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Sensitivity of electricity consumption to air temperature, air humidity and solar radiation in city-block scale − Based on 2013 Osaka city observation —

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1. Introduction

In recent years, increasing air temperature in cities has become a world problem. In Tokyo which is the capital of Japan, the average air temperature has risen by about 3 °C for around 100 years (JMA Website). It is suspected that Urban Heat Island (UHI) contribute to increase around 2 °C such air temperature rise in Tokyo. Rising air temperature has various impacts on human health, lifestyle and so on. In this study, we focused on influence on energy consumption by temperature rise.

Temperature rise increase the need for space cooling during the summer seasons. However, it decrease the need for space heating during the winter seasons. Many countermeasures against UHI decrease air temperature all year around. Therefore, they may boost energy consumption. In order to prevent such a situation, we should obtain the knowledge about relationship air temperature and energy consumption. It is better to gain not only air temperature but also air humidity because some of UHI countermeasures (e.g., greening) develop the need for dehumidifying by increasing air humidity (Ihara et al., 2008a). In addition, it is effective to know relation with a fine spatial and temporal resolutions because urban climate vary from hour to hour and according to characteristics of the city-scale.

Numerous studies have reported the relation meteorological factors and energy consumption. For instance, Valor et al. conducted the relationship between electricity load and daily air temperature in Spain (Valor et al., 2001). This study used daily data and area scale was country. Hence, this study does not adequately reflect hourly temperature change and attributes of the city-scale. Ihara et al. quantified the sensitivity of electricity consumption to air temperature and air humidity in typical business area in Japan (Ihara et al., 2008b).This study area is almost office. Therefore, we analyze the sensitivity of electricity consumption to air temperature and air humidity in city-block-scale including residential area. Furthermore, we try to evaluate the sensitivity of electricity consumption to solar radiation.

2. Data and Area

2.1 Target area

Osaka city is around 223 km^2 and has about 266 million residents. We delimited ten area which is from around two and four km^2 (Fig.1 and Table 1). Parts of them include out of Osaka city (Kadoma city and Higashiosaka city). In this paper, we selected five typical area: A, B, C, D and E. We obtained data of the land use from the Osaka Metropolitan Geographical Information System (GIS) in year 2007.

2.2 Meteorological and electricity consumption data

We set meteorological instruments at roof of ten schools which is representative our selected area. We could observed meteorological data: air temperature, relative humidity, air pressure and solar radiation (the amount of global solar radiation) continuously from March, 2013 to March, 2014 (351days). Air temperature, relative humidity and air pressure were detected every 10 minutes by TR-73U (T&D). Solar radiation was detected every 5 minutes by CMP3 (PREDE). Also, we calculated specific humidity from air temperature, relative humidity and air pressure.

We received electricity consumption data (unit: MWh) of areas near these schools. The hourly data span the period from April 1, 2013 to April 1 2014. We utilize the data of electricity consumption divided by floor area of the district.

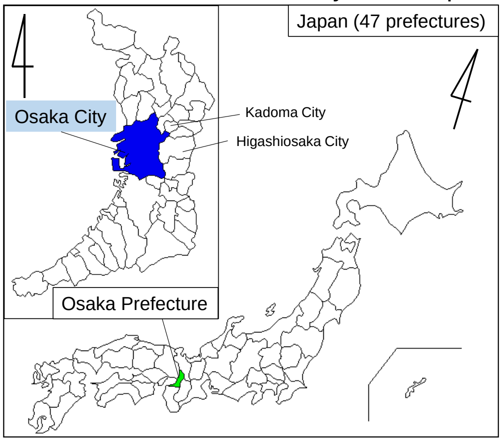

Fig. 1 The location of an observation area: Osaka City.

Table 1. Building use proportion in Osaka considered in this study.

Area name	Detached House	Apartment	Commerce	Office	Others	Total Area [km²]
A	37%	**44%**	9%	11%	31%	2.73
B	24%	**48%**	6%	3%	19%	2.52
C	**37%**	30%	11%	6%	16%	2.20
D	0%	8%	14%	**68%**	10%	2.25
E	0%	1%	3%	**87%**	9%	1.08

3. Hourly dependence of electric power consumption on air temperature

3.1 Methodology

Space cooling and heating rise the electricity consumption when air temperature increases more or decreases less than a given temperature. Ihara et al. developed the model expressed the relationship air temperature and electricity consumption (Ihara et al., 2008b). We use the same model as follows:

$$\left.\begin{aligned} E &= E_0 + \left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_\mathrm{w}(T - T_\mathrm{w}) \quad [T < T_\mathrm{w}] \\ E &= E_0 \quad [T_\mathrm{w} \le T \le T_\mathrm{s}] \\ E &= E_0 + \left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_\mathrm{s}(T - T_\mathrm{s}) \quad [T > T_\mathrm{s}] \end{aligned}\right\} \quad (1)$$

, where E[W/floor-m²] is electricity consumption per total floor area, T[°C] is air temperature, E_0 is the base load of electricity consumption, $T_{\mathrm{w},\mathrm{s}}$ are defined "turning points" of air temperature ("w" means winter and "s" means summer) and $\left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_{\mathrm{w,s}}$ [W/floor-m²/°C] is the sensitivity of the electricity consumption to air temperature.

We analyze dependence of the electricity consumption to air temperature during weekday and weekend. In this study, weekend defined Saturday, Sunday, holiday, summer vacation (from August 12th to 16th) and winter vacation (from December 29th to January 3th). We showed the results during weekday in this paper.

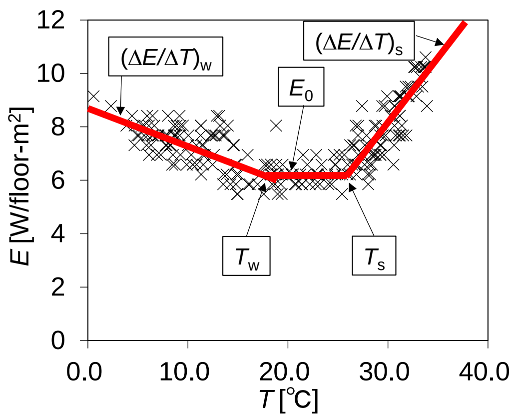

Fig. 2 Air temperature (T) vs. electricity consumption (E) at 12:00 in area A.

3.2 Result and discussion

Our analyses results are shown in Fig.3. The base loads of electricity consumption in business areas (D and E) were larger than residential areas (A, B and C) (Fig. 3 (a)). Coefficients of determination in residential areas were between 0.6 and 0.9 and nearly-constant to time. However, those in business areas were under 0.6 from 0 am to 6 am (Fig. 3 (b)).

Turning points of summer air temperature in the business areas were lower than that in the residential areas (Fig. 3 (c)). The difference was around 6°C. The reason is heat from office automation equipment. In addition, people work and emit heat in the same room. Office rooms are hotter than out of doors. Therefore, air conditioners in the business areas run earlier than one in the residential areas. Turning points of summer air temperature in the residential areas were around 28°C in the early afternoon (from 1 pm to 3 pm). We thought this result was higher than usual, however the result showed people act electricity saving. Branch points of winter air temperature in the business area were similar to that in the residential areas (Fig. 3 (d)). It is expected that branch points of winter air temperature in the business area were lower than that in the residential areas because office automation equipment emit heat. Fig. 3 (d) shows residential heating equipment need not only electricity but also town gas or kerosene.

Sensitivities of electricity consumption to winter and summer air temperature in the business areas were bigger than that in the residential areas (Fig. 3 (e)). However, sensitivities depends on base loads which is electricity consumption during not summer and winter, moreover we calculated sensitivity ratios. Sensitivity ratios were sensitivities divided by base loads (Fig. 3 (f)). Sensitivity ratios of electricity consumption to summer air temperature in the business areas were smaller than that in the residential areas. The result shows that air-conditioners in the residential areas had a more significant impact on electricity consumption than one in the business areas.

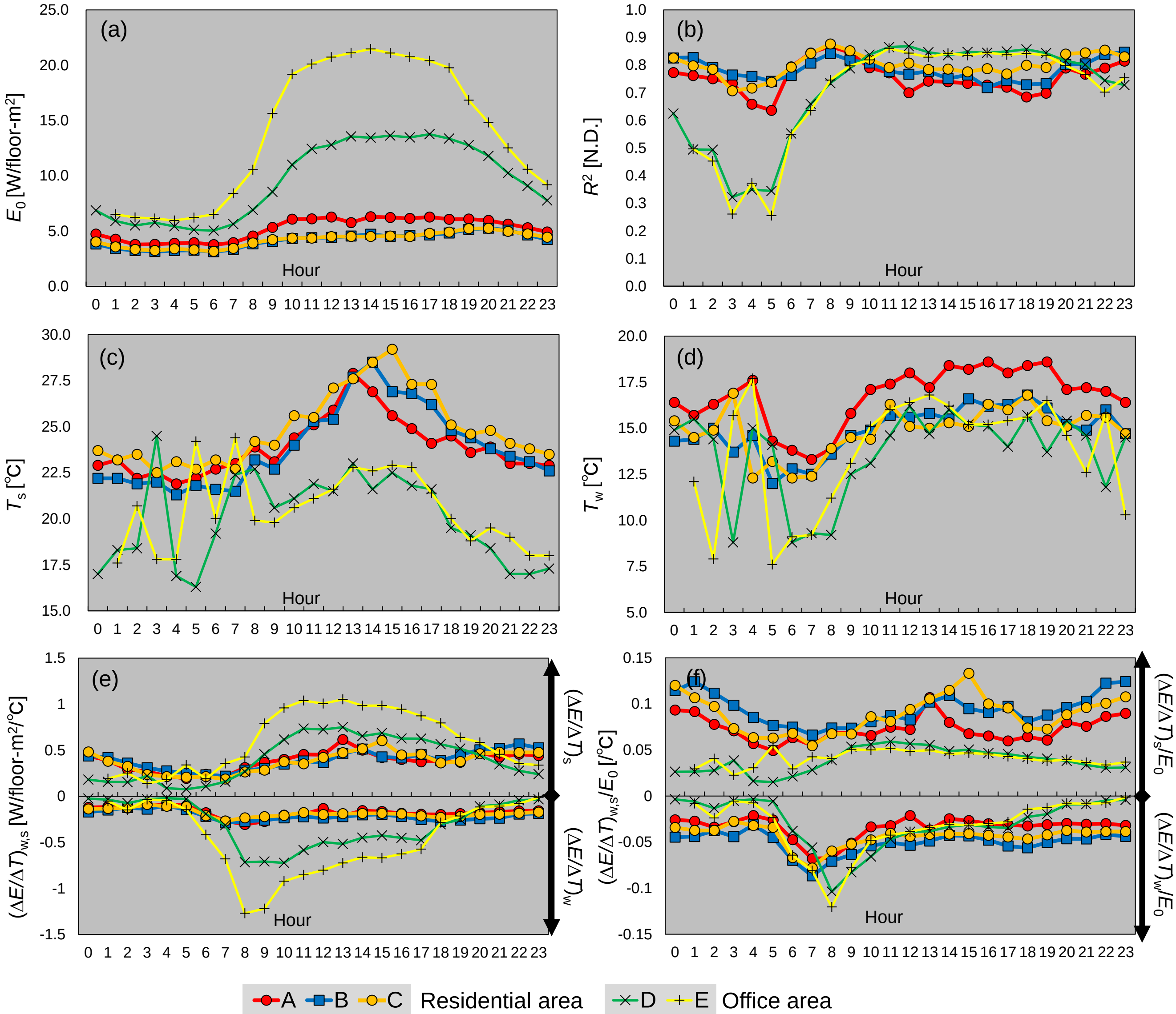

Fig. 3 Result of analyses about dependence of electricity consumption to air temperature during weekday (a) the base load (E_0), (b) coefficient of determination (R^2), (c) turning points of air temperature in winter, (d) turning points of air temperature in summer, (e) sensitivities of the electricity consumption and (f) sensitivity ratios of the electricity consumption. Note: The result of 0 am in Area D was not indeterminate.

4. Hourly dependence of electric power consumption on air humidity

4.1 Methodology

Electricity consumption is sensitive to air humidity similar to air temperature due to dehumidification. When the air temperature is decreased using air-conditioner in summer, the air around the air-conditioner's coil is condensed. Condensation need electricity to draw a latent heat, hence the higher air humidity is, the more electricity consumption is. The scheme is expressed by eq. (2) (Ihara et al., 2008b). The way of analysis is multiple regression.

$$\left.\begin{aligned} E &= E_0 + \left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_{\mathrm{w}} (T - T_{\mathrm{w}}) && [T < T_{\mathrm{w}}] \\ E &= E_0 && [T_{\mathrm{w}} \le T \le T_{\mathrm{s}}] \\ E &= E_0 + \left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_{\mathrm{s}} (T - T_{\mathrm{s}}) && [T > T_{\mathrm{s}} \text{ and } Q < Q_{\mathrm{s}}] \\ E &= E_0 + \left(\frac{\mathrm{d}E}{\mathrm{d}T}\right)_{\mathrm{s}} (T - T_{\mathrm{s}}) + \left(\frac{dE}{dQ}\right)_{\mathrm{s}} (Q - Q_{\mathrm{s}}) && [T > T_{\mathrm{s}} \text{ and } Q \ge Q_{\mathrm{s}}] \end{aligned}\right\} \quad (2)$$

, where Q[g/kg] is specific humidity, $Q_{\mathrm{w},\mathrm{s}}$ are turning points of specific humidity and $\left(\frac{\mathrm{d}E}{\mathrm{d}Q}\right)_{\mathrm{s}}$ [W/floor-m^2/g/kg] is the sensitivity of the electricity consumption to specific humidity.

4.2 Result and discussion

Turning points of summer air humidity in the business areas were lower than that in the residential areas (Fig. 3 (a)). Sensitivities of electricity consumption to summer air humidity in the business areas were bigger than that in the residential areas from 9:00 to 18:00 (Fig. 4 (b)). Sensitivity ratios from 8 am to 11 pm in the business areas were smaller than that in the residential areas (Fig. 4 (c)). The time varying of *t*-value of sensitivities in the business area was similar to that in the residential areas. The *t*-value increased until early afternoon and then decreased gradually. These results expresses ratio of air-conditioner utilization.

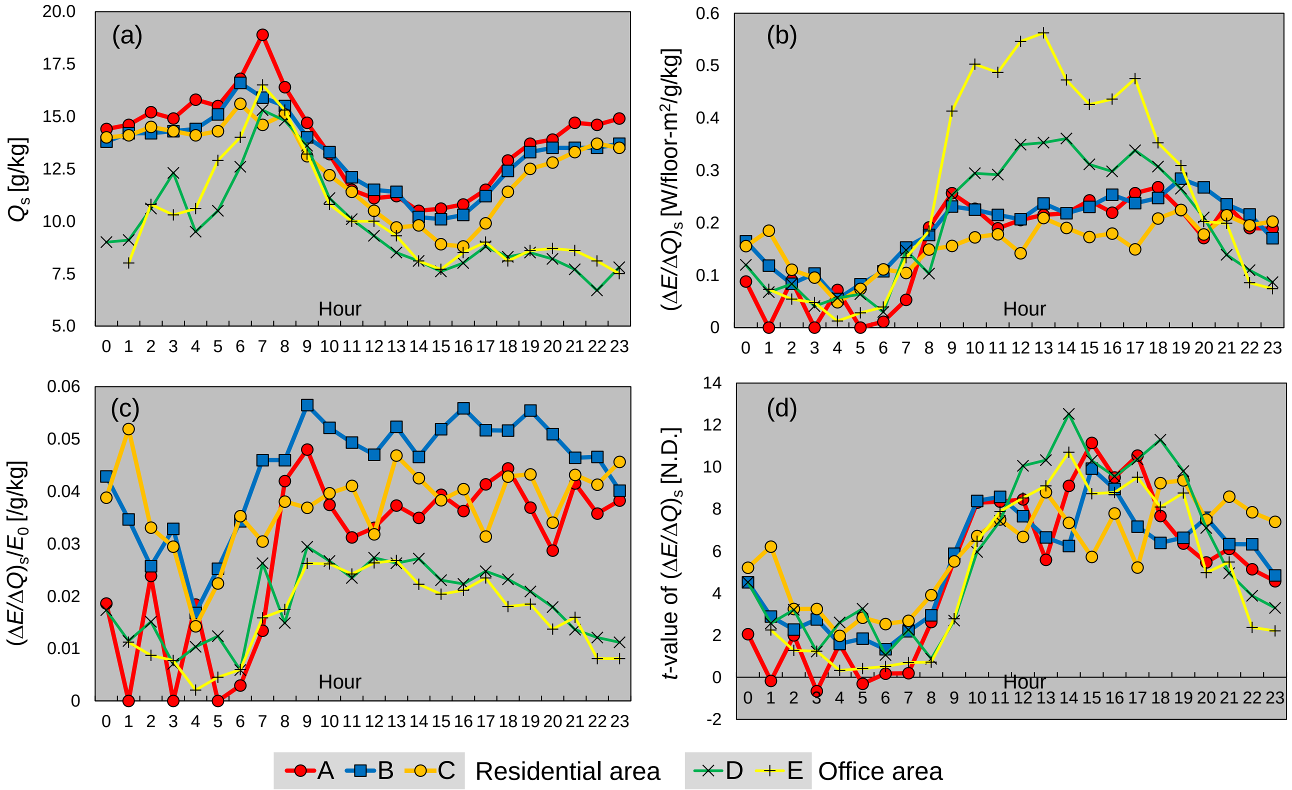

Fig. 4 Result of analyses about dependence of electricity consumption to air humidity during weekday (a) the sensitivity of the electricity consumption, (b) the sensitivity ratio of the electricity consumption and (c) t-value of the sensitivity. Note: The result of 0 am in Area D was not indeterminate.

5. Quantification dependence of electric power consumption on solar radiation

Solar radiation influence temperature and luminance in rooms. It is transmissive through windows and warming air of rooms. Also, solar illumes rooms. In the early morning and evening, the lower the amount of solar radiation is, the larger electricity consumption is. This is because people begin to switch on the illumination when it grows dark in rooms, which means solar radiation is decreased. In terms of increasing room temperature due to heat of solar radiation, the higher the amount of solar radiation is, the bigger electricity consumption is. Therefore, it complicate the relationship solar radiation and electricity consumption. Except for effect of cooling and heating, we found a negative correlation between solar radiation and electricity consumption (Fig. 5).

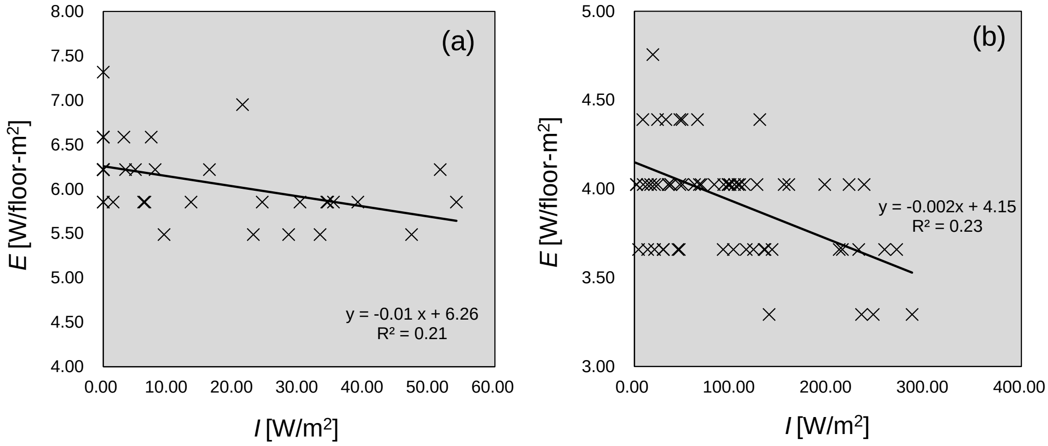

Fig. 5 The relationship solar radiation (I) and electricity consumption (E) during weekday (a) 7 am (early morning) and (b) 19 pm (evening) in Area A range of temperature is from T_w to T_s.

6. Conclusion

This study observed air temperature, relative humidity and solar radiation continuously for a year from March 2013 in Osaka city and analyzed the city-block-scale dependence of electric power consumption to air temperature, humidity. Our analysis and discussion gained the followings:

- Due to heat from office automation equipment, turning point of summer air temperature in business areas were smaller than that in residential area. The difference was about 6 °C.
- By results of sensitivity ratios, we found that air-conditioners in residential areas had a more significant impact on electricity consumption than one in the business areas.
- Turning points, sensitivities to air humidity and *t*-value of that show operation rate of air-conditioning.
- The relationship solar radiation and electricity consumption is complex because solar radiation work as light and heat. When the amount of solar radiation is small, electricity consumption of illumination and heating increase or that of cooling decrease.

Acknowledgment

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