Academic Article

A Case Study based on Measurements of Weather and Energy Use for Heating and Cooling in an Urban Area of Kumamoto City

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ABSTRACT

Measurement instruments of weather and air conditioning electric power were installed in a building in the center of an urban district of Kumamoto city and long term measurement was performed. Based on these records, the relation between atmospheric phenomena and electric power usage for heating and cooling in the target district was explored as follows: (1) The characteristics of the atmospheric phenomena and the characteristics of electric power usage for heating and cooling were analyzed over the course of one year. (2) The relation between daily mean temperature and daily electric energy use throughout that year was analyzed. (3) The energy loads for heating and cooling were calculated based on the observed values, and then compared with the actual electric power measurement results in order to assess their validity. (4) Based on these analyses, using the moving meteorological observation results, the heating and cooling loads due to the thermal environment in the target district were calculated spatiotemporally.

Key Words : Urban heat island, Weather observation, Heating and cooling energy use

1. Introduction

Due to the rise in air temperature in urban areas in summer, countermeasures are demanded from health and environmental viewpoints. Practically, it is desirable that we improve spaces that many people use. As a result, the heating and cooling load reduction can also be expected as a result of improvements to the heat environment of the city space.

The heat environment was investigated by mobile weather observations in and around the central urban district of Kumamoto city, and the heating and cooling load was examined based on these results(1)-(4). The results from weather observations show that a temporal difference of the air temperature occurs within the same block. From this, it is possible to achieve improvement of the heat environment is possible by taking precise measures within limited space and time. In addition, we installed a weather observation system and a device for measuring the heating and cooling electric power in one building of the urban district center of Kumamoto city.

In this study, relationships between atmospheric phenomena of the target urban districts and the heating and cooling electric power based on these records was analyzed. First, based on weather observation results and data provided by the Automated Meteorological Data Acquisition System (AMeDAS), the meteorological characteristics throughout the year in an urban district of Kumamoto city and the characteristics of the heating and cooling electricity usage in the target building were examined. Next, the relationship between the atmospheric phenomena of the district and the heating and cooling electric energy in this building throughout one year were examined. Furthermore, the heating and cooling load using meteorological observation data were calculated and compared with the measured electric energy. Finally, heating and cooling load calculations were performed using the mobile observation data. Although this was only a case study, the analysis provided of the relationship between heating and cooling space and the elctric energy required for heating and cooling is significant.

2. Outline of weather observation and the heating and cooling electric energy measurement

Fig.1 shows an urban district of Kumamoto city and the spot where measurements were taken. The ■ mark indicates the spot on the roof of the building in which the weather observation system (LUFFT: WS-501) was installed. The ● marks indicate observation points for the mobile weather observations that were carried out in previous studies[4]. The building was part of Sojo Collage, and the target room was used as an exhibition room. The observation elements were: air temperature, relative humidity, wind direction and velocity, and the intensity of solar radiation. The heating and cooling electric power for every ten minutes of the first floor of the building (Green Technology: Electric power monitoring system) was measured. The floor space of the measured area of the first floor was 321.00m^2. The measurement period was from August 21, 2012 to August 25, 2015. In this study, two data points from each month, the first and the middle of month, were extracted and analyzed from the complete records covering January to December, 2014. The frequency of sampling was determined by the amount of recorded data and the convinience of analysis.

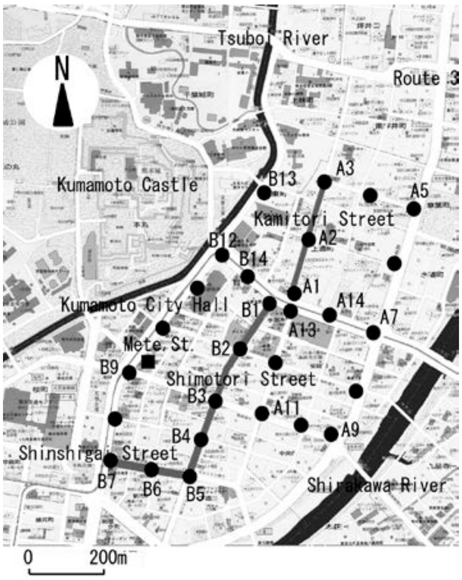


Fig.1 Kumamoto city district observation point (“Ground Machizu” by Fukuoka Jinbunsha). ■: Weather observation and air conditioning electric power measurement, ●: moving observation spots[4].

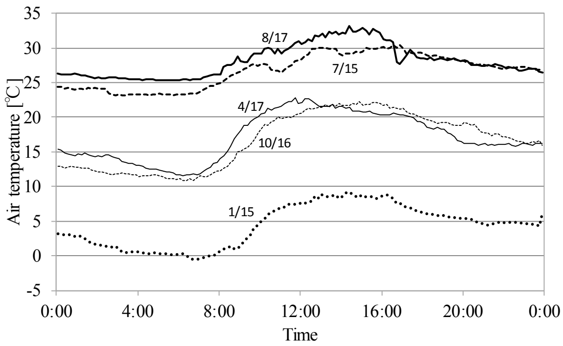
３. Observation and measurement results

3.1 Weather observation results

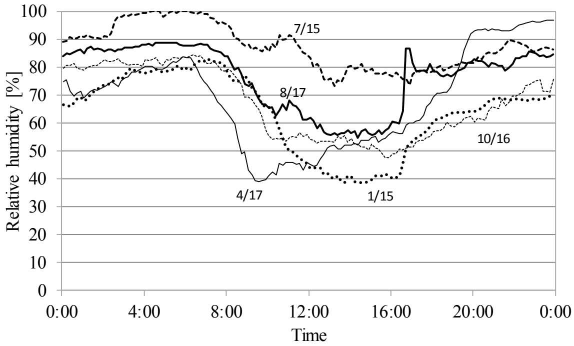
Fig.2 shows the typical seasonal weather on five separate days from the measurement records provided by the weather observation system. August 17 was a hot day where it reached 33.2℃ at 14:00, and was over 25℃ during the night. On January 15, the air temperature fell below the freezing point at night.

Fig.3 shows the daily mean, maximum and minimum temperatures, as well as the daily mean and minimum relative humidity, which were extracted from the two data points from each month in 2014. Fig.4 shows AMeDAS data at Kumamoto weather central[5] which is located approximately 1.5 km north of the weather observation spot.

As seen in Fig.3 and Fig.4, both sets of observational data corresponded well.

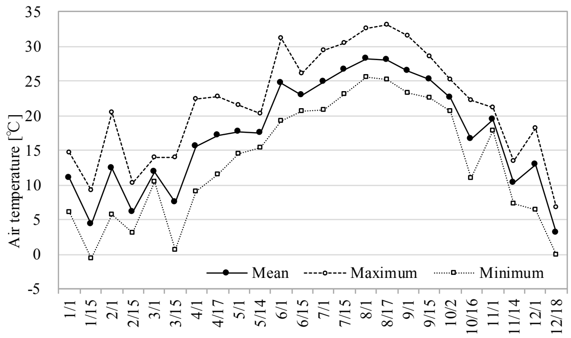


(a) Air temperature

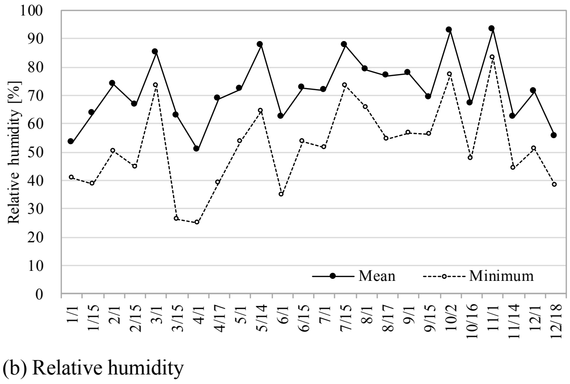


(b) Relative humidity

Fig.2 The measurement results of typical days for every season in 2014.

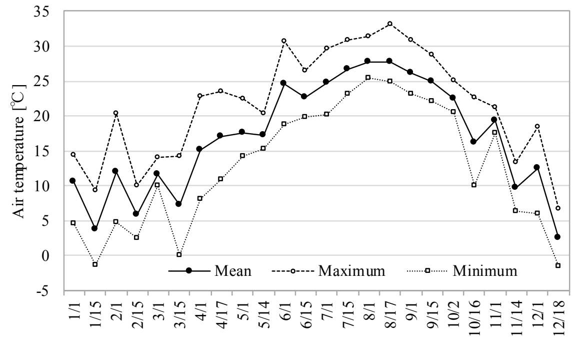


(a) Air temperature

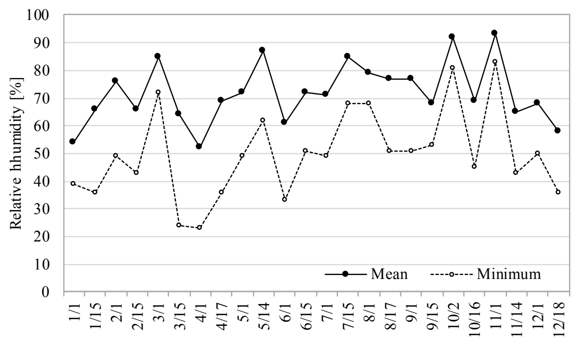


(b) Relative humidity

Fig.3 The daily mean data by observation (two selected days of each month in 2014).



(a) Air temperature

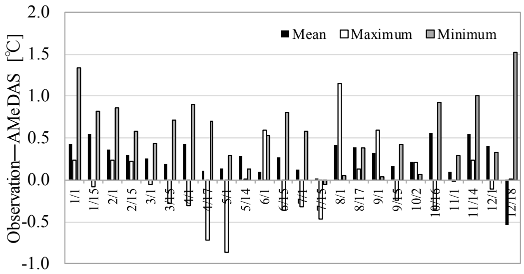


(b) Relative humidity

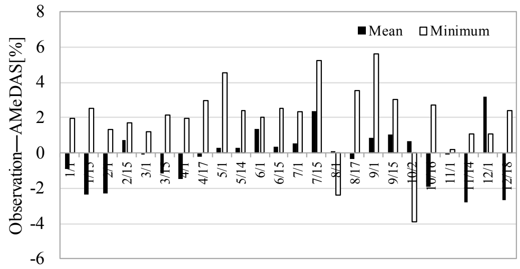
Fig.4 The daily mean data by AMeDAS (two selected days of each month in 2014)[5].

Fig.5 shows the differences in daily mean values between the meteorological observations and AMeDAS. For the mean temperature, the observation values are generally around 0.2 to 0.3℃ higher in comparison with AMeDAS values. Concerning the maximum temperature, there were days when it was around 1.2℃ higher in the summer, while the minimum temperature was, around 0.5 to 1.5℃ higher generally. In the winter, there were days when the temperature was 0.8 to 1.5℃ higher. The mean values for relative humidity were 1 to 2% higher in the summer and 1 to 2% lower in the winter, while the minimum values were 2 to 5% higher.

Fig.6 shows the correlation between the daily mean values of AMeDAS and the difference between the observation values and the AMeDAS values. To see mean temperatures, the differences of the air temperatures were not recognized so much and were around 0 to 0.5℃ higher generally. In terms of maximum temperature, there were days when the values were 1.2℃ higher than 25℃ or more. In terms of minimum temperatures, during cold seasons the temperature was 0.5 to 1.5℃ higher, and 0 to 0.5℃ higher during hot seasons. To see relative humidity, mean values varied from –3 to 2%, while the minimum values varied from1 to 5%.

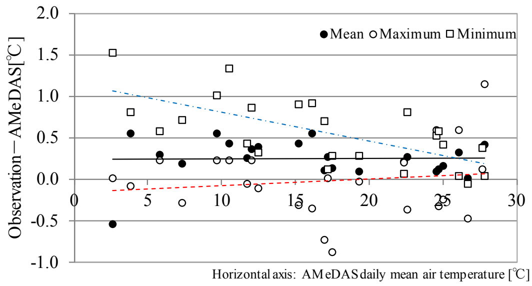


(a) Air temperature

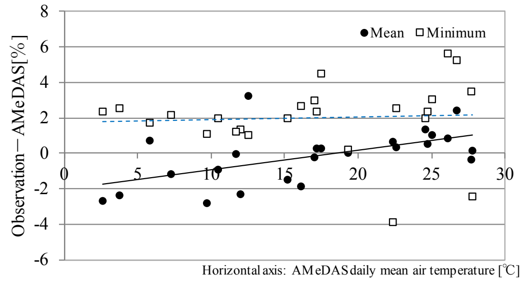


(b) Relative humidity

Fig.5 The difference of observation and AMeDAS (two selected days of each month in 2014).



(a) Air temperature

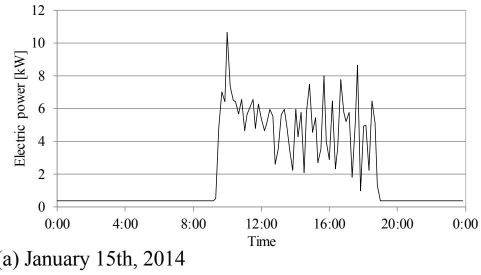


(b) Relative humidity

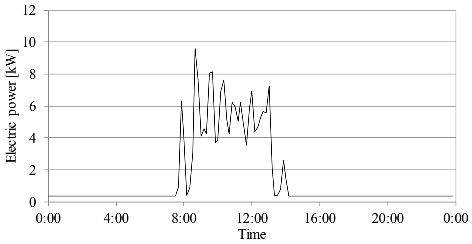
Fig.6 Correlation between AMeDAS and the difference of observation and AMeDAS (two days of each month in 2014).

3.2 Results of measurement of the heating and cooling energy use

Fig.7 shows two examples of the results of the heating and cooling energy use. On January 15th, the maximum was 10.623 kWh, the minimum was 0.372 kWh and the average was 2.251 kWh, and on August 17th, 9.950 kWh, 0.353 kWh, 1.505 kWh, respectively.



(a) January 15th, 2014



(b) August 17 th, 2014

Fig.7 Example of air conditioning energy measurements.

Fig.8 shows the daily electrical energy usage of two selected days of month throughout the year. The quantity of electricity in the winter was highest, and the electric energy, for example on January 15th when the mean temperature was 4.4℃, was 54.031 kWh which exceeded by 5 times the approximate 10 kWh value of the spring and autumn seasons. In the summer, for example on August 1st when the mean temperature was 28.2℃, the electrical energy was 39.228 kWh and it was approximately 4 times the value of the spring and autumn seasons.

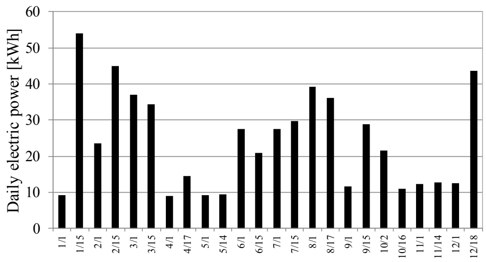


Fig.8 Daily electronic energy of each month (two selected days of each month in 2014).

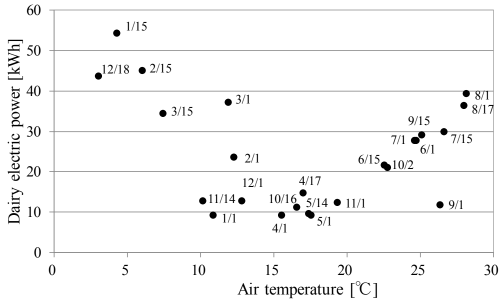
3.3 The relationship of meteorological observations and the use of heating and cooling

Fig.9 shows the relation of the mean values of temperature and relative humidity and the energy use for heating and cooling. In the winter, the electrical energy was proportional to the difference in air temperature compared with the spring and autumn seasons. It was similar in the summer. On the other hand, a clear correlation was not seen in regards to the relationship with relative humidity.

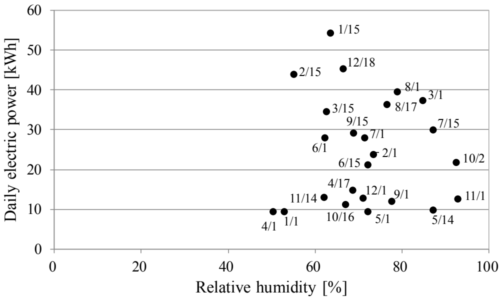
As for this measurement result, the summer and winter seasons were symmetric, so that the standard air temperature for both seasons was determined. Fig.10 shows the daily electrical energy on the vertical axis and the absolute value of the differences with the observation air temperature on the basis of 18℃ on the horizontal axis. The relationship of both are shown in this expression.

$$W = 2.693 \mid T - 18.0 \mid + 6.559 \qquad (1)$$

Here, W is daily electrical energy [kWh], and T is the daily mean temperature by observation [℃] . The coefficient of correlation was 0.822.



(a) Daily electric energy and daily mean temperature



(b) Daily electric energy and daily mean relative humidity

Fig.9 Daily electric energy and daily mean temperature and relative humidity.

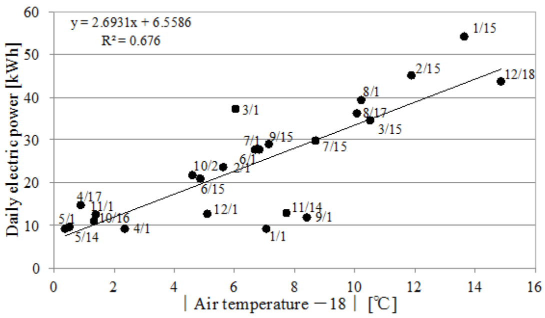


Fig.10 Daily electric energy and the absolute value of the differences with the observation air temperature on the basis of 18℃.

4. Discussion: the calculation of the energy use for heating and cooling

It is necessary to link this observation result with the heat load calculation to inform future analysis and examination. Although the model was simple and contained some hypotheses, the examination of heating and cooling calculations was performed.

4.1 **The calculation of heating and cooling energy use**

The heating and cooling load calculation was based on meteorological observation. The calculation method and the conditions of alignment were discussed in previous research[4]. A single room model of the building and calculated coefficient of heat transmission from floor space and the fixed number with reference to documents was assumed. The heating and cooling floor space was measured to be 321.00m^2 and the indoor temperature was hypothesized to be 18℃ based on the above-mentioned expression.

Fig.11 shows the relationship between the heating and cooling electrical power load that was calculated using meteorological observation and the measured electrical power. The lines in this figure show relations when the performance factor COP of the heating and cooling system was considered. The dispersion of the effective electric power depends on the operating situation of the heating and cooling system. It is necessary to investigate thoroughly the calculation method and supposition of the fixed value closely. However, as Fig.11 shows, the relations conforms well to expectations.

Fig.12 shows a value of the heating and cooling electric energy load per one hour for differences between heating and cooling temperature and outside air temperature. The relations at COP = 2 or 3 are also shown in this figure. Considering the case of the heating and cooling of one room with heating and cooling system of COP = 1, and assuming an outside air temperature of 33℃ and an indoor temperature of 28℃, then the difference becomes 10℃, and the heating and cooling electrical energy expenditure per one hour becomes 16.390 kWh/h (59.003 MJ/h). The heating and cooling electrical energy per unit area becomes 51.059 Wh/(m^{2}h) (183.31 kJ/(m^{2}h)) for one hour because the heating and cooling floor space is 321.00 m^2.

The results depicted in Fig.11 and Fig.12 suggest that the relations of the differences between outside air temperature and air conditioning temperature and the real heating and cooling electrical power can be shown with some accuracy.

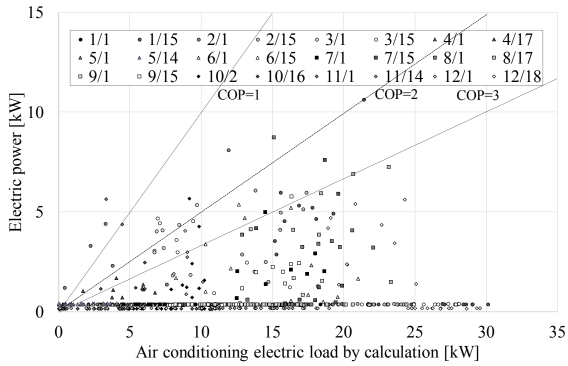


Fig.11 Comparison between air conditioning load calculated value and air conditioning electric power.

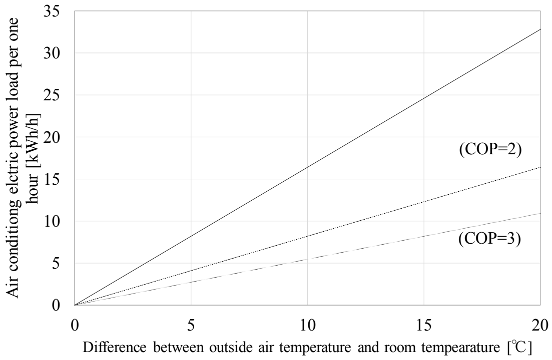


Fig.12 Sensitivity analysis of the air conditioning electric energy load calculation.

4.2 **Heating and cooling load calculation based on meteorological observation data**

Table 1 shows the calculated heating and cooling loads at 9:00, 12:00, 15:00 and 18:00 using air temperature from meteorological observations. Based on the above-mentioned considerations, a heating and cooling temperature of 18℃ and COP = 2 was assumed. Generaly, the COP value should be changed from summer to winter seasons, however, the value was determined simply because the calculation was not based on the detailed structure of the building. When the heating and cooling system is not in operation, the effective electric power becomes lower than the heating and cooling electric power load. Table 1 suggests that heating and cooling load calculation can be estimated with some precision based on meteorological observations.

Table 1 Air conditioning load calculation using the meteorological observation data in 2014 (air conditioning temperature 18℃, COP=2) .

Date	Ait temperature [℃]				Calculated air conditioning load [kJ/m^{2}h]			
	9:00	12:00	15:00	18:00	9:00	12:00	15:00	18:00
1/1	11.3	13.9	13.3	10.9	61.7	38.0	43.7	65.3
1/15	1.6	7.7	8.3	6.2	151.0	94.6	94.6	108.2
2/2	7.8	16.0	20.3	17.0	94.0	18.4	21.2	9.1
2/15	6.5	9.0	10.1	7.5	105.9	82.5	72.2	96.2
3/1	11.3	13.1	13.8	12.8	61.2	44.9	38.6	47.5
3/15	5.0	11.4	13.8	12.2	119.3	61.0	39.0	53.8
4/1	12.3	19.3	21.7	20.4	51.9	11.9	34.0	21.7
4/17	18.2	22.1	20.7	19.0	1.6	37.8	25.1	9.5
5/1	17.4	19.9	21.6	19.1	5.2	17.4	33.4	9.7
5/14	19.0	18.0	15.8	17.1	9.5	0.0	20.4	8.7
6/1	24.7	28.8	29.9	26.3	61.3	99.3	109.8	76.0
6/15	22.6	24.3	25.7	24.5	42.5	57.8	70.8	59.5
7/1	24.4	27.7	29.0	26.9	58.9	89.4	100.9	81.5
7/16	26.5	28.3	29.4	29.1	78.3	94.8	104.8	102.3
8/1	30.2	27.2	30.6	28.4	112.2	84.5	115.5	95.9
8/17	28.0	30.6	32.9	28.5	92.2	115.9	136.9	96.3
9/1	24.2	28.5	30.6	28.2	57.2	96.1	115.7	93.8
9/15	24.4	28.3	27.7	26.5	58.7	94.6	89.0	77.7
10/2	22.8	24.2	24.0	23.5	44.1	57.2	55.2	50.4
10/16	15.2	20.7	21.7	19.8	25.9	24.5	33.8	16.6
11/1	19.2	21.0	20.7	20.6	11.3	27.1	24.9	24.1
11/14	10.2	12.0	12.5	11.1	71.6	55.2	50.1	63.1
12/1	13.7	13.4	12.5	10.3	39.2	42.4	50.5	71.0
12/18	2.4	5.6	6.0	3.2	142.9	113.6	110.2	136.3

Table 2 shows the calculation of the heating and cooling load using moving observation data for August 8, 2013 assuming a heating and cooling temperature of 18℃ and COP = 2. It is thought that the temporal and spatial heating and cooling load of the target district can be shown with some reliability, although there is room to consider the operating situation, the calculation of the heating and cooling, the fixed value, and heating and cooling performance, among other factors. From this viewpoint, it is possible to demonstrate the validity of showing the heat environment of an urban district with heating and cooling load temporally and spatially using fixed-point and mobile meteorological observations.

Table 2 Test calculation of the air conditioning load using the moving meteorological observation data on August 8th, 2013 (air conditioning temperature 18℃, COP=2).

Point	Ait temperature [℃]				Calculated air conditioning load [kJ/m²h]			
	9:00	12:00	15:00	18:00	9:00	12:00	15:00	18:00
AMeDAS*	29.1	33.2	33.2	31.5	102.0	139.7	139.7	124.1
A1†	29.6	30.7	33.2	32.2	106.6	116.7	139.7	130.5
A2†	29.8	30.9	33.7	30.2	108.4	118.6	144.3	112.1
A3†	30.0	30.9	33.6	31.9	110.3	118.6	143.4	127.7
A4	30.4	32.8	34.8	33.5	114.0	136.0	154.4	142.5
A5	30.0	33.6	34.4	33.2	110.3	143.4	150.7	139.7
A6	30.1	34.3	35.5	33.4	111.2	149.8	160.8	141.5
A7	30.4	32.8	35.6	33.6	114.0	136.0	161.8	143.4
A8	29.5	33.4	36.2	33.0	105.7	141.5	167.3	137.9
A9	29.2	32.6	36.3	33.4	102.9	134.2	168.2	141.5
A10	28.6	31.0	35.5	32.8	97.4	119.5	160.8	136.0
A11	28.1	31.6	36.6	33.4	92.8	125.0	170.9	141.5
A12	29.0	30.3	36.5	32.3	101.1	113.0	170.0	131.4
A13	28.7	30.2	34.7	33.1	98.3	112.1	153.5	138.8
A14	28.8	30.1	34.5	33.2	99.3	111.2	151.6	139.7
B1†	30.9	32.7	33.8	32.1	118.6	135.1	145.2	129.6
B2†	30.3	31.7	31.9	30.7	113.0	125.9	127.7	116.7
B3†	30.7	33.9	34.3	32.8	116.7	146.1	149.8	136.0
B4†	30.6	34.9	34.3	32.8	115.8	155.3	149.8	136.0
B5†	30.4	35.0	34.1	32.5	114.0	156.2	148.0	133.3
B6†	29.9	33.8	33.4	32.7	109.4	145.2	141.5	135.1
B7†	29.7	32.0	33.9	32.3	107.5	128.7	146.1	131.4
B8	29.6	32.3	34.5	32.0	106.6	131.4	151.6	128.7
B9	29.8	32.4	34.4	32.6	108.4	132.3	150.7	134.2
B10	29.4	31.6	34.8	32.0	104.8	125.0	154.4	128.7
B11	29.6	31.3	34.4	32.5	106.6	122.2	150.7	133.3
B12	30.4	32.2	33.5	32.7	114.0	130.5	142.5	135.1
B13	30.1	32.1	33.7	33.5	111.2	129.6	144.3	142.5
B14	29.5	33.6	34.5	31.8	105.7	143.4	151.6	126.8

*: Value at each hour, †: acade street.

５. Conclusion

This study quantitatively examined atmospheric phenomena in an urban district and its relationship with heating and cooling electrical power in one room of one building. In addition, the results were connected to spatial information from previous mobile meteorological observation, and the possibility of connecting urban heat environments and heating and cooling loads was shown with some reliability. The main results of this study are as follows.

1) Meteorological observations from the target building corresponded well with AMeDAS.

2) The daily seasonal differences in electrical energy use were proportional to the differences in air temperature.

3) Regardless of heating or cooling, the use of electrical power increased in proportion to temperature differences on the basis of 18℃ air temperature.

4) Heating and cooling load calculations using meteorological observations were performed and the electrical power used for heating and cooling were quantitatively described.

5) The validity of describing the heating and cooling load in urban districts' heat environments temporally and spatially was shown using fixed-point and mobile meteorological observations.

The heating and cooling load depends greatly on the use of the building and the operating conditions of the air conditioning units. Through the accumulation and analysis of measurement records as described in this report, relations with the urban heat environment can be quantitatively evaluated with reliability. These evaluations enable a long-term analysis, and it is hoped the "LCE" evaluation can also be performed.

Although the mobile meteorological observation data and the fixed point meteorological observation data could not be connected directly, the relationship between fixed point meteorological observations and AMeDAS data was shown, as was the validity of using AMeDAS data as a standard value.

While this result emerges from a restrictive case, the analysis of the relationship between heating and cooling space and the electric energy required for temperature modulation is significant to future research in the field.

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References

(1) Takahito Ueno, Yusuke Shiki, Satoshi Doi, Chihiro Fujisue, Takahiro Tashiro, Spatiotemporal evaluation of thermal environment in urban districts: a case of Kumamoto city, Proceedings of 42th Annual Meeting of Environmental Systems Research 2014 (2014) , pp.423-428 [in Japanese].

(2) Takahito Ueno, Yusuke Shiki, Satoshi Doi, Chihiro Fujisue, Takahiro Tashiro: Spatiotemporal Evaluation of Thermal Environment in Kumamoto City Urban Districts, Journal of Heat Island Institute International, 9-2 (2014) , pp.73-81.

(3) Takahito Ueno, Tomoya Honda, Hiroki Fukushima, Daichi Masaki, A case study of thermal environment and air

conditioning energy loads in Kumamoto City urban districts, Proceedings of 41th Annual Meeting of Environmental Systems Research 2013 (2013) , pp.515-521 [in Japanese].

(4) Takahito Ueno, Takahiro Tashiro, Spatiotemporal evaluation of thermal environment in urban districts, Journal of structures and materials in civil engineering, 29 (2013) , pp.161-166 [in Japanese].

(5) Japan Meteorological Agency: Search past meteorological observation data, http://www.data.jma.go.jp/ (Accessed date: July 24, 2015) [in Japanese].

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