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# Regional Distribution of Perceived Temperatures Estimated by the Human Heat Budget Model (the Klima-Michel Model) in South Korea

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**ABSTRACT**

The regional distribution of perceived temperatures (PT) for 28 major weather stations in South Korea during the past 22 years (1983–2004) was investigated by employing a human heat budget model, the Klima-Michel model. The frequencies of a cold stress and a heat load by each region were compared. The sensitivity of PT in terms of the input of synoptic meteorological variables were successfully tested. Seogwipo in Jeju Island appears to be the most comfortable city in Korea. Busan also shows a high frequency in the comfortable PT range. The frequency of the thermal comfort in Seoul is similar to that of Daejeon with a relatively low frequency. In this study, inland cities like Daegu and Daejeon had very hot thermal sensations. Low frequencies of hot thermal sensations appeared in coastal cities (e.g., Busan, Incheon, and Seogwipo). Most of the 28 stations in Korea exhibited a comfort thermal sensation over 40% in its frequency, except for the mountainous regions. The frequency of a heat load is more frequent than that of a cold stress. There are no cities with very cold thermal sensations. In this study, we found the decreasing trend of mortality with an increasing PT. If the PT is over any critical temperature point, however, the mortality rate increases again. The mortality variation with the PT of a station seems to be associated with the latitudinal location of the station, implying that it results from a regional acclimation effect of inhabitants.

**Key words**: Klima-Michel model, perceived temperature, thermal comfort

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## 1. Introduction

During the past decades, numerous thermal indices such as the wind chill equivalent temperature (Court, 1948; Dixon and Prior, 1987; Bluestein and Zecher, 1999), the physiological equivalent temperature (Höppe, 1993 and 1999), and the apparent temperature (Steadman, 1971, 1984, 1994) have been developed and applied to express the complex mechanism of heat exchange between the human body and the surrounding thermal environment (ASHRAE, 2004; Driscoll, 1992; Gagge et al., 1986; Pickup and de Dear, 1999; Quayle and Steadman, 1998). Some of the indices use a simple combination of meteorological factors such as air temperature, humidity, wind velocity, and radiative flux in order to consider the role of the latent and sensible heat flux, or radiative flux, on the human heat budget under heat load and cold stress conditions. However, none of the traditional indices can take all the mechanisms of the human heat exchange into account (Jendritzky and Graetz, 1998; Jendritzky et al., 1998; Jendritzky and Tinz, 2000; Jendritzky et al., 2000).

A complete heat budget model, the Klima-Michel model, was developed by the Deutscher Wetterdienst to assess the thermal environment in thermophysiologically significant ways (Jendritzky et al., 2000; Kusch et al., 2004). The model is considered to be state-of-the-art in human heat budget models. The perceived temperature (PT) is computed by means of the Klima-

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Michel model, which is based on the comfort equation by Fanger (1970). PT can be applicable to all scales, from urban to global and both in daily thermal weather forecasts and in climatological time scales, in order to describe the spatial distribution and its temporal variations in the thermal environment.

According to Jendritzky et al. (2000), the PT in °C represents the air temperature of a reference environment in which the perception of heat and/or cold would be the same as under the actual conditions (see Table 1). In the reference environment, the wind velocity is reduced to a slight draught and the mean radiant temperature is equal to the air temperature (e.g., an extensive forest). The water vapor pressure is identical with the actual environment as long as it is not reduced by condensation. In addition, there have been some updates for the humid conditions in the model. Perceived heat and cold is computed by means of the comfort equation by Fanger (1970), which is based on a complete heat budget model of the human body. The thermo-physiological assessment is made for a male, the "Klima Michel" (Jendritzky and Kalkstein, 1997), 35 years old, 1.75 m tall, and weighing 75 kg. The work performance of the man is assumed to be 172.5 W, which corresponds to walking at 4 km $h^{-1}$ on flat ground. The assessment procedure is designed for staying outdoors. Accordingly, the standard male may choose between summer and winter clothing, in order to gain as much thermal comfort as possible.

In this study, the sensitivity of the Klima-Michel model was tested to understand which meteorological factors (e.g., air temperature, humidity, wind speed, cloud amount, and height) are sensitively related with the PT. Additionally, in order to know the bioclimatic environment in South Korea, the regional distribution of the PT in Korea was investigated, using long-term climate data through ground-based synoptic observations.

**Table 1.** Thermal sensation and stress level with perceived temperature (PT).

| PT in °C | Thermal sensation | Thermal stress level |
|---|---|---|
| >38 | Very hot | Extreme |
| 32–38 | Hot | Strong |
| 26–32 | Warm | Moderate |
| 20–26 | Slightly warm | Slight |
| 0–20 | Comfortable | None |
| −13–0 | Slightly cool | Slight |
| −26–−13 | Cool | Moderate |
| −39–−26 | Cold | Strong |
| < −39 | Very cold | Extreme |

## 2. Sensitivity of the Klima-Michel model on meteorological factors

### 2.1 *Model sensitivity tests on air temperature, humidity, and wind speed*

In order to know how PT varies with meteorological inputs such as air temperature, humidity, and wind speed, sensitivities of the Klima-Michel model were tested for the Korea Meteorological Administration (KMA)'s Seoul station (37°57′N, 126°58′E, and altitude: 85.5 m above mean sea level). The air temperature at the station was set to be 30°C as of 1500 local time on 1 August 2006 to evaluate the heat load in the summer. For the wintertime, the air temperature was set to be −10°C as of 1500 local time on 1 January 2007 for the testing of a cold stress for the season. Different levels of relative humidity were set to be ranging between 0 and 100 percent for the summer and winter seasons.

In order to calculate the PT representing the thermal comfort at the outdoor environment, the solar and terrestrial radiations need to be considered. Therefore, the elevation of the Sun, i.e., the local time and day of the season, is one of the important input factors of the Klima-Michel model. Wind speed is also one of the important factors to consider for determining the thermal comfort of the human body in both summer and winter, which affects the evaporative cooling capacity of sweat from the human's skin, releasing latent heat or transferring the sensible heat flux by the wind (Kessler, 1993). In the sensitivity test, the PT was calculated with an increasing wind speed (WS) from 0 m $s^{-1}$ to 10 m $s^{-1}$ with a 2 m $s^{-1}$ interval. Figures 1 and 2 show the decreasing trend of PT with an incr-

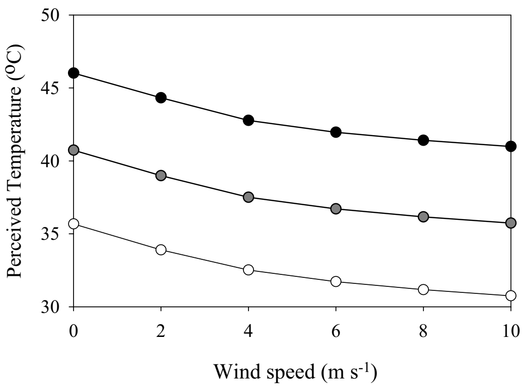


**Fig. 1.** Perceived temperatures with wind speed and relative humidity (40%: white circle, 60%: gray circle, and 80%: black circle) in the daytime of the summer season, 1500 LST 1 August 2006 at Seoul, Korea. Air temperature is assumed to be 30°C.

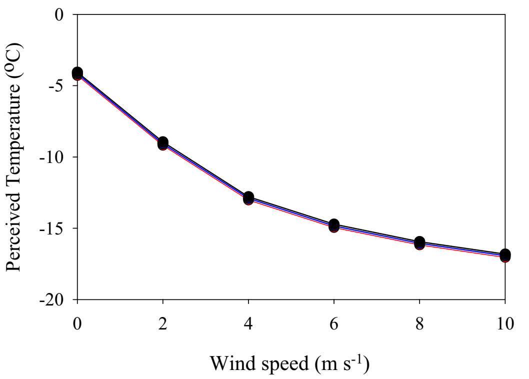


**Fig. 2.** Perceived temperature with wind speed and relative humidity (40%: red, 60%: blue, and 80%: black) in the daytime of winter season, 1500 LST 1 January 2007 at Seoul, Korea. Air temperature is assumed to be −10℃.

easing wind speed both in the summer and winter seasons. It can be noted that under windy conditions, we generally experience a more comfortable perception in the summer and a colder perception in the winter. However, the relative humidity in the cold environment does not affect the PT. More detailed results of the thermal sensation (or PTs) with wind and humidity are given in Table 2.

As shown in Table 2a (for the hot summer), the PT at 100% RH (relative humidity) can be increased up to about 52°C under calm and clear sky conditions. The result implies that the excess PT, of about 22°C, can be the result of the increased humidity, while the increased PTs with an increasing RH are reduced with an increasing wind speed. Table 2b (for the cold winter) shows the variation of PT with wind speed and relative humidity. The result shows that wind speed is the main factor that affects PT under very cold environments (i.e., air temperature $< -10°C$). RH effects appear to be very minor under very cold temperature ranges.

### 2.2 *Model sensitivity tests on cloud amount and height*

Cloud information as well as air temperature, wind speed, and relative humidity play a crucial role for estimating the perceived temperature. In particular, PT can be largely influenced by the altitude and thickness of the cloud layer along with the optical properties of the clouds. Although studies on the complex radiative transfer processes in cloud layers are still challenging and need to be improved (Kim et al., 2006a; Liou et al., 2007), we tested the sensitivity of PT with a varying altitude of the cloud layer and cloud amount. Although the radiation module in this study is adapted to European conditions (e.g., Linke turbidity factor), physical parameters of the atmosphere (e.g., aerosol or molecule concentrations) are assumed to be constant with the time and station.

Figure 3 shows the results of the PT sensitivity tests with cloud height (i.e., high, middle, and low clouds) and amount (octa is used to express the cloud amount. Therefore, if the cloud amount is 8, it means the entire sky is covered by clouds). As shown in Fig. 3., PTs vary sensitively with cloud height and amount. The effects are also different from the time of the day (daytime or nighttime) as well as the season (summer and winter). During the daytime in the summer and winter seasons, as shown in Figs. 3a and 3b, the effects of low and middle clouds on the PT appear to be similar, and high clouds have a minor effect on PT even if it is overcast during the daytime. During the nighttime (Figs. 3c and 3d), however, the effect of clouds on the PT is very different from that of the daytime. During the daytime of the summer season (Fig. 3a), PT increases with an increasing amount (from 0 to 4 octa) of low and middle clouds. If the cloud amount is above 4 octa, the PT gradually decreases with the cloud amount. During the daytime of the winter season (Fig. 3b), the PT gradually decreases with an increasing amount of low and middle clouds, while the PT increases during the nighttime of the winter season (Fig. 3d). During the nighttime of the summer season (Fig. 3c), the increasing and decreasing trends of the PTs with cloud amount are different for the height of each cloud.

The results of PT with cloud height and amount are basically dependent on reflection, absorption, and reemission of solar and terrestrial radiation in the atmosphere (including cloud droplets) and the land-surface. Improvements in radiative transfer modeling in a cloudy atmosphere would help to improve the accuracy of evaluating the PT under cloudy sky conditions (VDI, 1994, 1998).

## 3. Regional distribution of perceived temperature in South Korea

To investigate the regional distribution of perceived temperatures in South Korea, the air temperature, relative humidity, wind speed, and cloud information were used to yield a perceived temperature every 6 hours for KMA's 28 stations during the past 22 years (1983 to 2004), employing the Klima-Michel model.

Table 3 shows a regional frequency distribution of the thermal comfort in major cities of South Korea (Seoul, Daejeon, Daegu, Busan, Gwangju, Incheon, Ulsan, Suwon, and Seogwipo). The frequency values in Table 3 are obtained from the results of PT estimation every 6 hours (i.e., 0000, 0600, 1200, and 1800 LST) for a given station. The values in the table are in percent. In this study, Seogwipo in Jeju Island ap-

**Table 2.** Results of a sensitivity test of PT as a function of the relative humidity (RH) in % and wind speed (WS) in m $s^{-1}$ using the Klima-Michel model, for (a) 1500 LST in the mid-summer month of 1 August 2006 and (b) 1500 LST in the mid-winter month of 1 January 2007. In (a) and (b), air temperatures are assumed to be 30°C and −10°C, respectively. The geographical location for the model calculation was set to KMA's Seoul station.

| | WS (m $s^{-1}$) | RH 20% | RH 30% | RH 40% | RH 50% | RH 60% | RH 70% | RH 80% | RH 90% | RH 100% |
|---|---|---|---|---|---|---|---|---|---|---|
| (a) | 0 | 31.64 | 33.39 | 35.68 | 38.11 | 40.73 | 43.35 | 46.02 | 48.77 | 51.53 |
| | 2 | 29.94 | 31.65 | 33.90 | 36.35 | 38.99 | 41.63 | 44.32 | 47.09 | 49.87 |
| | 4 | 28.56 | 30.27 | 32.52 | 34.92 | 37.51 | 40.11 | 42.77 | 45.52 | 48.29 |
| | 6 | 27.75 | 29.48 | 31.72 | 34.12 | 36.71 | 39.31 | 41.96 | 44.71 | 47.47 |
| | 8 | 27.19 | 28.92 | 31.17 | 33.57 | 36.16 | 38.76 | 41.41 | 44.15 | 46.92 |
| | 10 | 26.80 | 28.49 | 30.75 | 33.15 | 35.74 | 38.34 | 40.99 | 43.74 | 46.50 |
| (b) | 0 | −4.41 | −4.35 | −4.29 | −4.23 | −4.17 | −4.11 | −4.06 | −3.99 | −3.94 |
| | 2 | −9.30 | −9.24 | −9.18 | −9.12 | −9.07 | −9.01 | −8.95 | −8.89 | −8.83 |
| | 4 | −13.13 | −13.08 | −13.02 | −12.96 | −12.90 | −12.84 | −12.79 | −12.72 | −12.66 |
| | 6 | −15.06 | −15.00 | −14.95 | −14.89 | −14.83 | −14.77 | −14.71 | −14.65 | −14.59 |
| | 8 | −16.29 | −16.23 | −16.17 | −16.11 | −16.05 | −15.99 | −15.94 | −15.87 | −15.82 |
| | 10 | −17.16 | −17.10 | −17.04 | −16.98 | −16.92 | −16.86 | −16.81 | −16.74 | −16.69 |

**Table 3.** Frequency (in percent) of the thermal comfort classified by perceived temperature levels at major cities of South Korea.

| PT in °C | Seoul | Daejeon | Daegu | Busan | Gwangju | Incheon | Ulsan | Suwon | Seogwipo |
|---|---|---|---|---|---|---|---|---|---|
| < −39 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| −39–−26 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.2 | 0.0 |
| −26–−13 | 6.0 | 4.7 | 3.2 | 1.7 | 2.3 | 6.1 | 2.1 | 6.3 | 0.0 |
| −13–0 | 20.4 | 20.2 | 18.8 | 15.1 | 19.6 | 21.1 | 17.3 | 20.8 | 9.0 |
| 0–20 | 50.3 | 50.2 | 52.9 | 62.0 | 52.7 | 52.1 | 56.1 | 49.0 | 63.6 |
| 20–26 | 9.7 | 10.0 | 10.2 | 10.6 | 11.0 | 9.3 | 11.1 | 9.9 | 13.4 |
| 26–32 | 6.0 | 6.3 | 6.3 | 5.3 | 6.2 | 5.3 | 5.9 | 6.3 | 6.9 |
| 32–38 | 4.2 | 4.5 | 4.4 | 3.3 | 4.4 | 3.7 | 3.9 | 4.2 | 4.1 |
| >38 | 3.3 | 4.1 | 4.1 | 2.1 | 3.8 | 2.3 | 3.5 | 3.4 | 3.0 |

pears to be the most comfortable city with a 63.6% in the comfortable PT range (i.e., 0°–20°C). Busan (the second largest city in Korea) also shows a high frequency (62.0%) in the comfortable range. However, the frequency of the comfortable range in Seoul (50.3%) is similar to that of Daejeon (50.2%) and it is relatively low. The frequencies of the comfortable range for Daegu, Gwangju, and Incheon are 52.9%, 52.7%, and 52.1%, respectively while Ulsan and Suwon are 56.1% and 49.0%, respectively.

Cities with a very hot thermal sensation appeared in Daegu and Daejeon (4.1% frequencies for both cities) while the frequencies of Seoul and Busan are 3.3% and 2.1%, respectively. The frequencies of Gwangju and Incheon are 3.8% and 2.3%, respectively while the frequencies of Ulsan, Suwon, and Seogwipo are 3.5%, 3.4%, and 3.0%, respectively. The results distinctly show the relatively low frequencies of hot thermal sensations in coastal cities (e.g., Busan, Incheon, and Seogwipo). It implies that a cool sea-breeze can contribute to the reduction of a hot thermal sensation in the coastal cities in the summer time. Figure 4 presents a pie diagram to explain the frequencies of thermal sensations of 28 stations in South Korea. Larger circles indicate 6 major cities. Most of the stations appeared to have a comfortable thermal sensation over 40%, except for a mountainous station (Daegwallyeong). In addition, heat loads are more frequent than cold stresses in most stations used in this study.

Three cities, located in the middle part of the Korean Peninsula (Seoul, Incheon, and Suwon), occupy 0.2% of the cold thermal sensations. The result is likely associated with the high latitudinal location of the cities. However, there are no cities with very cold thermal sensations. On the other hand, many mountainous regions of the Korean Peninsula may expect to have different temperatures and wind speeds compared to the flat regions.

## 4. Relationship between PT and mortality

The daily PT and mortality of 6 major cities of Korea (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) are compared and investigated to look at the

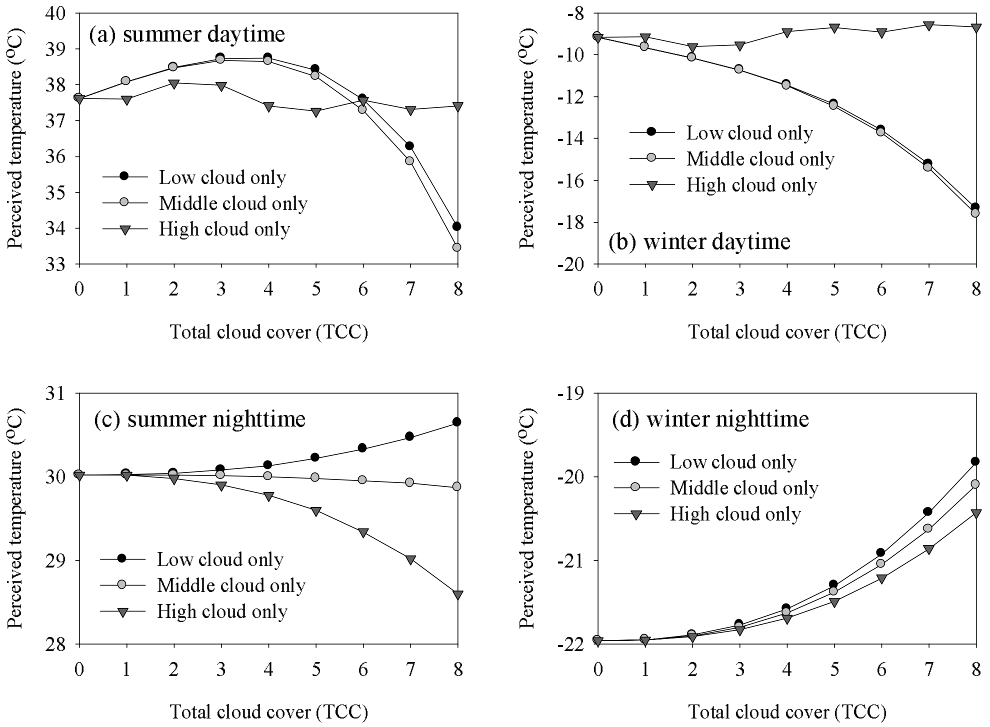


**Fig. 3.** Sensitivity of perceived temperatures according to cloud amount and height in cases of (a) summer daytime, (b) winter daytime, (c) summer nighttime, and (d) winter nighttime.

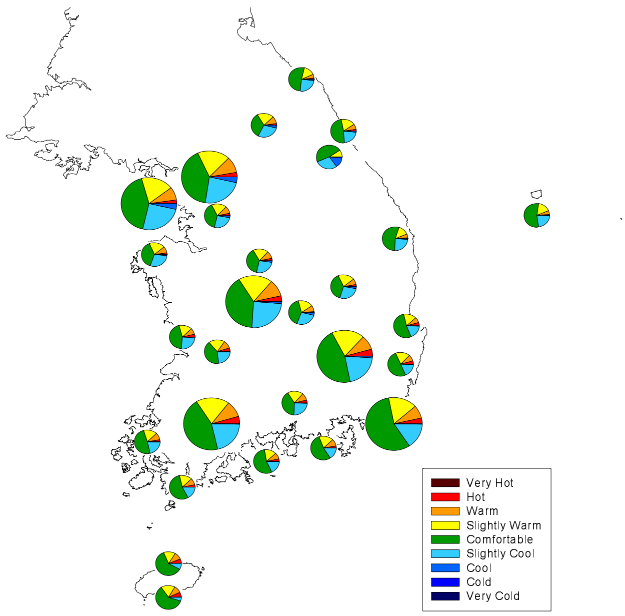


**Fig. 4.** Regional distribution of perceived temperatures in Korea. Larger circles indicate 6 major cities (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) of South Korea.

relationship between the thermal stress and mortality for each city (Fig. 5). The daily death data for the cities are used and converted to estimate a daily-standardized mortality rate (per 100000 populations) (Kim et al., 2006b). PT levels are classified by each 4°C. Significant levels are presented as vertical bars in the figures. The daily mortality is compared with the PT of the previous day because health effects due to the thermal sensation is generally associated with an enhanced mortality within one day (Kysely, 2002, 2004; Kysely and Huth, 2004; Kim et al., 2006b, 2007). The results in Fig. 5 show a decreasing mortality trend with an increasing PT. However, if the PT is over any critical temperature point (threshold perceive temperature), we found that mortality increases again. In addition, we found that the PT values that determine the lowest mortality at a given station depend on the latitude of the station. The result implies a regional acclimation effect of inhabitants in each region.

## 5. Conclusion and discussion

In order to investigate the regional distribution of PT for KMA's 28 stations of South Korea during the past 22 years (1983 to 2004), the Klima-Michel model was employed to estimate the PT, using synoptic input variables such as air temperature, relative humidity,

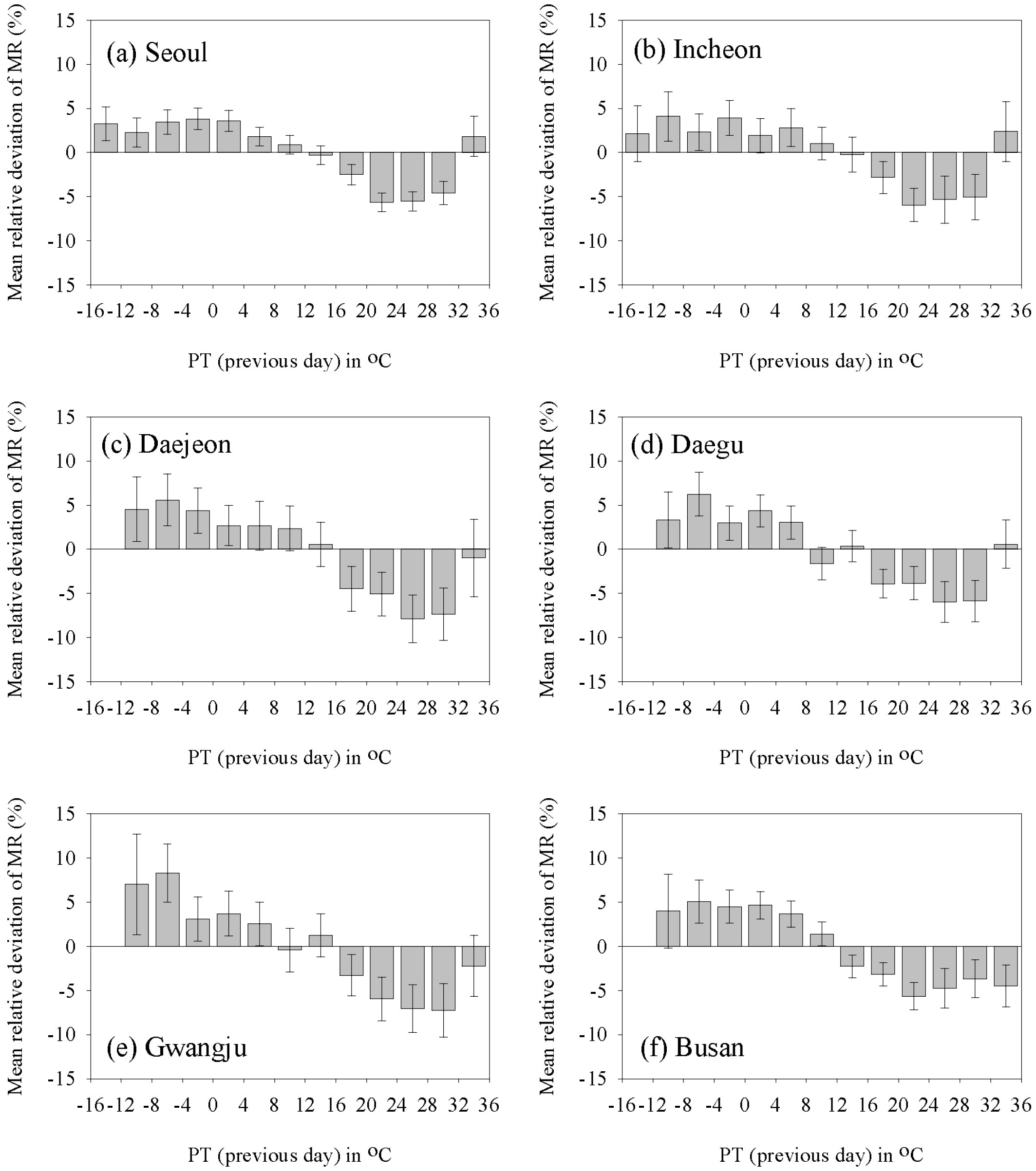


**Fig. 5.** Relationship between perceived temperatures (previous day) and daily mortality in the major 6 cities of South Korea, (a) Seoul, (b) Incheon, (c) Daejeon, (d) Daegu, (e) Gwangju, and (f) Busan.

wind speed, and cloud information.

Seogwipo in Jeju Island appears to be the most comfortable city in Korea. Busan also shows a high frequency (62.0%) in the comfortable PT range. However, the frequency in Seoul is similar to Daejeon with a relatively low frequency in the comfortable range. Cities with a very hot thermal sensation appeared in Daegu and Daejeon. The results distinctly show the relatively low frequencies of hot thermal sensations in coastal cities (e.g., Busam, Incheon, and Seogwipo). Most of the 28 stations of Korea appear to have a comfort thermal sensation over 40%, except for the mountainous station. Generally in Korea, heat loads are more frequent than cold stresses. Only three cities, located in the middle part of the Korean Peninsula, have a 0.2% of frequency in cold thermal sensations. It is likely associated with their higher latitudinal location than the other cities. There are no cities with very cold thermal sensations. However, further studies are needed to construct a digitized bioclimate map for the Korean Peninsula, considering the detailed topographical characteristics of Korea and the downscaled input variables for the Klima-Michel model. Geographical Information System (GIS) can be used to interpolate the spatial distribution of the input variables.

We found that in general, mortality shows a decreasing trend with an increasing PT. If PT is over any critical temperature point (a threshold value of PT), however, the mortality increases again. We found that the PT values that determine the lowest mortality at a given station seem to be dependant on its latitude. The result implies a regional acclimation effect of inhabitants. As shown in Fig. 5, the thermal comfortable range in Korea seems to be 8 (or 12) to 32 (or 36) with some regional differences. It is different from the range in Table 1 (i.e., 0 to 20) as introduced by Jendritzky et al., 2000. This difference stems from the regional climate and the assumed persons between Middle-Europe (or North America) and East Asia. This kind of a regional acclimation effect should be considered if the global distribution of the PT is to be estimated.

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