3.4 **EVALUATION OF HUMAN THERMAL COMFORT USING A METEOROLOGICAL APPROACH**

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1. INTRODUCTION

Climate change issues—their impact and importance—are not only of interest to climatologists, but also to the general public. Climate change and variations affect many aspects of human life (e.g., agriculture, economics, and human health). Human thermal comfort has close relationships with behavioral temperature regulation, such as adding or removing clothing and opening or closing of windows, and with the mean skin temperature, which is affected by the environment. The indoor thermal comfort temperature for humans is often described relative to the outdoor climate conditions. Based on the results of many field surveys, Humphreys (1976) reported that the relationship between a comfortable temperature and the outdoor monthly mean temperatures is closely correlated. Auliciems (1981) proposed the Adaptive Model (AM), which provides a linear expression of the relationship between comfortable temperatures and the outdoor monthly mean temperatures that explains building structures and clothing, depending on the

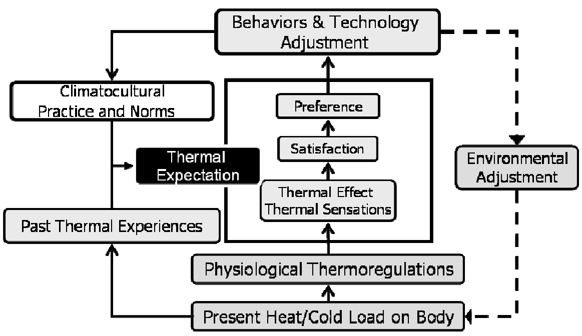

Fig. 1. Conceptual scheme of thermoregulatory functions caused by both autonomic and behavior control (after de Dear et al. 1997)

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climate of each region. de Dear et al. (1997) and de Dear and Brager (1998) suggested that the AM is a more suitable criterion for describing indoor thermal comfort, especially with natural ventilation, than other criteria of thermal comfort derived from energy balance equations. The AM was adopted as ASHRAE standard-55 for spaces with natural ventilation (ANTI/ASHRAE 2004).

The optimal levels of human health and temperature regulation resulting from past exposure serve as benchmarks for environmental evaluation.

Human thermal regulation systems function as a negative feedback control system, and play a role in thermal comfort by triggering behavioral temperature control and reacting to the environment, including the outdoor climate, as turbulence (Fig. 1). Some studies suggest that the climatic values for explaining human health or thermal comfort should be derived by a feedback system (McCartney and Nicol 2002; Horie et al. 2008). Additionally, the monthly mean air temperature, as defined for the AM, or an assessment of human health, is almost little ground of thermal regulation, although disorders or mortality due to climatic occurrences lags from the onset of climate events by 0-13 days in winter and 0-1 days in summer (Hajat *et al.* 2007). However, few studies describe human temperature regulation as a negative feedback control system and climatology to be its disturbance factor. For evaluating the effect of climate on humans, we often use an unweighted average, such as the monthly mean. Thermal comfort for indoor conditions is sometimes evaluated by the monthly mean air temperature. However, these techniques are insufficient because: (1) human temperature regulation might act as a negative feedback control system and climatology might be its disturbance factor; (2) the most suitable period for determining the impact of climate change on humans is during the time lag between the experiences of the climatic events and the observation of the effects on humans. The objective of this study is to improve techniques for

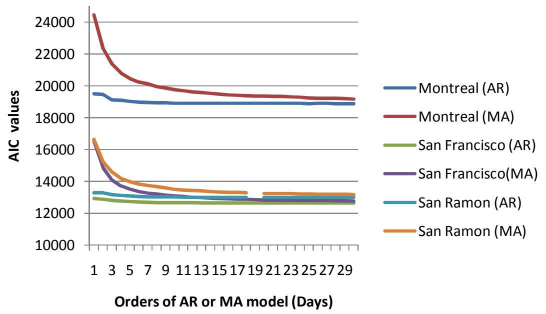

Fig. 2 Relationships between model orders and AIC values applied AR models and MA models to T_{day} in Montreal (1986–1995), San Francisco (1981–1990), and San Ramon (1986–1995)

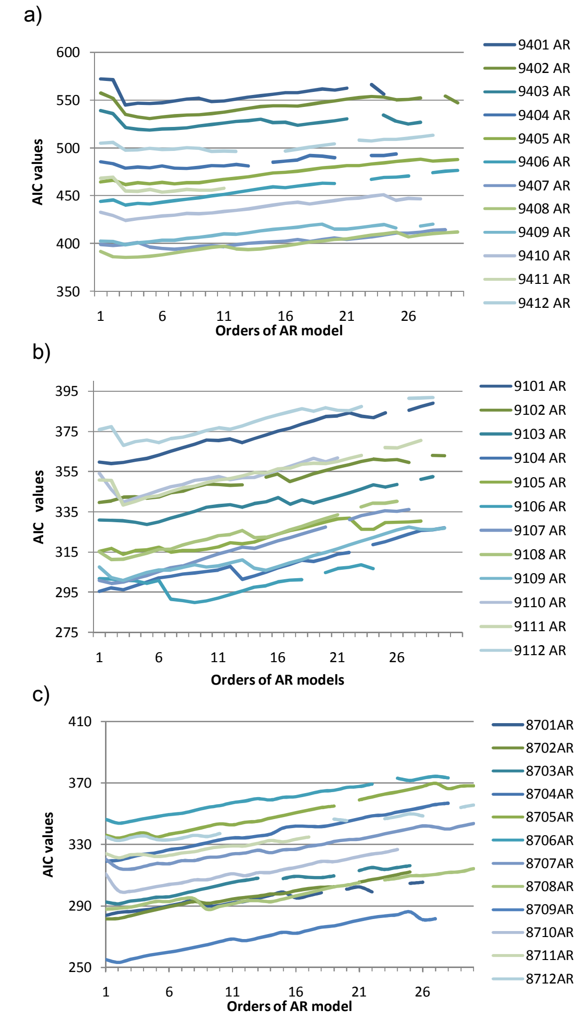

Fig. 3 AIC for applied AR models to T_{day} during three months in a) Montreal in 1994, b) San Francisco in 1987, and c) Montreal in 1991.

assessing the effect of climate on human health or comfort by considering the abovementioned points with feedback-optimized models or no-feedback models.

This study aims to evaluate the periodic of feedback or no-feedback models for Adaptive Models applied to daily air temperature and the validity of the models for human indoor comfort temperature. In this study, we assume the suitability of different models for studying the impact of different climatic conditions on humans. Therefore, we used daily climate data of Montreal (Subarctic climate), San Francisco (Mediterranean climate), and San Ramon (Mediterranean climate), obtained from the National Climatic Data Center, and of Sapporo (Subarctic climate), obtained from the Japan Meteorology Agency. Both Montreal and Sapporo are located on the East coast of continents at high latitudes and have wide annual temperature ranges. On the other hand, both San Francisco and San Ramon are located with West coast of North America in a middle latitude, and have a mild climate throughout the year. The meteorological elements of the data were the daily maximum and minimum air temperatures. To assess the impact of these temperatures, the climatic values were considered to be the average of the daily maximum and minimum temperature values (T_{day}). Next, to consider the feedback effect of human temperature regulation, we applied an autoregressive (AR) model and moving-average (MA) models to the above T_{day} in the four cities. After that, we examined the relationships between the models and thermal comfort temperatures from the authors' investigation (Sapporo) and ASHRAE RP-884 (Montreal, San Francisco, and San Ramon). Finally, we discuss these from the viewpoint of meteorology and human thermal regulation.

2. APPLICATION OF FEEDBACK MODELS

To describe the feedback effect of climate change, and to simulate future climatic conditions, many previous studies have employed the AR, or AR moving average (ARMA) model (Katz and Skaggs ARMA model to evaluate the affect of climate on human health based on a human thermo-regulation feedback loop. Therefore, based on the past climatic conditions, statistical methods are applied to try to adapt to the current thermal environment for simulation. We specifically applied the AR model as the feedback model and the MA model as the no-feedback model for each value of T_{day}. The AR model is a prediction method that uses the previous outputs of a system, and the MA model provides predictions based on the previous inputs of a system. The notation AR(p) refers to an AR model of the order p, and the notation MA(q) refers to an MA model of the order q. Normally, the strong periodicity of row data, such as the annual cycles of air temperature, should be removed. However, these operations often create another bias due to incorrect periodicity. Hence, we applied the AR and MA models without eliminating the annual cycles of air temperature. For comparison with the existing Adaptive Models, we also applied averages for the past 30 days (30-day model). The number of prior days to be considered varied from 1 to 30 as the model order varied from 1st to 30th, and was determined using AIC to detect the best values for these models. The most optimum model is defined when AIC of a order models is the minimum or the local minimum value.

3. DATA OF THERMAL COMFORT

3.1 RP-884 DATA

To reassess the AM, de Dear and Brager (1998) corrected approximately 21,000 sets of raw thermal comfort data from 160 buildings, which covered almost all climatic zones by field research groups. The authors also evaluated the accuracy of the AM under the control with or without an air conditioner, and the relationships between the parameter of concerned parameters such as clothes or metabolic and monthly as outdoor climate. The ASHRAE RP-884 database is available for free access at http://aws.mq.edu.au/rp-884/ashrae_rp884_home.html.

The thermal comfort data for Montreal, from 1994 to 1995 (Donnini et al. 1996), San Francisco from 1987 to 1988 (Schiller et al. 1988), and San Ramon from 1991 to 1993 (Benton and Brager 1994) were obtained from this web site. The questionnaires consisted of six comfort level scales (1, very uncomfortable; 2, uncomfortable; 3, slight uncomfortable; 4, slight comfortable; 5, comfortable; 6, very comfortable), three scales for desires concerning the thermal environment (1, make it cooler; 2, no change; 3, make it warmer), and the 7-level ASHRAE thermal sensation scale (−3, cold; −2, cool; −1, slightly cold; 0, neutral; 1, slightly warm; 2, warm; 3, hot). We categorized these results into 0.5°C divisions and defined the comfort temperatures for each division per 0.25°C.

3.2 Thermal Comfort in Sapporo in 2006

To verify the improved adaptive model, we conducted field experiments using questionnaires and meteorological observations from May 10, 2006 to July 12, 2006, in cooperation with engineering students. The examinees were 919 undergraduate students. The items in the questionnaire and the survey methods were based on the ASHRAE Standard-55 (ASHRAE 2004).

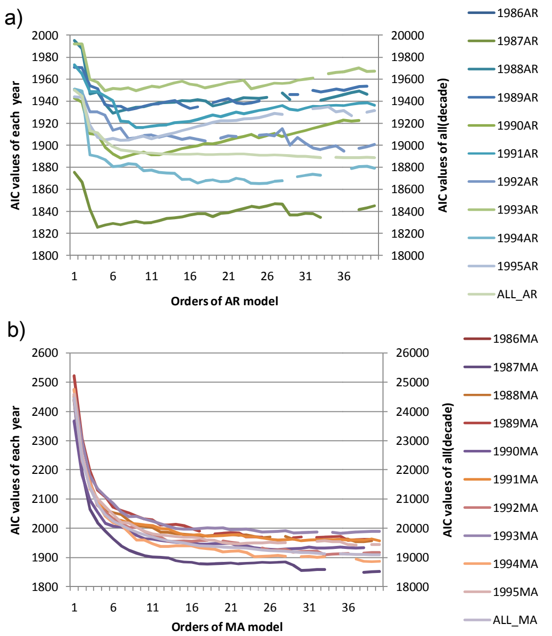

Fig. 4 Relationships between model orders and AIC values applied a) AR models and b) MA models to T_{day} of one-year cycles.

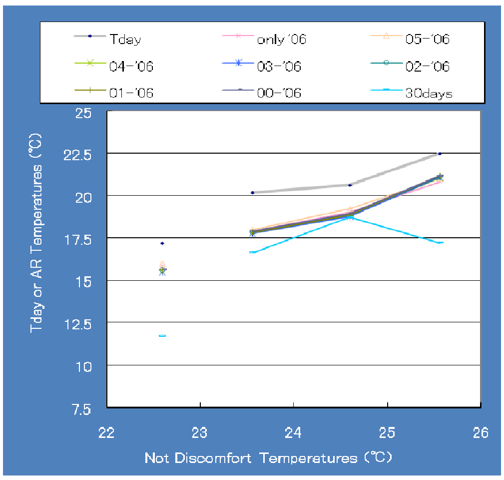

Fig. 5 Relationships between T_{day} or AR applied and not discomfort temperatures at indoor thermal environment in Sapporo.

When these investigations were carried out, we mentioned that the purpose was only to research indoor thermal environments; whether they answered the questionnaire or not was left to the individual. We also explained that there was no penalty, no matter how they answered the questions.

4. RESULTS AND DISCUSSIONS

4.1 Application of Feedback Models

The most optimum orders applied AR models to the past decade T_{day} are 14th in Montreal, 13th in San Francisco, and 16th in San Ramon. On the other hand, the most suitable order of MA model is no order from 1st to 30th. These magnitude relationship AIC in Montreal applied AR or MA models are overwhelming large values compared to in San Francisco and San Ramon (Fig.2). In addition, the colder the climate are, the more values AIC applied the models are (Fig.3). Fig. 3 also indicates the regions with large range of air-temperatures validations or with cold climate tend to have the most optimum higher. We also perform AR and MA models to one-year data (Fig. 4). AIC value in 1993 is the highest was relative correspondent to the relative low annual mean temperature in 1993 and that AIC value in 1987 is the highest is also correspondent to relative high temperature in 1987(Fig. 4). The more values of AIC have a tendency to be the higher optimum orders. Wakaura and Ogata (2007) applied the AR model to air temperatures from observation points throughout Japan and reported that the optimal orders of the AR model are higher in cold regions and in winter, and lower in hot regions and in summer.

The most optimum models under the above conditions applied air temperatures for the past 7-9 and around 14 days. In contrast, each MA model applied to data for one-year only have the suitable order at 4th or 15th lagging from 1-3 days behind each AR model (Fig 4). One-year AR model in Montreal categorized the same climatic zone of Sapporo have the local minimum value of AIC at 14th order. During the same term, the most suitable order of AR model in Sapporo is 10th when the AR and MA models are applied to daily air temperatures for the past 4–7 years. Current studies on biometeorology reported a lag between the occurrence of climatic events and the onset of disorder, i.e., three days in summer and two weeks in winter (Hajat et al. 2007). An approximate 3-day lag corresponds to the 3-14 days required to gain the human thermal acclimatization in summer (WHO 2003).

4.2 Climate & Indoor Thermal Comfort

We examined the relationship between the outdoor climate and a comfortable indoor temperature in Sapporo (Fig. 5). We clarify that the relation between the "not uncomfortable temperature" and climatic values are classified into 2 groups: (1) a one-year MA model and a 30-day averaged model, and (2) a MA model, except the one-year cycle and an AR model. The results suggest that group (2) is more suitable for evaluating thermal comfort conditions. However, this result is valid only in Sapporo. Therefore, we examined the relationships between the outdoor climate and indoor thermal comfort temperature with the RP-884 database, as demonstrated in Fig. 5.

The comfortable temperatures depend more on the outdoor climate in summer than they do in winter. This is because, in winter, a comfortable temperature ranges from 20 to 23°C in Montreal, San Francisco,

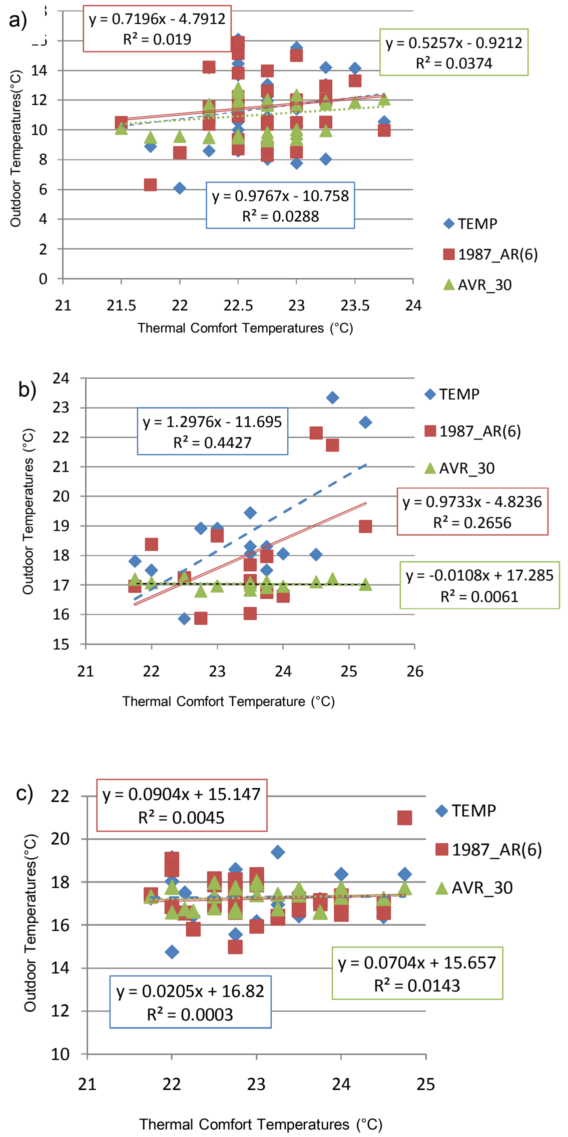

Fig. 6 Relationships between outdoor temperatures and indoor thermal comfort temperature in San Francisco a) in summer controlled by air-conditioner, b) in summer controlled by natural ventilation , and c) in winter.

and San Ramon although the outdoor climate air temperature is the −15°C in only Montreal and is the 10°C in San Francisco or San Ramon. In summer, however, a comfortable temperature appears in the range of 22 to 25°C for the similar outdoor climates of Montreal and San Francisco. In addition, the figures demonstrated contrasts depending on whether the indoor temperature is controlled by natural ventilation or by an air conditioner (Fig. 6).

Finally, we clarified the differences between the simple daily air temperature, an AR model, and a 30-day model. In summer, both temperatures applied to the simple daily and AR model have almost the same correlation coefficient and are greater than those of the applied 30-day average. In winter, there is no sign of decreasing order of these three relationships. In Sapporo, the relationship between the "not uncomfortable temperature" and climatic values in spring are classified into two groups (1) a one-year MA model and a 30-day averaged model, and (2) an MA model, except the one-year cycle, and an AR model. The results suggest that group (2) is better suited for evaluating thermal comfort conditions. Horie et al. (2008) also reported the relationships between an outdoor climate calculated using an AR model, and a human disorder caused by heat wave is closer than that of the outdoor climate using simple daily averaged models. Consequently, thermal comfort criteria calculated with AR models is better than simple daily air temperatures during a rapid rise or drop in temperature, or during extreme events, such as a heat wave.

ACKNOWLEDGEMENT

This study is supported by Hokkaido University Clark Memorial Foundation.

REFERENCES

ASHRAE, 2004: *ANSI/ASHRAE 55-2004, Thermal environmental condition for human occupancy.* Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Auliciems, A. 1981: Towards a psychophysiological model of thermal perception. *International Journal of Biometeorology,* 25, 109–122.

Benton, C.C., and G.S. Brager. 1994: *Sunset Building: Final Report -- A Study of Occupant Thermal Comfort in Support of PG&E's Advanced Customer Technology Test (ACT^2) for Maximum Energy Efficiency.* Center for Environmental Design Research, University of California, Berkeley, CA.

de Dear, R. J., Brager, G. S., and D. Cooper, 1997: *Developing an adaptive model of thermal comfort and preference-Final report on RP-884.* Sydney, MRL,.

de Dear, R. J., and G.S. Brager. 1998: Towards an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions,* 104 (1), 145-167.

Donnini, G., Molina, J., Martello, C., Lai, D.H.C., Lai, H.K., Chang, C.Y., Laflamme, M., Nguyen, V.H., and F. Haghighat, 1996: Field study of occupant comfort and office thermal environments in a cold climate. *ASHRAE Trans.*, 103 (part 2).

Katz, R. W., and R. H. Skaggs,1981: On the use of autoregressive-moving average model to meteorological time series. *Mon. Wea. Rev.,* 109, 479–484.

Hajat, S., Kovats, R. S., and K. Lachowycz, 2007: Heat-related and cold-related deaths in England and Wales: Who is at risk?. *Occup. Environ. Med.,* 64, 93–100.

Horie, Y., Kimura, K., and T. Honma, 2008: Statistical assessment of climate impact on feedback effects on thermoregulation in humans. *Climate Research. (*in review).

Humphreys, M.A., 1976: Field studies of thermal comfort compared and applied. *Building Services Engineer,* 44, 5–27.

McCartney, K. J., and J. F. Nicol, 2002: Developing an adaptive control algorithm for Europe. *Energy and Buildings,* 34, 623–635.

Schiller, G., E. Arens, F. Bauman, C. Benton, M. Fountain, T. Doherty, and K. Craik, 1988: *A Field Study of Thermal Environments and Comfort in Office Buildings: Final Report, ASHRAE 462-RP.* Center for Environmental Design Research, University of California, Berkeley, CA.

Wakaura, M., and Ogata Y., 2007: A time series analysis on the seasonality of air temperature anomalies. *Meteorological Applications,* 14(4), 425-434.

WHO, 2003: *Heat-waves: risks and responses, Health and global environmental change. SERIES 2.* World Health Organization, Regional Office for Europe, Slovenia.