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Trends of Climate Change and Air-Conditioning Load of Residential Buildings in China

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Abstract

In this paper, using historical weather observations, the trends of outdoor temperature and solar radiation were analyzed. A model to estimate cooling degree-hours was developed using daily average temperature and solar radiation as parameters. Using heating/cooling load models developed by the authors in previous studies, trends of heating and cooling loads of residential buildings at 22 Chinese locations were clarified. The main conclusions from this study are as follows: (1) The yearly average dry-bulb temperature has risen by 1.0 degree during the period of 1961-2000; (2) The increasing rate of outdoor temperature in January is larger than that in July; (3) Solar radiation is decreasing at most of the 22 locations; there is little difference between seasons in the decreasing trends; (4) The heating load is decreasing at all the 22 locations; (5) The increasing rate of cooling load is positive at some locations while negative at others; (6) With the improvement of thermal insulation of buildings, heating and cooling loads will be less affected by climate change.

Keywords: climate change; temperature; solar radiation; heating load; cooling load

1. Introduction

The climate has been changing significantly since the last century mainly due to global warming. Because the indoor environment and residential energy consumption are influenced by weather conditions, it is necessary to predict the trends of residential energy consumption due to climate change. In residential buildings, energy is consumed for air-conditioning, hot water supply, lighting, cooking and household electrical appliances. Among these, energy consumption for air-conditioning is strongly influenced by climatic elements like temperature, solar radiation, humidity etc.

In the previous studies, one of the authors Zhang established regression equations of heating and cooling loads using heating degree-days, cooling degree-hours, solar radiation etc. as parameters[1),2)]. Zhang also analyzed climate change in China using the observations in the period from 1982-2002, and demonstrated the trends of temperature and solar radiation in this period[3)]. Nevertheless, there have been very few studies analyzing the trend of air-conditioning load related to climatic change in China.

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In this paper, using the observations of 1961-2000 at 22 Chinese locations (Beijing, Changchun, Chengdu, Guangzhou, Harbin, Tianjin etc.), increasing rates of temperature and solar radiation were calculated. Using the regression equations developed in the previous studies, trends of heating and cooling loads were analyzed.

2. Trends of Climatic Elements

2.1 Original Data

Observations of dry-bulb temperature, and solar radiation at the 22 locations during the period from 1961-2000 were used in the study. The original data was based on a daily average, by which monthly or yearly averages were calculated. In selecting the locations for analyses in this paper, geographic distribution was considered in order to make the analyses more representative.

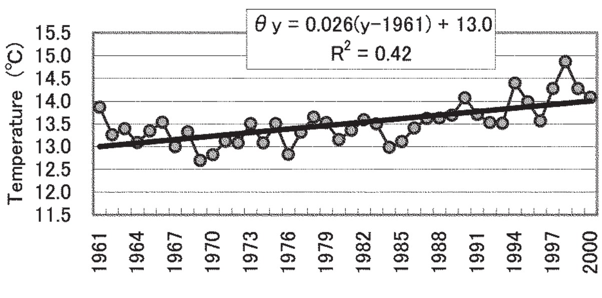

Fig.1. Fluctuation of Yearly Average Temperature Over the 22 Chinese Locations

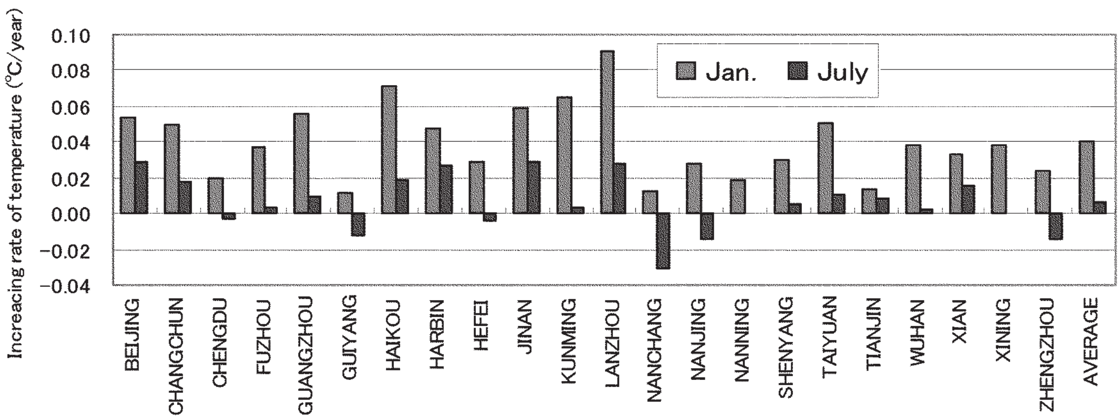

Fig. 2. Increasing Rate of Monthly-average Temperature

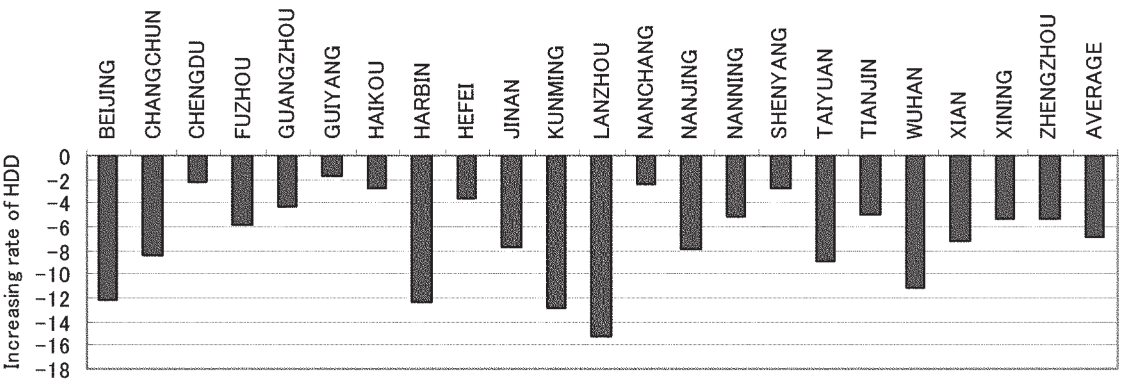

Fig.3. Increasing Rate of Heating Degree-days

2.2 Increasing Rate of Temperature

In order to clarify the trend of global warming, fluctuation of yearly average temperature over the 22 locations was examined and is shown in Fig.1. Obviously, the average temperature is increasing, and the trend becomes remarkable after the 1970s. The regression equation from the least square method is as follows:

$$\theta_y = 0.026 \cdot (y - 1961) + 13.0 \qquad (1)$$

where θ_y means the yearly average temperature in °C, y means time of year, the number of 0.026 means increasing rate of temperature in °C /year, the number of 13.0 means the average temperature over the 22 Chinese locations in the year 1961. Fig.1. and Equation (1) show that the average temperature is increasing at a speed of 2.6°C per hundred years, which means a rise of 1.0°C within 40 years.

Because heating load is influenced by the air temperature in winter, and the cooling load is related to the temperature in summer, the trend of temperature change should be examined monthly or seasonally. The increasing rate of monthly temperature can be calculated by using the least square method to find the slope of the regression line similar to Fig.1. The only difference is that monthly average temperature, instead of the yearly average temperature, is used in the regression process. Fig.2. shows the increasing rate of monthly temperature in January and July at the 22 locations. The increasing rate of monthly temperature in January is larger than that of July at all these locations. In Nanchang, Nanjing, Zhengzhou, Heifei, Guiyang and Chengdu, the increasing rate for July is negative. The average rate of increase over the 22 locations in January and July is 0.042°C/year and 0.009°C /year, respectively. The reason for the higher rate of increase in January can be explained by the density of carbon dioxide in the atmosphere. Observations by Machida show that the density of carbon dioxide in the atmosphere in winter is higher than that in summer due to fewer plants absorbing carbon dioxide in winter[4)].

The most influential factors directly affecting annual heating and cooling loads are heating degree-days and cooling degree-hours, rather than the outdoor temperature. Heating degree-days represent the accumulated indoor-outdoor differences during heating days. In this paper, the indoor temperature was fixed at 20°C when calculating heating degree-days, because the room temperature was set at 20°C when heating load was calculated in the previous study[1)]. In this case, 20°C-based degree-days should be used

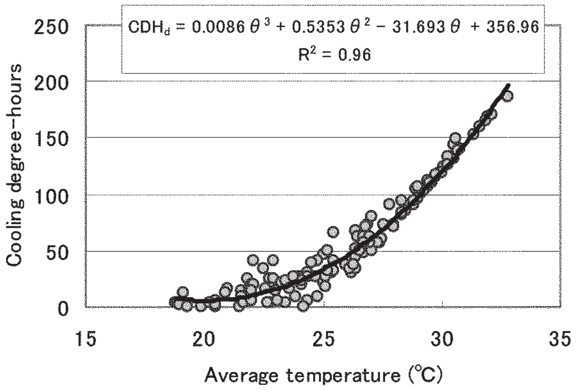

Fig.4. Relations between Cooling Degree-hours and Average Temperature in Beijing (2000)

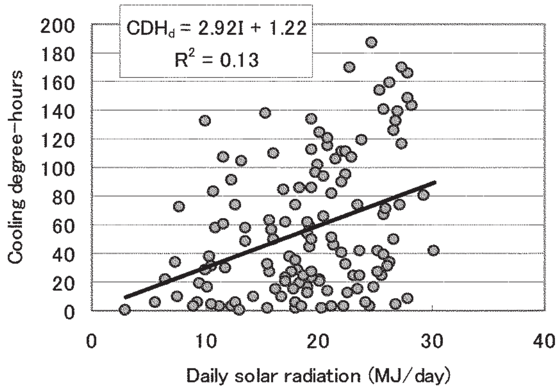

Fig.5. Relations between Cooling Degree-days and Daily Solar Radiation in Beijing (2000)

Table 1. Values of Constants A_0 to A_4 in Equation (2)

	Lat.(N)	Long.(E)	Ele. (m)	A_0	A_1	A_2	A_3	A_4
BEIJING	39 ° 56'	116 ° 17'	54.0	401.343	-0.0023	1.188	-43.842	1.1383
CHANGCHUN	43°54'	125°13'	236.8	-140.85	0.0447	-2.04	29.232	0.799
CHENGDU	30 ° 40'	104 ° 01'	506.1	-524.27	0.0703	-3.96	76.398	1.3539
FUZHOU	26 ° 05'	119 ° 17'	84.0	101.824	0.0307	-0.976	1.875	0.5115
GUANGZHOU	23 ° 08'	113 ° 19'	6.6	249.097	0.0214	-0.26	-16.251	0.8473
GUIYANG	26 ° 35'	106 ° 43'	1,074.3	-927	0.1147	-6.811	136.101	0.8401
HAIKOU	20°02'	110°21'	13.9	2945.57	-0.1219	11.285	-323.3	0.3931
HARBIN	45 ° 45'	126 ° 46'	143.0	3.19	0.032	-1.163	9.503	0.8527
HEFEI	31 ° 52'	117 ° 14'	27.9	963.325	-0.0265	3.309	-104.13	0.7659
JINAN	36 ° 41'	116 ° 59'	57.8	807.727	-0.0208	2.781	-88.016	0.539
KUNMING	25 ° 01'	102 ° 41'	1,896.8	1.925	0.0437	-1.68	15.412	0.5967
LANZHOU	36 ° 03'	103 ° 53'	1,518.3	146.23	0.0048	0.417	-18.572	1.2567
NANCHANG	28 ° 36'	115 ° 55'	45.7	1160.75	-0.0348	4.049	-125.37	0.6289
NANJING	32 ° 00'	118 ° 48'	12.5	413.139	0.0034	0.918	-41.04	0.8797
NANNING	22 ° 49'	108 ° 21'	73.7	-137.89	0.0439	-2.036	29.516	0.9186
SHENYANG	41 ° 46'	123 ° 26'	45.2	-132.11	0.0415	-1.887	27.054	0.9542
TAIYUAN	37°47'	112°33'	779.5	-97.886	0.0322	-1.371	18.761	1.0442
TIANJIN	39 ° 06'	117 ° 10'	5.2	40.866	0.026	-0.834	3.648	0.8966
WUHAN	30 ° 37'	114 ° 08'	27.0	1216.77	-0.0416	4.493	-134.35	0.645
XIAN	34 ° 18'	108 ° 56'	398.6	449.874	-0.006	1.453	-50.011	1.1937
XINING	36 ° 37'	101 ° 46'	2,262.2	-114.44	0.0384	-1.543	20.911	0.7555
ZHENGZHOU	34 ° 43'	113 ° 39'	111.3	-59.673	0.0332	-1.366	16.379	1.0754

instead of 18°C-based degree-days. As shown in Fig.3., the increasing rate of heating degree-days at all the 22 locations has a negative value, which means that heating degree-days are decreasing. In Lanzhou, heating degree-days decrease at a rate of 15 degree-days each year. The yearly decrease in Beijing, Harbin and Kunming is also larger than 12 degree-days.

In contrast to the case of heating load, degree-hour is a better parameter in predicting cooling load than degree-day because cooling is usually carried out intermittently throughout the day. Because hourly data was not available for this study, we had to estimate cooling degree-hours using daily average data. In deciding parameters for predicting cooling degree-hours, the relations between cooling degree-hours and daily average temperature was examined. Fig.4. is an example showing the relation between degree-hours each day and average temperature of the same day using observational data of Beijing in 2000. The cooling degree-hours can be expressed approximately as a cubic function of daily average temperature with a coefficient of determination of 0.96.

To decide whether daily accumulated solar radiation could be another parameter for predicting degree-hours, the relations between solar radiation and cooling degree-hours were examined. The relations between these two variables are shown in Fig.5. There is a weak positive correlation between cooling degree-hours and daily solar radiation, therefore solar radiation was selected as another parameter besides the average temperature in predicting cooling degree-hours. Using the least square method, a regression equation was established:

$$CDH_d = A_0 + A_1\theta^3 + A_2\theta^2 + A_3\theta + A_4 I \qquad (2)$$

where $A_o \ldots A_4$ are constants shown in Table 1, θ is the daily average temperature in °C, I is the daily accumulated solar radiation in MJ/m^2/day, CDH_d means daily cooling degree-hours with a base temperature of 25°C. Cooling degree-hours can be calculated based on other temperatures such as 26°C or 24°C. The reason why the 25°C-based degree-hour is adopted in this study is that the room temperature was set at 25°C when cooling load was calculated in the previous study[2]. Yearly cooling degree-hours can be obtained by adding up the daily cooling degree-hours CDH_d.

Fig.6. shows a comparison of observational and predicted degree-hours in 2001 at the 22 locations. The errors from this prediction are small, therefore Equation (2) was used in estimating cooling degree-hours.

The increasing rate of cooling degree-hours estimated by Equation (2) is shown in Fig.7. The increasing rate of cooling degree-hours is quite different from place to place. In Haikou, cooling degree-hours are increasing by 118 degree-hours each year, while in Nanchang, Nanjing and Zhengzhou, the increasing rate is negative, meaning that cooling degree-hours are decreasing.

2.3 Increasing Rate of Solar Radiation

Solar radiation affects both heating and cooling loads; therefore it is necessary to clarify the trend of solar radiation. Fig.8. shows the increasing rate of monthly solar radiation in January and July. Except for the increasing rate for July in Changchun, Harbin and Zhengzhou, and January in Kunming, solar radiation is declining in both January and July. One of the reasons for this may be the increase of aerosol density in the atmosphere caused by industrialization in recent years[5]. The declination of solar radiation tends to increase heating load and decrease cooling load. The average increasing rates of solar radiation in January and July are -1.8 MJ/m^2/year in both January and July; therefore the difference between seasons is not obvious.

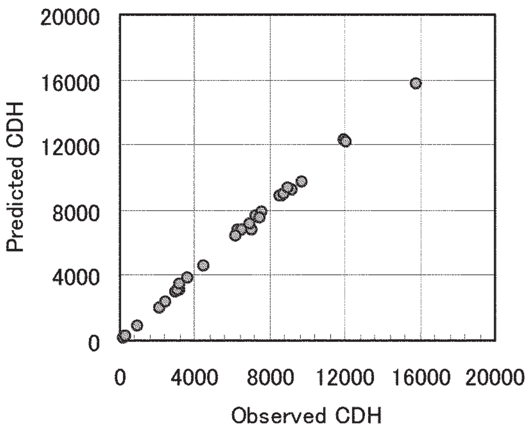

Fig.6. Comparison of Observational and Estimated Degree-hours at the 22 Locations in 2001

3. Trend of Cooling and Heating Loads in Residential Buildings

3.1 Prediction Methodology

In order to predict heating or cooling loads of residential buildings, regression equations developed by Zhang *et al.* were used. Annual heating load for each square meter of floor area L_H can be predicted by Equation (3)[1]:

$$L_H = 1.01 + 1.1696 \cdot Q \cdot 0.0864 \cdot HDD_{20} - 0.351 \cdot \mu \cdot I_1 \cdot HD - 0.227 \cdot (H_B + H_E + H_L) \cdot HD / S \quad (\mathrm{MJ/m^2}) \qquad (3)$$

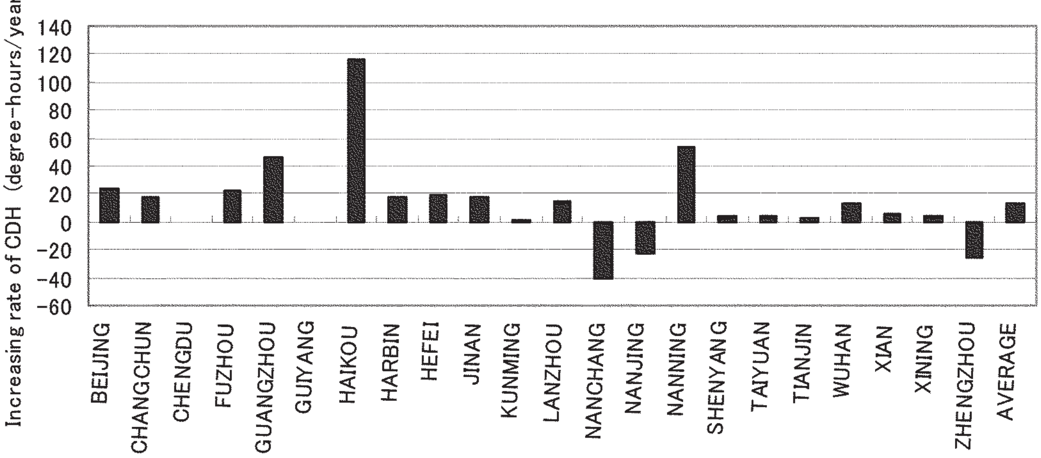

Fig.7. Increasing Rate of Cooling Degree-hours

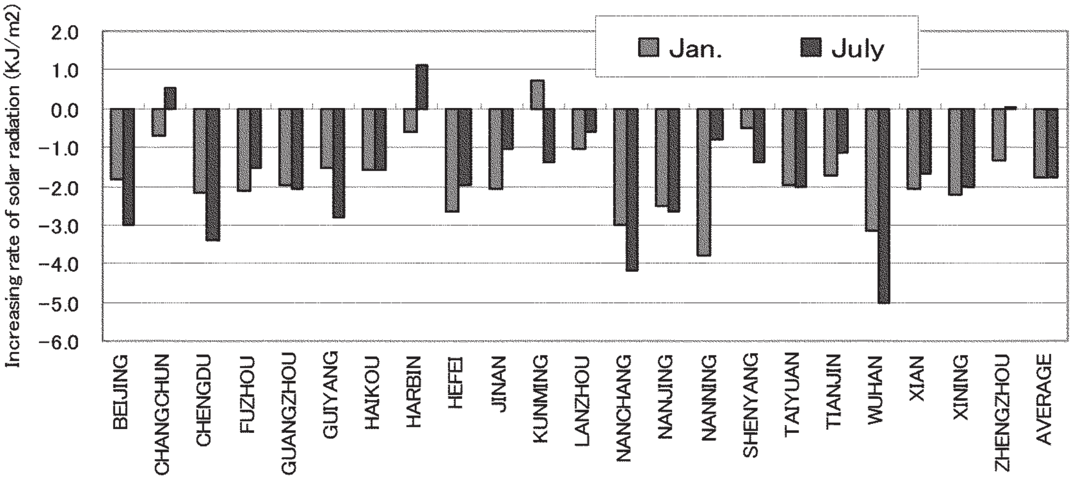

Fig.8. Increasing Rate of Solar Radiation

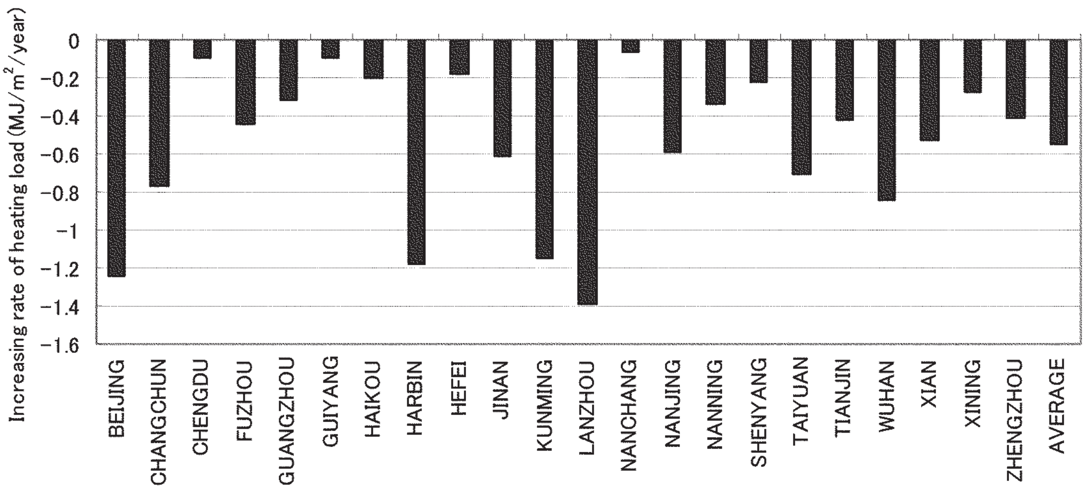

Fig.9. Increasing Rate of Heating Load

where Q is the heat lose coefficient in W/m^2/K, μ is the solar gain coefficient, I_1 is accumulated daily solar radiation in January in MJ/ m^2, HDD_{20} is heating degree-days with the base temperature of 20°C, HD is the heating days, H_B is the sensible heat from human bodies in MJ/day, H_E is the heat from electrical appliances in MJ/day, H_L is heat from lighting in MJ/day, S is the floor area in m^2.

The cooling load (only sensible component) per square meter of floor area is estimated with the following equation[2)]:

$$L_C = 6.405 + 1.938 \cdot Q \cdot CDH_{25} \cdot 0.0036 + 0.012 \cdot \mu \cdot I_7 \cdot CD$$
$$+ \{0.5938 \cdot (H_B + H_E + H_L) \cdot CD + 0.0033 \cdot \theta_d \cdot C\} / S \quad (\text{MJ/m}^2) \qquad (4)$$

where CDH_{25} is cooling degree-hours with the base temperature of 25°C, I_7 is the average daily solar radiation in July in MJ/m^2, CD is cooling days, θ_d is the average temperature difference between the highest and lowest in July in °C, C is the heat capacity of an apartment house in MJ/K.

3.2 Increasing Rate of Heating Load

Substituting the heating degree-days, heating days and average daily solar radiation in January for each year into Equation (3), heating load from 1961 to 2000 was calculated. Using the least square method, a regression equation of heating load against the years can be obtained, the slope of which is called the increasing rate of heating load. During the prediction using equation (3), the heat loss coefficient Q was assumed to be 1.0 W/m^2/K, and the floor area S was 100 m^2.

Fig.9. shows the increasing rate of heating load at the 22 locations. In spite of the fact that solar radiation is in an overall decreasing trend, heating load is decreasing at all of these 22 locations. The decrease in heating load in Lanzhou, Harbin, Kunming and Beijing is larger than that at other locations. The average increasing rate over the 22 locations is -0.54 MJ/m^2/year.

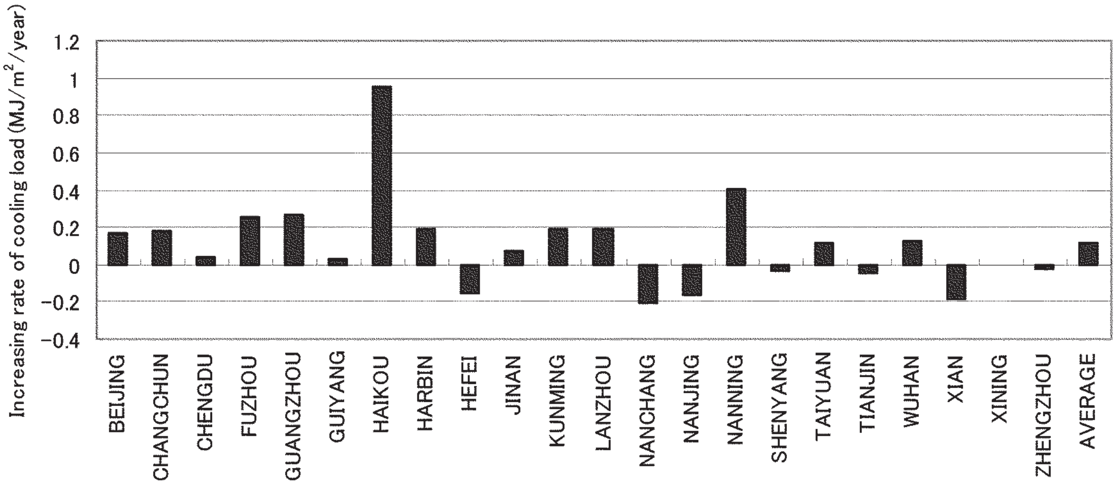

Fig.10. Increasing Rate of Cooling Load

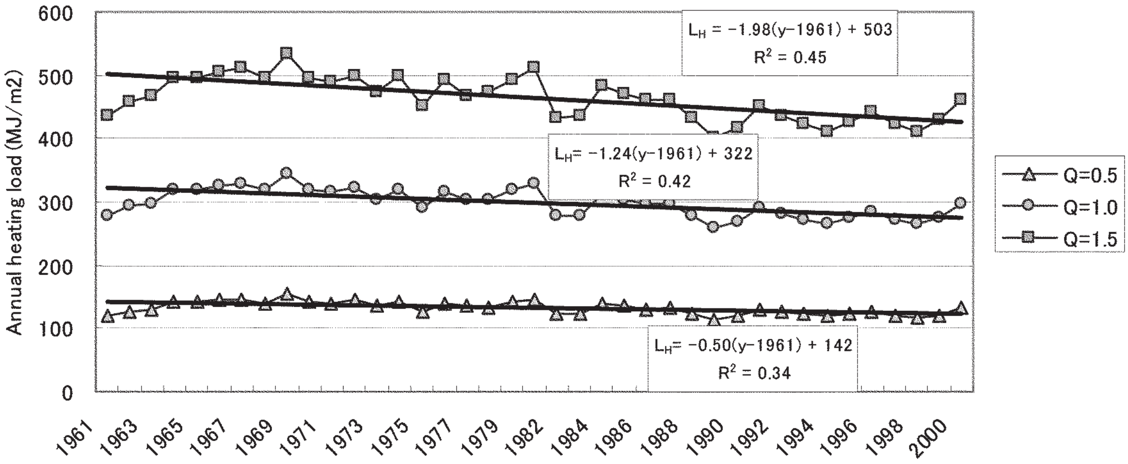

Fig.11. Fluctuations of Heating Load with Different Values of Heat Loss Coefficient Q in Beijing

3.3 Increasing Rate of Cooling Load

Using Equation (4), the annual cooling load per square meter of floor area was estimated. The increasing rate of cooling load is shown in Fig.10. Differing from the trend of heating load, the tendency of cooling load is different from location to location. Cooling load tends to increase at 15 locations while it tends to decrease at other locations. Whether cooling load is increasing or decreasing is determined by the combination of trends of cooling degree-hours and solar radiation.

4. Discussion

The above analyses concerning heating and cooling loads were conducted based on the assumption that the heat loss coefficient Q of the residential buildings was fixed at 1.0 W/m^2/K. The heat loss coefficient Q, however, may take other values and the change in Q may affect the increasing rate of heating or cooling load. Fig.11. shows the fluctuations of heating load with the values of heat loss coefficient Q=0.5, 1.0, 1.5W/m^2/K, respectively in Beijing. The regression equations in Fig.11. demonstrate that the increasing rate of heating load is -0.5MJ/year, -1.24 MJ/year and -1.98 MJ/year, respectively when Q equals 0.5, 1.0, and 1.5 W/m^2/K. This means that with the improvement of thermal insulation and air-tightness of buildings, the heating load will be less affected by climate change. This is also true where cooling load is concerned.

Besides heating and cooling loads, energy consumption for air-conditioning is also important to house owners and policy makers, as well as building engineers. In spite of the conclusions that heating load is decreasing in residential buildings, energy consumption for air-conditioning remains a problem because it depends also on the efficiency of air-conditioning equipment etc. A study of residential energy consumption related to climate change will be conducted in the near future.

The trend of temperature increase in urban areas is not only caused by global warming, but also by other regional factors expressing the level of urbanization and climatic elements besides temperature. In this study, we pay more attention to the influence on the air-conditioning load, taking the climate as an input condition. Therefore, the difference in the increasing rate of temperature among different locations in Section 2.2 was considered as 'fact', the reason for which was not discussed in detail in this study.

5. Conclusions

In this study, using observational data, trends of outdoor temperature and solar radiation were examined. Using models for heating and cooling loads developed in previous studies, the increasing rates of heating and cooling loads were clarified for 22 Chinese locations. The main conclusions from this study are as follows:

(1) The yearly average dry-bulb temperature has risen by 1.0 degree during the period from 1961-2000.
(2) The increasing rate of outdoor temperature in January is larger than that in July.
(3) Solar radiation is decreasing at most of the 22 locations; there is little difference between seasons in the decreasing trends.
(4) The heating load is decreasing at all the 22 locations.
(5) As for cooling load, the increasing rate is positive at some locations while negative at others.
(6) With the improvement of thermal insulation of buildings, heating and cooling loads will be less affected by climate change.

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