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# Cross-Correlations among daily variations of Thermal Control Use, Thermal Sensation, Clothing Insulation and Outdoor Temperature during Cooling Season in Japan

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## Abstract

This survey was designed to investigate university student rooms to realize energy savings related to thermal control use and the relations among thermal sensation, clothing insulation, and outdoor air temperature in pre-cooling and post-cooling seasons. Results revealed the following: 1) Phase shifts to the outdoor air temperature mutually differ in pre-cooling and post-cooling seasons. 2) For neutral temperatures, although the effect of pre-cooling makes the act of opening a window less likely, that is not true in the post-cooling season. 3) For thermal sensations, the section rates of thermal control use vary in the pre-cooling season, but do not vary in the post-cooling season. 4) The clothing amount varies more during the pre-cooling season than during the post-cooling season.

## 1 Introduction

The saturation level of air-conditioner use for cooling reached 90.0% in households in Japan in 2012. An average 3.0 air-conditioners are used per domicile. The figures include cooler summer districts such as Hokkaido and Tohoku, which receive much snow during winter. It is not unusual that households have an air-conditioner for every room in the central area of general climate in Japan.

Sakane et al. (2012), however, reported that people do not necessarily depend on air-conditioners to cope with summer heat. The survey shows that 15.6% ‘Very frequently’, 45.1% ‘Frequently’, 26.6% ‘Occasionally’ and 10.4% ‘Rarely’ use air-conditioners for cooling in residences. 67.2% answered ‘I usually keep windows open in my house during the daytime in summer’. 41.2% responded that ‘I usually keep windows open in my house when sleeping in summer’. Furthermore, 10.0% chose ‘I can bear summer heat in my house only by natural ventilation’, whereas 65.1% chose ‘I can bear summer heat in my house using air-conditioners occasionally’. Surprisingly, only 24.9% chose ‘I cannot bear summer heat in my house without air-conditioners’ in a survey of 313 apartment residents in Osaka, Japan.

People do not necessarily want to use air-conditioners. They prefer to open windows instead of using air-conditioners, although the daily maximum air temperature sometimes exceeds 35°C in Osaka. Comparison to another survey by Rin et al. (2005) for similar districts reveals that the rate of satisfaction for air-conditioners was 66.8% in 2004. That rate in a survey conducted by Sakane et al. was 79.6% in 2011. Despite improvement according to the development of air-conditioners in terms of both electricity cost and thermal comfort, Miyata et al. (2012) found that various traditional measures such as sprinkling water in the garden, paper fans, bamboo blinds, and cool clothing or bedding are still used to bear the heat.

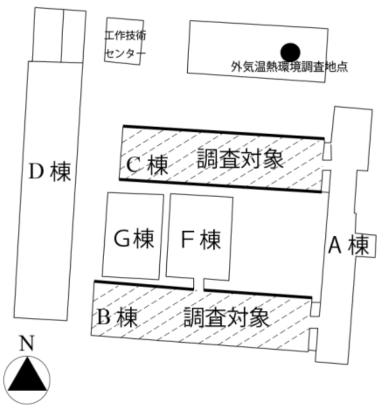
Umemiya et al. (2006) recorded both window opening and air conditioner use along with indoor thermal environment in apartment houses. They demonstrated the limit outdoor temperature of natural cooling by window opening and modelled a relation between the ratio of air-conditioner use and indoor and outdoor temperatures. Asawa et al. (2005) measured both window opening and air conditioning use in detached houses in summer. Their results showed that the outdoor wind environment affected window opening and predicted air conditioner use under specific air temperature conditions. This study examined daily records of both window opening and air conditioner use during pre-cooling and post-cooling seasons. Moreover, thermal sensations in indoor and outdoor and clothing were recorded. The subjects of the study were university students. The thermal environment was measured in laboratory rooms.

## 2 Methods

### 2.1 Measurements and observations

University laboratory rooms are spaces where students spend almost all of their time from early morning to late evening. Students select clothing, open windows, and change air-conditioner setting temperatures as they like without payment of an energy charge. Indoor air temperatures and humidity, and outlet air temperatures of the air conditioners were recorded in 28 laboratory rooms from the second to fifth floor in two university buildings at intervals of 30 min during May–November. Rooms with temperature control for special experiments were excluded. Only rooms occupied by students were chosen.

States of window opening were recorded by observations conducted from outside of the buildings at around 10:30 and 16:10 during Monday–Friday for all windows of the buildings. There were 352 windows on one side of the building. Three sides were examined, as Figure 1 shows. The opening ratio to the maximum opening area was recorded at five degrees. The observers were students occupying the measured rooms. The observation took about ten minutes. Observers also recorded their indoor and outdoor thermal sensation in the ASHRAE scale, thermal comfort using a four point scale, in addition to humidity sensation and clothing ensembles at the same time as the window observations. The outdoor air temperature, humidity, solar irradiance, wind velocity, and direction were measured at intervals of ten minutes on the rooftop of the neighbouring building.




● : outdoor measurement point

Windows of thick lined sides were observed.

Figure 1. Plan of the buildings and picture of the north elevation of Building-C.

### 2.2 Definitions of ratio of air-conditioner use and ratio of opening

Air conditioner use was judged from the difference of indoor and outlet temperatures. The ratio of air conditioner use was defined as the ratio of the number of air-conditioned rooms to all measured rooms for three records before and after the window observation time. The ratio of opening is defined as the ratio of opening area of all student room windows against the full open area.

### 2.3 Definitions of seasons

Figure 2 shows the daily variation of the ratio of air conditioner use averaged for morning and afternoon. The ratio begins to increase from mid-May. The period before June 2 is defined as the 'spring natural ventilation season' when the daily mean number of air-conditioned rooms is less than 1.5. The period between June 3 and June 22 is defined as the 'early cooling season' until the use ratio reaches 0.5. The period between June 23 and September 21 is defined as the 'cooling season' when the use ratio is higher than 0.5. The period between September 22 and October 3 is defined as the 'late cooling season' when the number of air-conditioner use is greater than two. The period between October 4 to November 7 is defined as the 'autumn natural ventilation season' because 9 of the 28 rooms began to use heaters from the week of November 7. In this study, the spring natural ventilation season and early cooling season are collectively designated as the pre-cooling season. The late cooling season and autumn natural ventilation season are collectively designated as the post-cooling season.

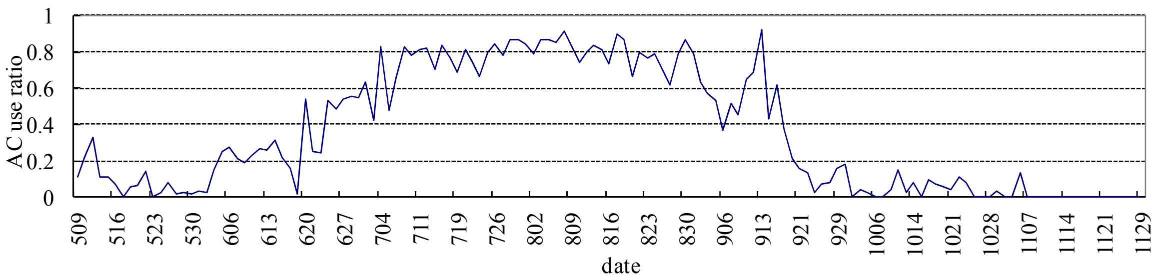



Figure 2. Daily variation of air-conditioner use ratio.

### 2.4 Data preparation to assess the phase difference

Raw data acquired twice a day were averaged for the day, except for failed measurements. Daily data were averaged for a week. In this study, weekly variations of thermal environment, thermal control use, thermal sensation and clothing insulation were standardized for mutual comparison. In equation form, standardized values $z_n$ are the following.

$$z_n = \frac{(u_n - \bar{u})}{s} \qquad n = 1, 2, \ldots, N \qquad (1)$$

In those equations, $N$ stands for the number of data samples. $u_n$ are the original data values. $\bar{u}$ signifies the sample mean. $s$ denotes the sample standard deviation. The sample mean of $z_n$ is zero. The sample standard deviation is unity.

## 3 Weekly variations

### 3.1 Variations of outdoor thermal environments

Figure 3 shows weekly variations of outdoor thermal environments. Outdoor thermal environments were measured at intervals of 10 min and were averaged for 1 h before and after the observation. The metabolic rate for SET* is presumed as 1.5 for conditions of standing and walking slowly. The clothing insulation was estimated according to ISO9920-1995. Indoor clothing was the same as outdoor clothing in almost all cases.

The outdoor temperature increases steeply during the rainy season of May 26 – July 8. After the season it becomes stable at high values of nearly 30°C. It begins to decrease from September to the end of the survey with the decreasing gradient lower than when it increases.

The outdoor humidity ratio is higher in summer and lower in pre-cooling and post-cooling seasons. The data vary similarly to those of the outdoor temperature, although outdoor relative humidity is almost constant for the survey period.

No particular tendencies are apparent for variations of solar irradiance or wind velocity. The variation of outdoor SET* is similar to that of outdoor temperature.

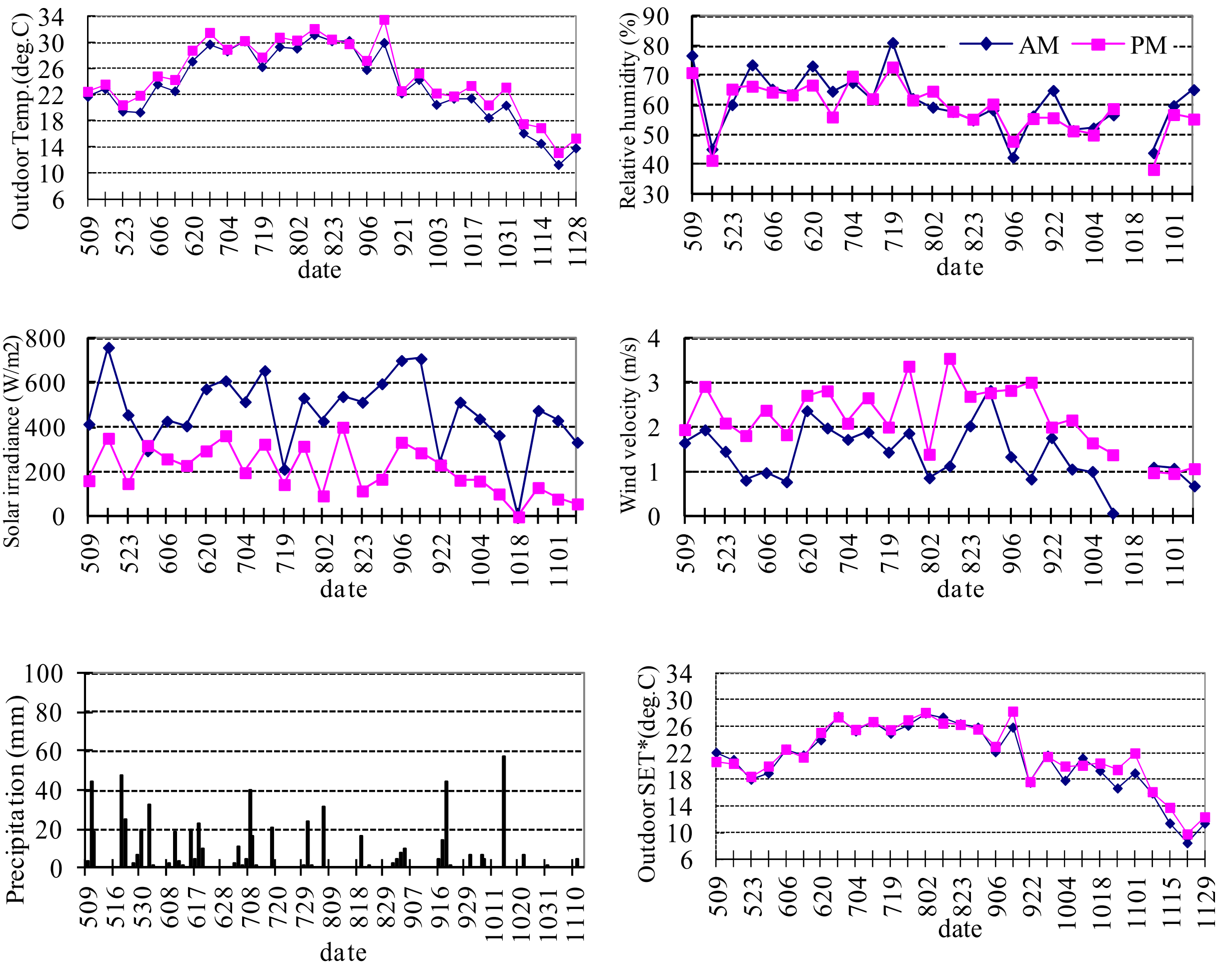



Figure 3. Weekly variations of outdoor thermal environments.

### 3.2 Variations of indoor thermal environments

Figure 4 shows weekly variations of indoor thermal environments. Indoor air temperature and humidity values were the averages of measurements for 28 rooms. Indoor wind velocity was not measured in this survey, but it was presumed to be 0.2 m/s for 22 rooms without electric fans and 0.8 m/s for six rooms with electric fans until the beginning of October.

The indoor air temperature was maintained at around 27°C from the beginning of July to mid-September, probably because of air conditioning. It begins to decrease since mid-September at an almost uniform gradient to the end of the survey. Both the indoor relative humidity and the humidity ratio vary similarly to the indoor temperature. The indoor relative humidity falls less than 40% from October.

Indoor SET* in rooms with an electric fan varies around 24°C. From July through September, it is about 3° cooler than in rooms without electric fans.

If indoor temperatures are compared according to the direction of the rooms' facing, either north or south, little difference is apparent until late September, but from October, temperature in rooms facing south are about 1 degree higher than in rooms facing north.

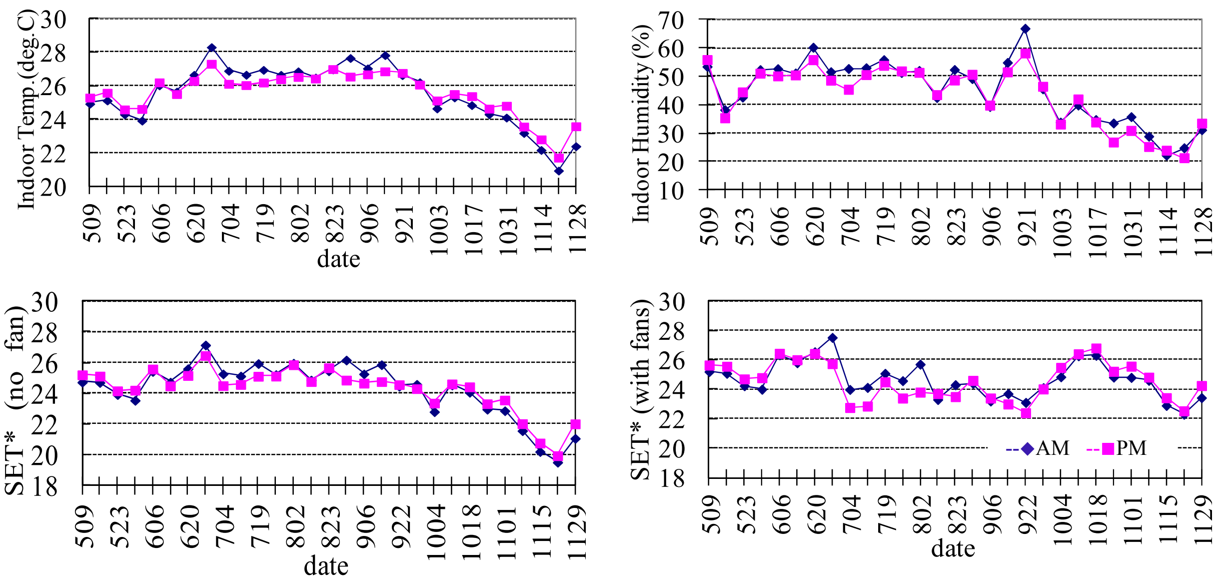



Figure 4. Weekly variations of indoor thermal environments.

### 3.3 Variations of thermal sensation and clothing insulation

Figure 5 shows weekly variations of outdoor and indoor thermal sensation and clothing insulation. Outdoor thermal sensation begins to increase from a neutral sensation at the end of May and reaches 7 at the end of August. Then the fluctuation decreases. It fell short of 4 at the end of September. Outdoor thermal comfort changes gradually from 'comfortable' to 'slightly uncomfortable' from May to late June. It is around 'slightly uncomfortable' from late June to the end of July. The fluctuation decreases in August and September. It is most 'comfortable' in October and increases again in November. The indoor thermal sensation is maintained at around 'neutral' until the beginning of November.

Clothing insulation begins to increase gradually at the beginning of June. It varies between 0.4 and 0.5 clo from July through September and begins to increase in late September. It increases steeply and reaches 0.6 clo in mid-October. Then it approaches 0.6 slowly.

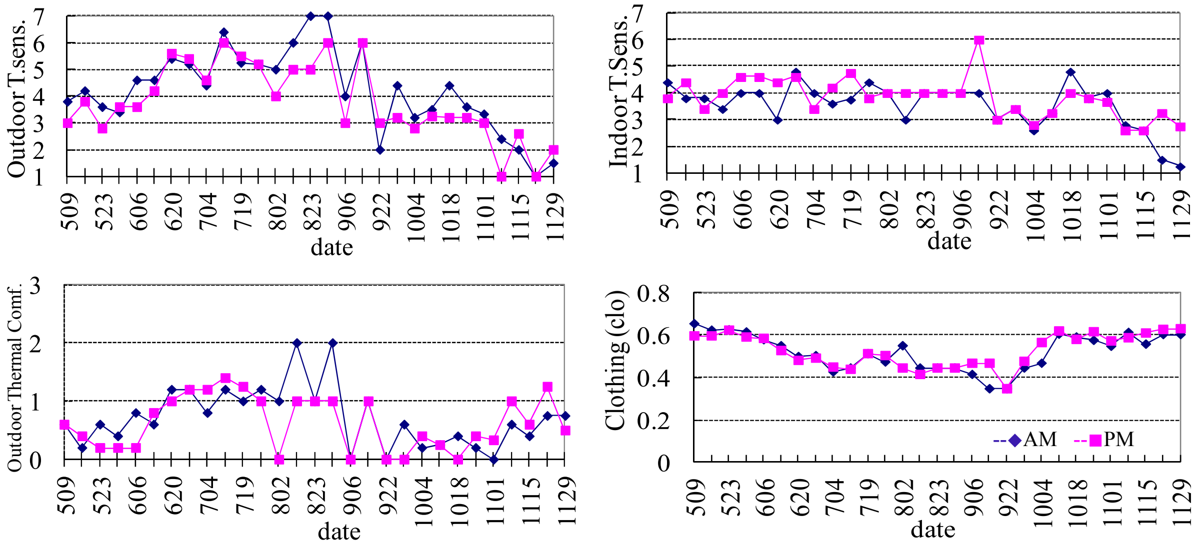



Figure 5. Weekly variations of thermal sensation and clothing insulation.

### 3.4 Variations of air-conditioner use ratio and window opening ratio

Figure 6 portrays weekly variations of the air-conditioner use and window opening ratios.

The ratio of air-conditioner use decreases in mid-May and increases again from June. It increases constantly and reaches a peak in mid-July. The high ratio is maintained until mid-August, when it begins to decrease, reaching zero in October. The rate of decrease is higher than the rate of increase. It increases smoothly but fluctuates more than when it is decreasing.

All windows of the buildings were observed. The opening ratio of all windows of laboratory rooms was used to define the window opening ratio.

The window opening ratio increases steeply between late May and mid-June. The peak value for the survey period comes in mid-June. After that peak, it begins to decrease steeply. The decreasing period accords to the rainy season. From mid-July, the end of the rainy season, it varies around 0.01 until early September. It becomes higher in September, although a trough is apparent in mid-September. It peaks again at mid-October and decreases slowly in November.

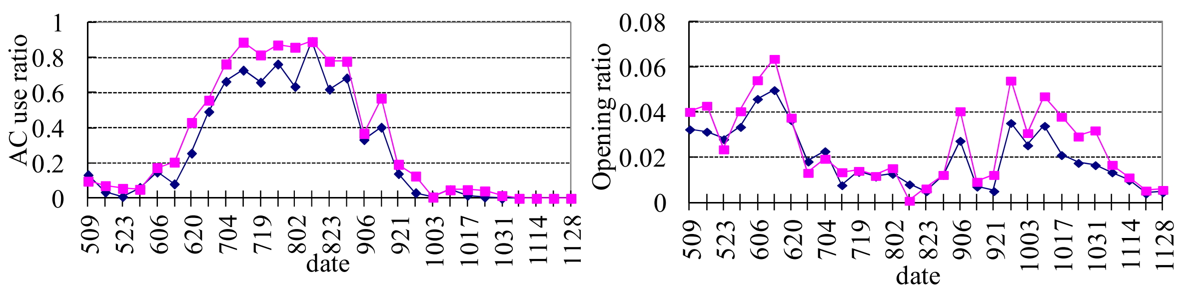



Figure 6. Weekly variations of thermal control use

## 4 Comparison among variations

Figure 7 portrays a comparison of variations of outdoor air temperature, outdoor thermal sensation, clothing insulation, air-conditioner use ratio, and window opening ratio. Values were standardized by the sample means and sample standard deviations, as described in 2.4.

Outdoor temperatures change from minus to plus at the end of May and change from plus to minus in mid-September. The plus duration is consistent with the total period of the early cooling season and cooling season.

Phase differences can be clarified by standardizing by each mean and each standard deviation. The variation of outdoor thermal sensation almost agrees with the variation of outdoor temperature. Air-conditioner use also changes similarly to outdoor temperature in the post-cooling season, but it is delayed about two weeks to the outdoor temperature in the pre-cooling season. Variations of air-conditioner use and window opening have just the reverse phases: they cross zero at almost identical times. Window opening changes reversely to the outdoor temperature. The zero agrees in the post-cooling season, but it is delayed about two weeks in the pre-cooling season. Clothing insulation lags the outdoor temperature by about one week in the pre-cooling season, but it lags about two weeks in the post-cooling season.

Agreement between air-conditioner use and window opening signifies that natural ventilation by window opening is used to control the indoor thermal environment as a substitute of air-conditioners. It supports the results of the former questionnaire surveys showing that occupants tend not to depend entirely on air-conditioners.

Certain time lags are apparent in adaptation to the change of outdoor temperatures in the changes of clothing and thermal control use. Occupants change their clothing in response to the outdoor temperature change, not in anticipation of it. The delay period is longer in the post-cooling season than in pre-cooling season. That fact might be associated to physiological or social aspects, or it might be associated with the difference of the effort to replace the wardrobe. Differences of clothing insulation are mainly caused by differences between short sleeve shirts and long sleeve shirts. Long sleeve shirts can be worn in all seasons, but students must prepare short sleeved shirts only for summer.

Air-conditioner use also lags the outdoor temperature. Air conditioners are used as the outdoor temperature increases, but with a time lag of about two weeks. However, air-conditioner use stops without a time lag when the temperature decreases. This is apparently related to the consciousness of air-conditioners as luxury devices. People feel hesitation to start air-conditioning in the pre-cooling season even if they feel warm. However, they feel able to stop it easily in the post-cooling season because they can stop it at the end of the day.

There is no adaptation time lag in thermal sensation to the outdoor temperature change in both pre-cooling and post-cooling seasons, different from the clothing and thermal control

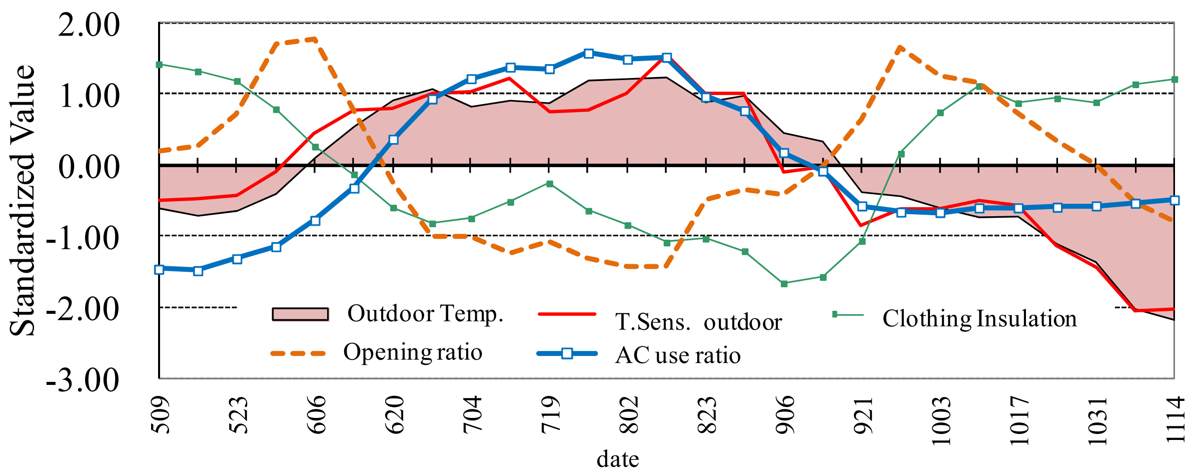



Figure 7. Comparison among weekly variations.

use. Occupants begin to feel warmer or cooler without lags according to the outdoor temperature change. Physiological abilities such as perspiration or blood flow control require a certain time to complete. However, Umemiya (2006) shows that the metabolic rate fall preceded the outdoor temperature increase in summer on the basis of identical thermal condition experiments throughout a year. Physiological items were not measured in this survey, but it is presumed that these abilities are acquired gradually in advance of the outdoor temperature change, so thermal sensation has no delay compared to the outdoor temperature change.

## 5 Conclusions

The indoor and outdoor thermal environment and air-conditioner use were measured in 28 rooms at 30 min intervals. In addition, the opening situations of 1056 windows were observed and indoor and outdoor thermal sensation and clothing ensembles were recorded twice a day from pre-cooling to post-cooling seasons at a university in Osaka. Results of the survey reveal the presence of a phase shift to the outdoor air temperature in thermal control use and clothing insulation, although no shift difference is found for thermal sensation. The phase shift differs between pre-cooling and post-cooling seasons. Variations of ratios of air-conditioner use and the area ratio of window opening are just in-phase in both pre-cooling and post-cooling seasons.

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