - 2013)

Year	Date	Remarks
2012	September 11 October 31 December 18	On August 31 was canceled because of bad weather.
2013	July 17, 19 August 8 September 13 October 31 November 28	On July 26 and August 29 were canceled because of bad weather.

●: Moving observation point

■: Meteorological measurement station

-: Arcaded street

Fig.1 Observation points in the central district of Kumamoto City (Map: Fukuoka Jinbun, Co. 'Kumamoto Grand Machizu')

Fig.2 shows the AMeDAS observation temperatures at Kumamoto meteorological observatory on July 17, July 19 and August 8, 2013. According to this data, it was seen that temperature at this time exceeded 30˚C. On August 8, the highest temperature was 33.2˚C at 12:00. The minimum

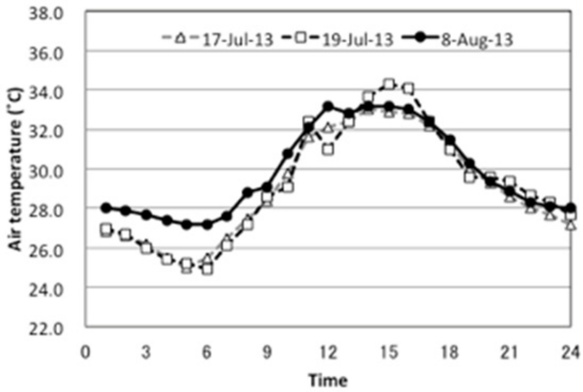


Fig.2 AMeDAS air temperature at Kumamoto meteorological observatory (July 17, 19 and August 8, 2013) [4]

temperature was 27.2˚C at 5:00 and 6:00.

There were two observation courses. With both courses, the start point of the measurement was A1, and the end point was also A1, which was the "Bipuresu Hiroba (public square)" a central downtown location. Course A moved sequentially from observation point A1 of the east side to A14, and came back to A1. Course B moved from A1 to western point B1 to B14 and came back to A1. On the basis of the observation value at A1, measuring errors were distributed proportionally depending on the movement times, and the observation data were revised at 9:00, 12:00, 15:00 and 18:00. The expression to revise the temperature were as follows:

$$T_{i,cor.} = T_{i,obs.} - \left(\frac{\Delta T}{\Delta t}\right)_{datum} \times t_{i,obs.} - def._{inst.} \quad ... (1)$$

where $T_{i,cor.}$ - corrected temperature at i point [˚C], $T_{i,obs.}$ - observation temperature at i point [˚C], $(\Delta T/\Delta t)_{datum}$ - rate of air temperature change at datum point at precise time [˚C/min], $t_{i,obs.}$ - elapsed time from precise time to i point observation [min], $def._{inst.}$ - a measurement error of the instrument [˚C].

The observations of course A were done with measuring apparatuses No. 2 and No. 4. All apparatuses were corrected on the basis of the value at 9:00 of measuring apparatuses No. 3. Generally the measurement errors by the differences of the apparatus were small.

At 9:00, the tendencies were different between the north side, A1 to A7, and the south side, A8 to A14, where these areas were separated by "Torichosuji" street. The temperature of the north side area was approximately 1.0˚C higher than the south side area. It is hypothesized that this discrepancy was caused by the cooling effect of a river. At 12:00, the temperatures exceeded 33.0˚C and over 34.0˚C between A4 to A9. It was thought that this was caused by exhaust heat from cars. At 12:00, differences in temperature were over 3.0˚C. At 15:00, there were many points at over 35.0˚C, and the places were not the same as 12:00.

So, the temperature rose between A7 to A1 and B7 to B13. It was thought that the temperatures at B7 to B13 became high because the shade of the building disappeared at 15:00. In addition, it was thought that the high temperatures at A7 to A11 were caused because they were facing the main street and that those at A12 to A14 were caused because there was a concentration of cars in the small street. When it was 18:00, the temperature difference decreased by 1.0˚C to 1.5˚C.

The observations of course B were made with measuring apparatus No. 1 and No. 3. In course B, remarkable differences were seen at 12:00. B4 and B5 were approximately 35.0˚C or more than other observation points. B14, in addition, was approximately 34.0˚C.

In case of *WBGT*, some small differences with the apparatus occurred. *WBGT* is defined and calculated as follows [3]:

$$\begin{cases} WBGT_{in} = 0.7 \times T_w + 0.2 \times T_g + 0.1 \times T_d \\ WBGT_{out} = 0.7 \times T_w + 0.3 \times T_g \end{cases} \quad \text{... (2)}$$

where, $WBGT_{in}$ - indoor *WBGT* [˚C], T_w - wet-bulb temperature [˚C], T_g – globe temperature [˚C], T_d - dry-bulb temperature [˚C], $WBGT_{out}$ – outdoor WBGT [˚C].

The expression of $WBGT_{out}$ was used in this measurement. Referring to this expression, it was thought that unevenness of *WBGT* measurement values occurred because the measurement precision of the wet-bulb temperature and the blackball temperature were lower than the case of the dry-bulb temperature measurement, including the handling of the apparatus. Table 2 shows the relations between *WBGT* and the work environment. Regarding this, the summer thermal environment at 9:00 was not as extreme because it was under 28.0˚C in course A and in course B it was around 28.0˚C. However, at 12:00 some points reached more than 30.0˚C in course A and B, and at 15:00, many points were over 30.0˚C. In addition, the points where *WBGT* were relatively high were different between 12:00 and 15:00. At 12:00, between A10 to A14 and B7 to B11, such temperatures could not be seen, but they rose remarkably at 15:00, and in places temperatures higher than 32.0˚C were seen. This tendency was similar with the case of air temperature.

3. Area classifications of the thermal environment in urban districts

Fig.3 to Fig.6 show the results of air temperature observation of course A and B. As mentioned above, all apparatuses were corrected on the basis of a value at 9:00 of measuring apparatus No. 3. Generally the measurement errors caused by the differences of the apparatuses were small.

Table 2 Relation between *WBGT* and work environment [3]

WBGT [˚C]	Permissible work level	Work strength
32.5	Very light work	*RMR*-1
30.5	Light work	*RMR*-2
29.0	Moderate work	*RMR*-3
27.5	Moderate work	*RMR*-4
26.5	Hard work	*RMR*-5

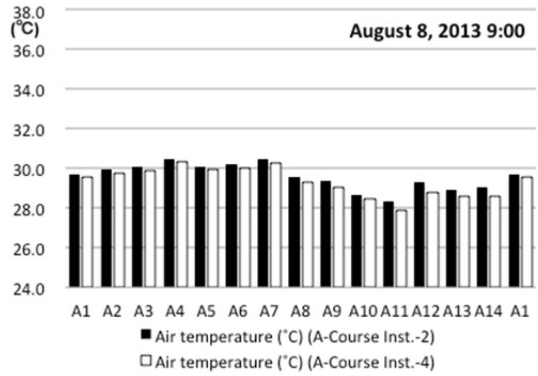
RMR: relative metabolic ratio (= energy spent by work / basal metabolism)

Table 3 shows the differences between observed temperatures and AMeDAS temperatures. Here, it should be noted that these AMeDAS values were not single-moment values but average values of several hours. The temperatures of the central districts

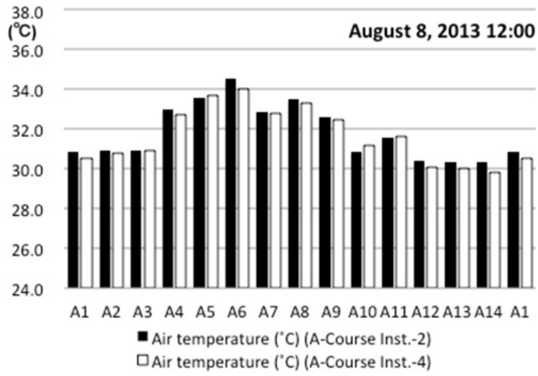
Table 3 Differences between observed temperatures and AMeDAS temperatures [˚C] (August 8, 2013).

	9:00	12:00	15:00	18:00	Remarks
AMeDAS *	29.1	33.2	33.2	31.5	
A1 †	0.5	-2.5	0.0	0.7	End of arcade, half-open
A2 †	0.7	-2.3	0.5	-1.3	
A3 †	0.9	-2.3	0.4	0.4	End of arcade, half-open
A4	1.3	-0.4	1.6	2.0	
A5	0.9	0.4	1.2	1.7	Along a national highway
A6	1.0	1.1	2.3	1.9	
A7	1.3	-0.4	2.4	2.1	
A8	0.4	0.2	3.0	1.5	
A9	0.1	-0.6	3.1	1.9	
A10	-0.5	-2.2	2.3	1.3	
A11	-1.0	-1.6	3.4	1.9	
A12	-0.1	-2.9	3.3	0.8	
A13	-0.4	-3.0	1.5	1.6	
A14	-0.3	-3.1	1.3	1.7	
B1 †	1.8	-0.5	0.6	0.6	End of arcade, half-open
B2 †	1.2	-1.5	-1.3	-0.8	Store air conditioning
B3 †	1.6	0.7	1.1	1.3	Road crossing
B4 †	1.5	1.7	1.1	1.3	
B5 †	1.3	1.8	0.9	1.0	Half-opening
B6 †	0.8	0.6	0.2	1.2	
B7 †	0.6	-1.2	0.7	0.8	End of arcade, half-open
B8	0.5	-0.9	1.3	0.5	
B9	0.7	-0.8	1.2	1.1	
B10	0.3	-1.6	1.6	0.5	
B11	0.5	-1.9	1.2	1.0	In front of city hall
B12	1.3	-1.0	0.3	1.2	
B13	1.0	-1.1	0.5	2.0	
B14	0.4	0.4	1.3	0.3	

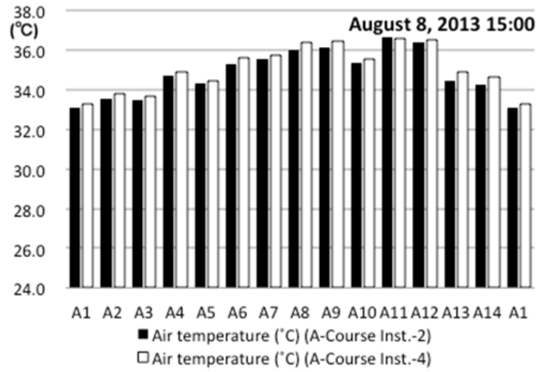
* : AMeDAS "a value every one hour ", † : Arcade.



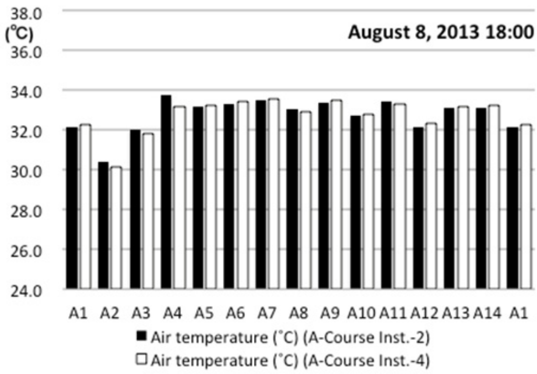
(a) 9:00



(b) 12:00

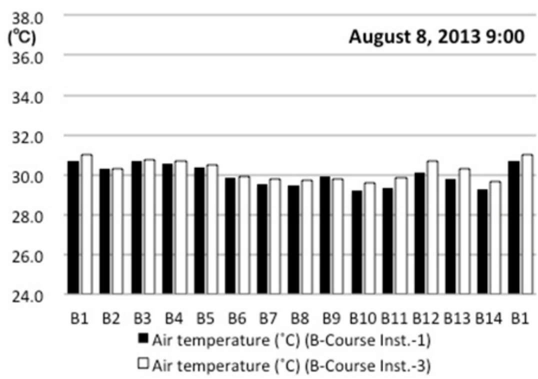


(c) 15:00

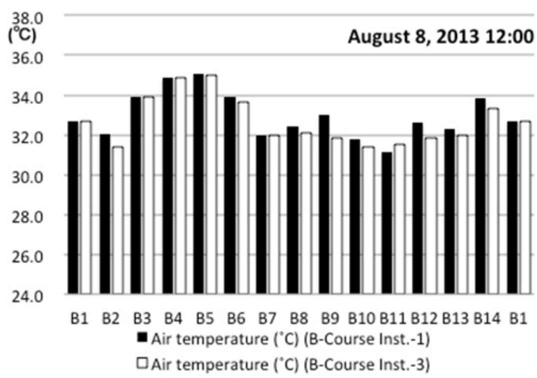


(d) 18:00

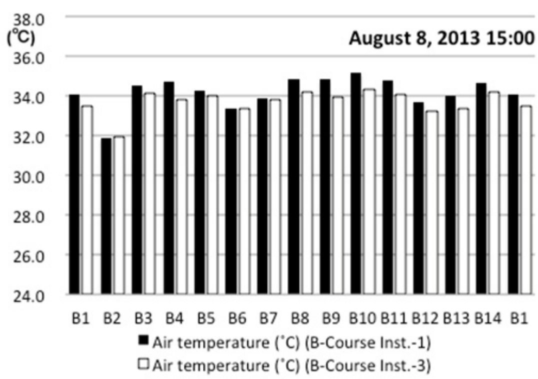
Fig.3 Revised air temperature (course A, apparatus No. 2 and 4)



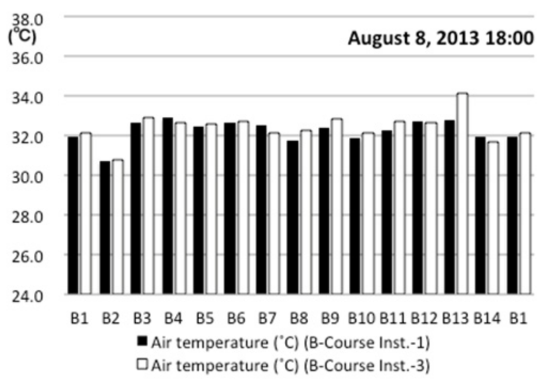
(a) 9:00



(b) 12:00

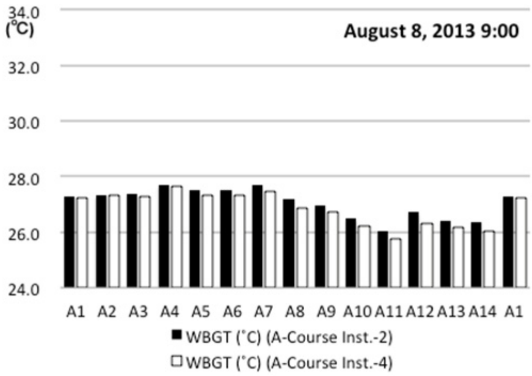


(c) 15:00

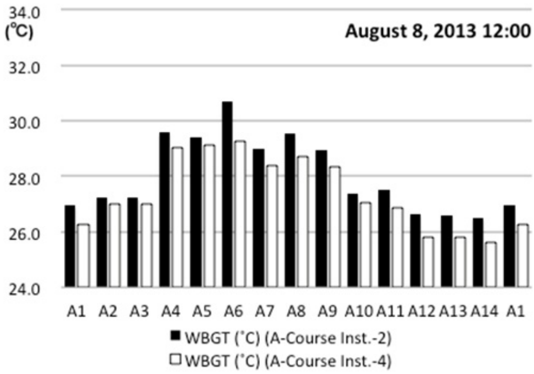


(d) 18:00

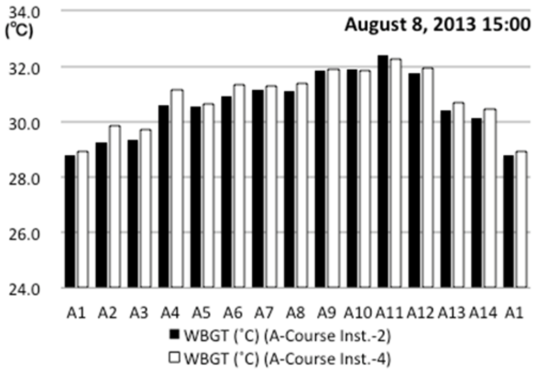
Fig.4 Revised air temperature (course B, apparatus No. 1 and 3)



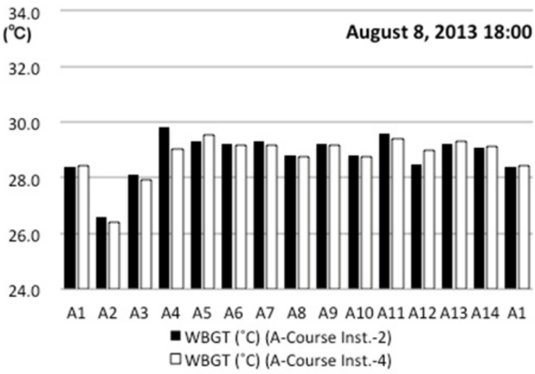
(a) 9:00



(b) 12:00

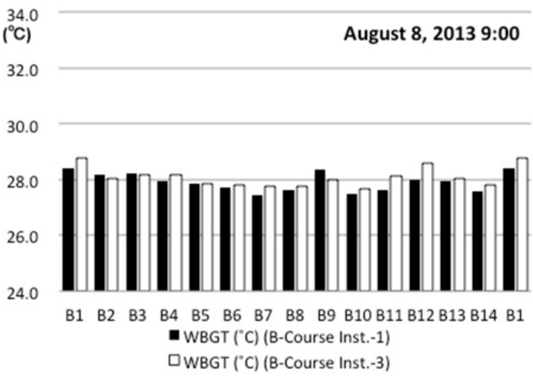


(c) 15:00

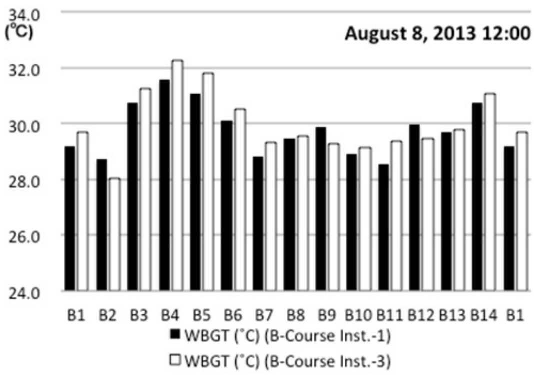


(d) 18:00

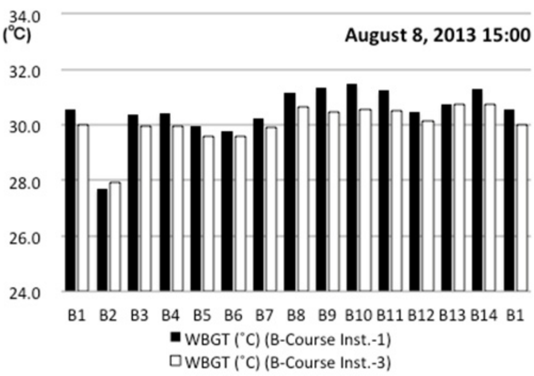
Fig.5 Revised *WBGT* (course A, apparatus No. 2 and 4)



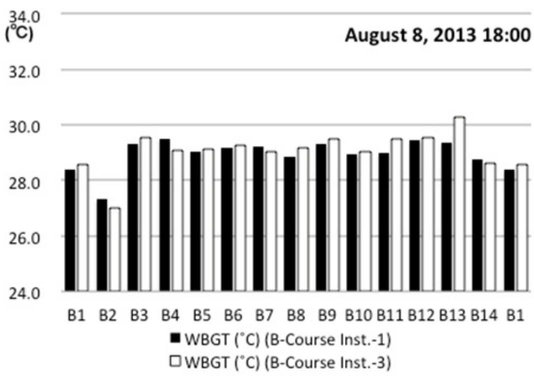
(a) 9:00



(b) 12:00



(c) 15:00

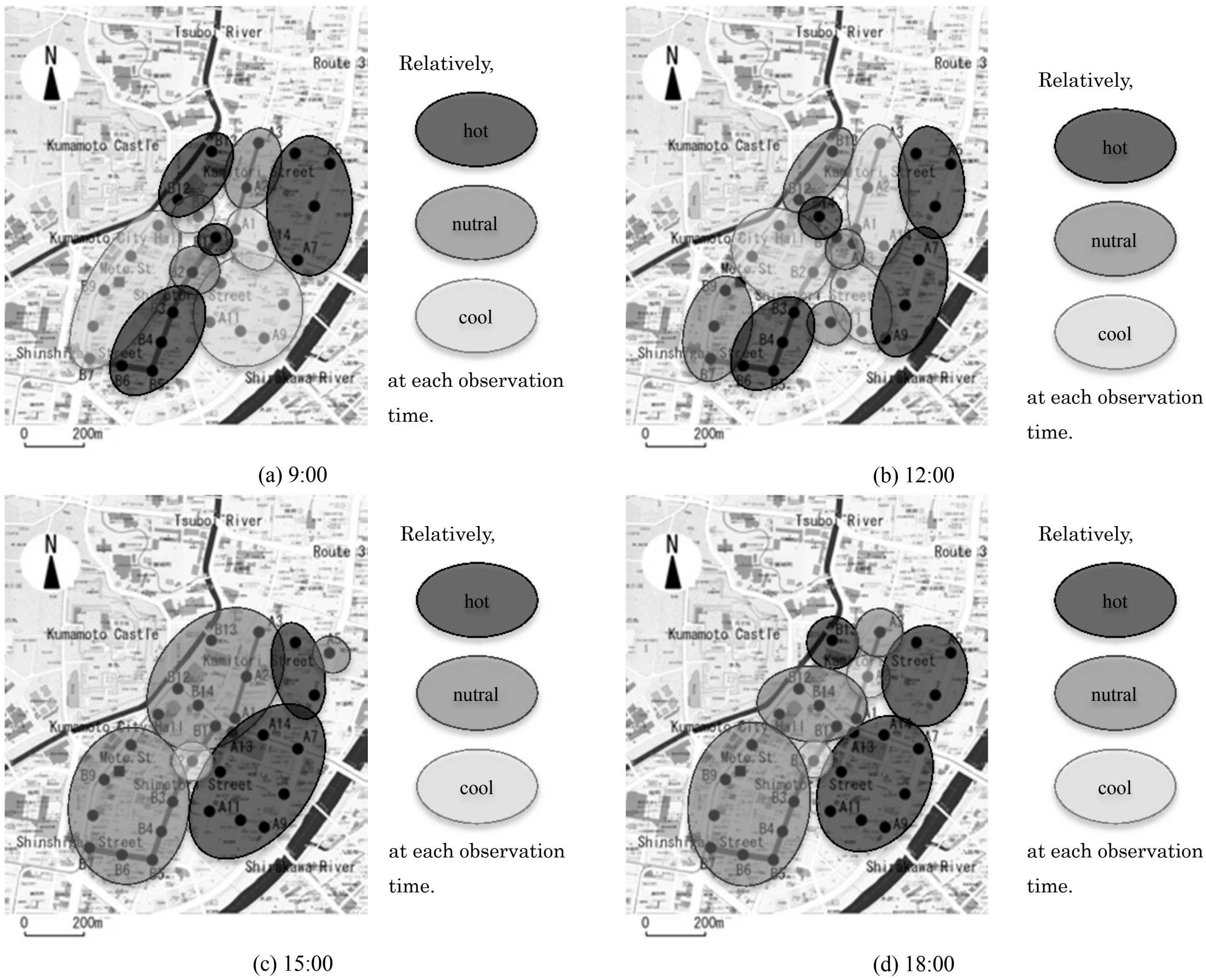


(d) 18:00

Fig.6 Revised *WBGT* (course B, apparatus No. 1 and 3) were not higher than the ones by AMeDAS at 12:00, however, they were higher than AMeDAS data at the points along National highway, A10 to A12, and at the street with a lot of traffic density.

Fig.7 shows the area classifications of the temperature differences in comparison with the AMeDAS data as the standard temperature. The points exceeding 30.0°C spread through the northern and western area at 9:00. On the other hand, the low points of 28.5˚C to 29.0˚C spread through the southwestern area. At 12:00, high temperature points of 33.0˚C to 34.0˚C were seen in the points along the National highway No. 3, the central area including points B1 and B14, and the south of the "Shimotori" arcade street including B3 to B6. The relatively low points spread through the northern and western area of the "Shimotori" arcade street. At 15:00, the points in the east area were very high and exceeded 35.0°C. It was thought that this result was caused by there the traffic of National highway No. 3. The northern and western area were beyond 33.0°C, but were relatively low. B2 was lower, but this was because air conditioning leaked outside. In the area along the national highway, drops of temperatures were slow and were 33.0˚C to 34.0˚C at 18:00. The temperatures fell relatively fast in the center of the urban districts and were almost 32.0˚C. B13 was exceptional, because the point was placed in a area of high traffic density.

These features were merely the results caused by the regional characteristics such us land use, local wind system, solar radiation shielding, stagnation of wind, and direct artificial heat. Therefore, those mechanisms should be analysed in detail to elucidate the influences of these features. However those may be, these results show the features of air temperature distributions of the related districts and how varied they can be in a relatively small space and various times of the day. Especially, the influence of heavy traffic is considered conspicuous.



(a) 9:00

(b) 12:00

(c) 15:00

(d) 18:00

Fig.7 Area classification of air temperature and *WBGT* (August 8, 2013).

4. Experimental application : examination of air conditioning energy load

Based on these results, the air conditioning energy loads were calculated. The proportions against the datum temperature (AMeDAS) were compared. The method and parameters were those of the building "Bipuresu" near A1 as in the last report (a simple room model, floor space : 5,495m^2, air conditioning temperature : 25.0˚C, building structure : reinforced concrete building) [(1)]. Table 4 shows the results of the calculation of air conditioning load for each measuring point. Additionally, Table 5 shows the proportion of air conditioning load against datum values of each time by AMeDAS. Table 6 also shows the proportion of air conditioning load against datum values of 12:00. Fig.8 shows the spatiotemporal distribution of air conditioning load change against datum AMeDAS data at 12:00.

Table 4 Calculated air conditioning load [kJ/m^{2}h]

	9:00	12:00	15:00	18:00
AMeDAS *	49.3	98.7	98.7	78.2
A1 †	55.3	68.6	98.7	86.6
A2 †	57.7	71.0	104.7	62.6
A3 †	60.2	71.0	103.5	83.0
A4	65.0	93.8	117.9	102.3
A5	60.2	103.5	113.1	98.7
A6	61.4	111.9	126.3	101.1
A7	65.0	93.8	127.5	103.5
A8	54.1	101.1	134.7	96.2
A9	50.5	91.4	135.9	101.1
A10	43.3	72.2	126.3	93.8
A11	37.3	79.4	139.6	101.1
A12	48.1	63.8	138.4	87.8
A13	44.5	62.6	116.7	97.4
A14	45.7	61.4	114.3	98.7
B1 †	71.0	92.6	105.9	85.4
B2 †	63.8	80.6	83.0	68.6
B3 †	68.6	107.1	111.9	93.8
B4 †	67.4	119.1	111.9	93.8
B5 †	65.0	120.3	109.5	90.2
B6 †	59.0	105.9	101.1	92.6
B7 †	56.5	84.2	107.1	87.8
B8	55.3	87.8	114.3	84.2
B9	57.7	89.0	113.1	91.4
B10	52.9	79.4	117.9	84.2
B11	55.3	75.8	113.1	90.2
B12	65.0	86.6	102.3	92.6
B13	61.4	85.4	104.7	102.3
B14	54.1	103.5	114.3	81.8

* : AMeDAS "a value every one hour ", † : Arcade.

5. Conclusions

To investigate urban climate by moving method is a simple method and the reliability cannot be highly asserted. However, in this study the observation differences using two apparatuses were revised and the measured values were also revised by the elapsed observation time, which improved the fault. Thus, the characteristics of the summer thermal environments of Kumamoto City districts were able to be evaluated temporally and spatially with some accuracy. It was also possible to classify the characteristic districts in each observation time. The findings of this study are briefly as follows:

1) The southeastern district, in the morning, was relatively low at a difference of 1.5˚C. It is hypothesized that this was due to the existence of a river.

Table 5 Proportion of air conditioning load against each datum value calculated using AMeDAS data [%]

	9:00	12:00	15:00	18:00
AMeDAS *	100	100	100	100
A1 †	112	70	100	111
A2 †	117	72	106	80
A3 †	122	72	105	106
A4	132	95	119	131
A5	122	105	115	126
A6	125	113	128	129
A7	132	95	129	132
A8	110	102	136	123
A9	102	93	138	129
A10	88	73	128	120
A11	76	80	141	129
A12	98	65	140	112
A13	90	63	118	125
A14	93	62	116	126
B1 †	144	94	107	109
B2 †	129	82	84	88
B3 †	139	109	113	120
B4 †	137	121	113	120
B5 †	132	122	111	115
B6 †	120	107	102	118
B7 †	115	85	109	112
B8	112	89	116	108
B9	117	90	115	117
B10	107	80	119	108
B11	112	77	115	115
B12	132	88	104	118
B13	125	87	106	131
B14	110	105	116	105

* : AMeDAS "a value every one hour ", † : Arcade.

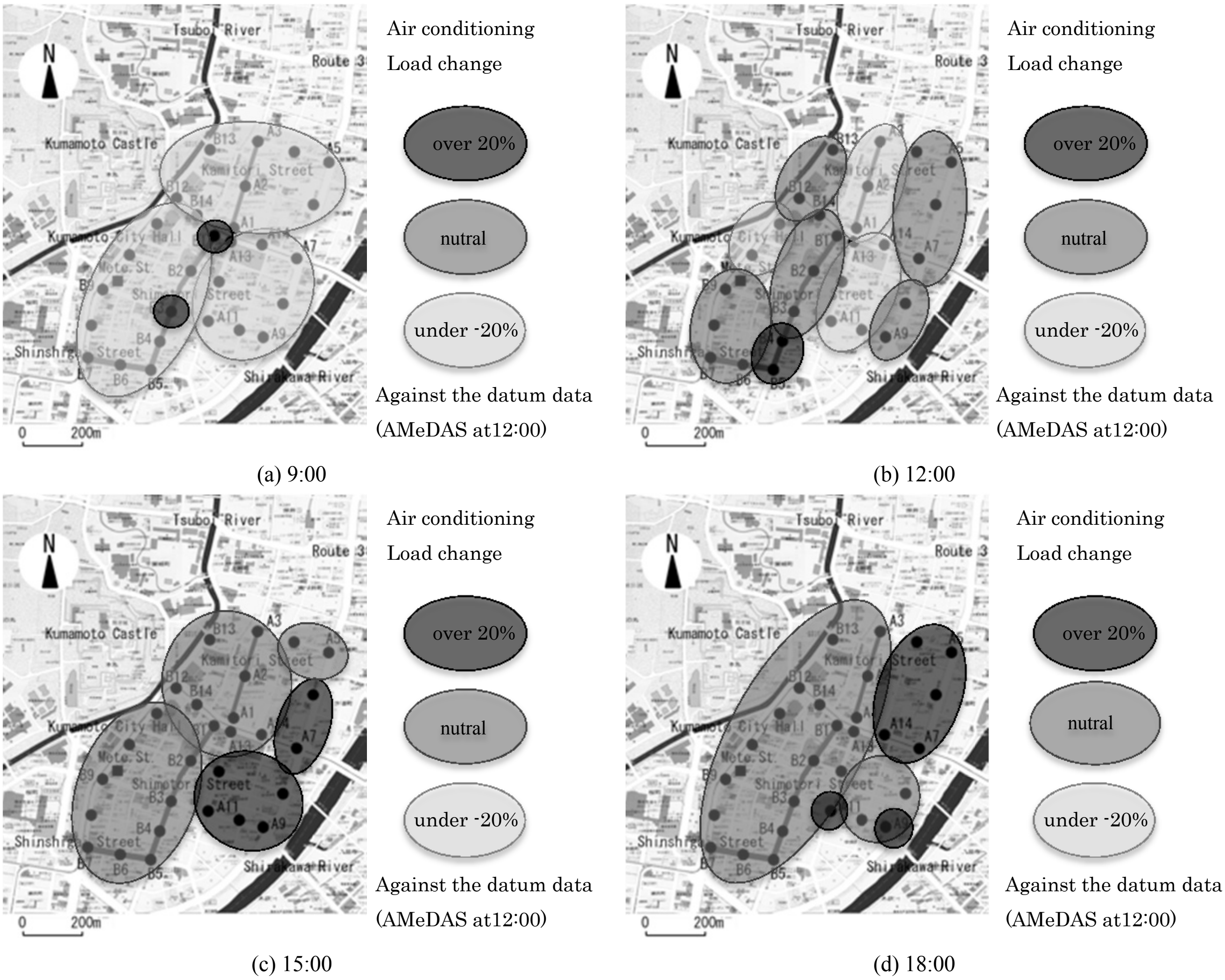


Fig.8 Spatiotemporal distribution of air conditioning load: proportion against datum observation data by AMeDAS at 12:00.

2) There were differences of 3.5˚C to 4.0˚C at noon, and the relative high temperature areas and the low temperature areas were mixed.

3) There were differences of around 2.0˚C to 3.0˚C, in the afternoon, and the high temperatures were observed along the national highway with much traffic density.

4) There were differences of around 3.5˚C, in the evening, and it was shown that areas where traffic densities were high and included extensive traffic jams had higher temperatures.

As above, it is thought that this technique is useful when the thermal environmental countermeasures of urban districts are examined because it provides effective information easily about urban districts and enables an evaluation of the influences n health and energy consumption of urban design. In addition, this technique could be applied to evaluations of air conditioning loads and carbon dioxide increases due to the aggravation of the thermal environment. Furthermore, it is thought that making spatial figure every time, as in this study, is an effective procedure and offers useful information when the thermal environmental planning and the design of urban districts are performed. Incidentally, data from another survey are currently under analysis, and a report of other findings will be taken up in the future.

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(3) Kyoto Electronic Manufacturing Co., Ltd., The heat disease

Table 6 Proportion of air conditioning load variations against each datum value calculated using AMeDAS data at 12:00 [%]

	9:00	12:00	15:00	18:00
AMeDAS *	-	100	-	-
A1 †	+6	-30	0	+9
A2 †	+9	-28	+6	-16
A3 †	+11	-28	+5	+5
A4	+16	-5	+19	+24
A5	+11	+5	+15	+21
A6	+12	+13	+28	+23
A7	+16	-5	+29	+26
A8	+5	+2	+36	+18
A9	+1	-7	+38	+23
A10	-6	-27	+28	+16
A11	-12	-20	+41	+23
A12	-1	-35	+40	+10
A13	-5	-37	+18	+19
A14	-4	-38	+16	+21
B1 †	+22	-6	+7	+7
B2 †	+15	-18	-16	-10
B3 †	+20	9	+13	+16
B4 †	+18	21	+13	+16
B5 †	+16	22	+11	+12
B6 †	+10	7	+2	+15
B7 †	+7	-15	+9	+10
B8	+6	-11	+16	+6
B9	+9	-10	+15	+13
B10	+4	-20	+19	+6
B11	+6	-23	+15	+12
B12	+16	-12	+4	+15
B13	+12	-13	+6	+24
B14	+5	5	+16	+4

* : AMeDAS "a value every one hour ", † : Arcade.

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