METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **21**: 141–148 (2014)
Published online 27 March 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.1313

A study on the electric power load of Beijing and its relationships with meteorological factors during summer and winter

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ABSTRACT: Using the daily electric power load and meteorological data over the period from January 2006 to September 2010 in Beijing, the general features of the electric power load and the main factors affecting this load have been analysed. The results indicate that winter and summer are the two peak power consumption seasons in each year. This finding could be mainly attributed to the consumption of energy for urban residential cooling or heating. In the summer, the daily minimum temperature was most closely correlated with the maximum power load (correlation co-efficient of 0.65, significant at the 0.1% level); the primary effect of temperature on the maximum power load varied largely from 376 to 858 MW $^{\circ}C^{-1}$, and it increased sharply when the daily minimum temperature was higher than 24 °C or the daily maximum temperature was higher than 32 °C. In the winter, the daily maximum temperature was most closely correlated with the power load (−0.45, 0.1% significance), and the primary effect varied from 109 to 391 MW $^{\circ}C^{-1}$. However, the relationship between the power load and the temperature was more complicated in the winter: this relationship varied during the central heating period and its pre- and post-periods. Moreover, the temperature humidity index (THI) could explain more of the variance in the daily maximum power load than any single temperature factor in the summer, while the wind-chill temperature index (WCT) did not contribute to this variance in the winter. Finally, due to the rapid urbanization of Beijing, the power load and the priamry effect increased each year.

KEY WORDS electric power load; temperature; heating period; Beijing

Received 4 June 2011; Revised 2 January 2012; Accepted 27 February 2012

1. Introduction

A safe and stable power system is one of the necessary conditions for the normal functioning of any city. The electrical power supply is a basic guarantee for industrial production, communication, transportation and daily life. In a modern grid (electric power system), a local accident can spread to the entire electric grid instantaneously, usually resulting in huge economic losses. An abnormal increase in the power load can often cause an accident for the power grid. The power grid of Beijing is a typical receive-side grid: the North China Power Grid supplies about two thirds of its demand. Thus, an accurate prediction of the electricity load of Beijing is important for power dispatching and the safe operation of the entire grid. Although significant research has been performed (Douglas *et al*., 1981; Chen and Hong, 2000; Zhang *et al*., 2000; Zhou, 2000; Valor *et al*., 2001; Zhang and Wang, 2002; Luo *et al*., 2005; Miller *et al*., 2008), it is still a challenge today to predict the power load variability of Beijing, especially on a daily time scale. A quantitative study of the daily power load variability and its main contributing factors would facilitate the precise prediction of the daily power load in Beijing.

With the rapid development of the national economy in China, many cities face severe power shortages, especially larger cities during peak power consumption seasons. For example, in Beijing, Shanghai and Guangzhou, power shortages have often occurred in mid-summer and winter in recent years, which has resulted in the government having to restrict power use by means of switching off the power supply to many factories. These observations suggest that power consumption will increase when temperature rises or declines to a certain extent, creating a ‘U’-shaped correlation between power load and temperature, which denotes that the power consumption peaks during the winter and summer. Socio-economic activities can not fully explain these phenomena. One plausible, partial, explanation involves the weather and climate. High summer temperatures would spur electricity demand as people turn up their air conditioning to stay cool. In contrast, people will use heat pumps or other heating equipment to stay warm during severe winter weather.

At present, some studies on the relationships between the power load and meteorological factors in particular cities or regions of China have been carried out. For example, Chen and Hong (2000) pointed out that there are significant positive correlations between the daily power load and the daily mean temperature in central China in the summer, but they do not correlate significantly in the winter. However, Zhang *et al*. (2000) demonstrated that in Shenyang (a capital city in northeast China), the power load is significantly affected by meteorological factors in the transitional seasons (the early and the later period of summer or winter) but not in autumn and mid-winter. From the previous studies, it is clear that the relationship between the power load and meteorological factors varies in different regions and different seasons. Similarly, according to a study on the power load and its relationship to temperature in Nanjing (a capital city in east China), Zhang *et al*. (2009) indicated that there are seasonal differences and cyclical features in the effects of temperature variations upon the daily maximum load, and they emphasized that one of

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the most significant correlations is the short-term impact of temperature on the power load in Nanjing. As for Beijing, Zhang and Wang (2002) researched the relationship between the power load and meteorological factors in the summer based on 2 years of data (1998 and 1999). They pointed out that temperature was the factor most closely correlated with the Beijing power load in the summer: the relative humidity, wind speed, sunshine duration and rainfall were also correlated with the power load over the same period. Furthermore, they tried to predict the power load variations with model simulations, and these simulations provided insights into power load predictions. Subsequently, Wu and Zhang (2008) used econometric analysis methods to research the response of the Beijing power load to temperature variations during the period 2002–2004. Chen *et al*. (2009) indicated that the rapid development of urbanization and the residential air conditioning ratio in Beijing increased sharply in the period 1996–2007. These factors directly affected the urban residential consumption of cooling energy by air conditioning, and climate warming was the only factor that could act to save energy in the winter.

All of the previous studies have played important roles in improving the understanding of the relationship between the power load and meteorological factors in Beijing and several other cities in China. However, there are some differences among the different research foci, and the power data used in previous studies are relatively limited. In addition, the rapid economic and social development in Beijing in the last few decades, as well as the influence of global warming, may have introduced new or more complex features in the relationships between the power load and meteorological factors. Therefore, it is necessary to pursue further studies on this issue. Moreover, in recent years, electric scarcity has exerted a huge influence on social and economic development in China. As a result, the public and the government have taken a stronger interest in this issue, and there has also been increased interest on the part of meteorological scientists in researching the relationships between power consumption and the weather and climate change. Based on the above, the main purpose of this paper is to analyse the daily power load variability and its relationship with meteorological factors in Beijing during winter and summer. Next, statistical prediction models for the daily maximum power load variability during the two seasons are discussed.

2. Data and methods

The daily power load data sets used in this paper were derived from the Beijing Electric Power Company and covered the period from 1 January 2006 to 27 September 2010. The meteorological data sets were obtained from the Beijing Meteorological Bureau and contained the following factors: daily maximum/minimum/mean temperature, daily mean wind speed, daily mean relative humidity, daily precipitation amount and daily sunshine hours. Furthermore, the wind-chill temperature index (WCT) and temperature humidity index (THI, also known as thermal discomfort index) are also used here, and these indices represent the quantitative index for the human comfort status in the winter and summer, respectively. The daily WCT formula is:

$$WCT = 13.12 + 0.6215 \times T - 11.37 \times V_{10\,m}^{0.16} + 0.3965 \times T \times V_{10\,m}^{0.16} \quad (1)$$

where the unit of WCT is °C, T is the daily mean temperature in °C, V is the wind speed measured at 10 m height and the unit is km h^{-1} (Shitzer, 2006). The daily THI formula is:

$$THI = (1.8 \times T + 32) - (0.55 - 0.55 \times RH) \times (1.8 \times T - 26) \quad (2)$$

where the T is also the daily mean temperature in °C, and the RH is the daily mean relative humidity in % (Wu and Deng, 2001).

The commonly used methods of mathematical statistics, such as correlation and regression analysis, are employed in this research. It is worth noting that the high-frequency correlation is also inspected for each correlation analysis in order to examine whether the day-to-day correspondence of the power load and meteorological factors is stable. More importantly, the high-frequency correlation could reflect the response of power load to synoptic scale disturbances better, without the influences of long term trend and annual or seasonal cycles. All time series are high-pass filtered using a Butterworth filter (Hamming, 1977) with a filtering window of 10 in the high-frequency correlation analysis.

3. The general features of Beijing power load variability

The daily maximum, mean and minimum power loads in Beijing during the period 1 January 2006 to 27 September 2010 are shown in Figure 1. There are some power load data missing for September to October 2006, February 2007, July to September and November 2008, and September 2009: 130 days are missing in total. The deletion rate is 10.7%. As shown in Figure 1, the daily maximum, minimum and mean power load shared the same fluctuations for the whole period. At the same time, all of these time points followed an obviously increasing trend during the study period. The increase in the power load from year-to-year may be attributed to social and economical developments. In any event, the relationships between this annual increase and social and economical factors are not inspected in this paper. These intra-annual variations are characterized by the double-peak features in the power load curves, which means that the winter and summer are the two highest value periods for electricity demand in Beijing. Assuming that the electricity consumption for industrial and agricultural production, urban lighting, municipal facilities and traffic remained unchanged throughout the year, then the increased power load could be mainly attributed to cooling energy consumption by urban residents in the summer and heating energy consumption in the winter. In the following sections, the relationships between the daily power load variability and the meteorological factors will be discussed quantitatively regarding the summer and winter.

For the power sector or enterprise, the greatest concern is the everyday maximum electricity demand. Thus, in the following analysis, only the daily maximum power load variability and its relationships with meteorological factors were analysed. The eight curves shown in Figure 2 are the daily maximum power load (a), daily mean temperature (b), mean wind speed (c), mean relative humidity (d), precipitation amount (e), sunshine hours (f), THI (g) and WCT (h). The variations in the daily maximum and minimum temperature are closely related to the daily mean temperature such that the two curves are excluded. In contrast to the double-peak features of

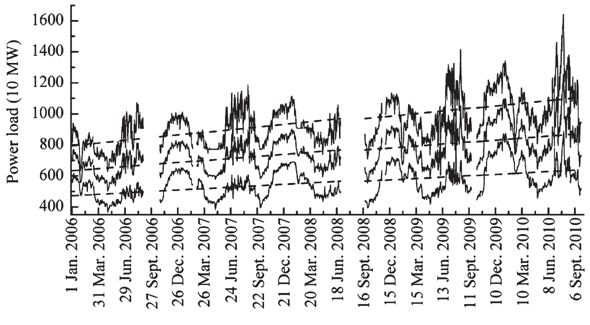

Figure 1. The daily maximum (top), mean (middle) and minimum (bottom) power load in Beijing over the past 5 years (The dashed lines denote the linear trends).

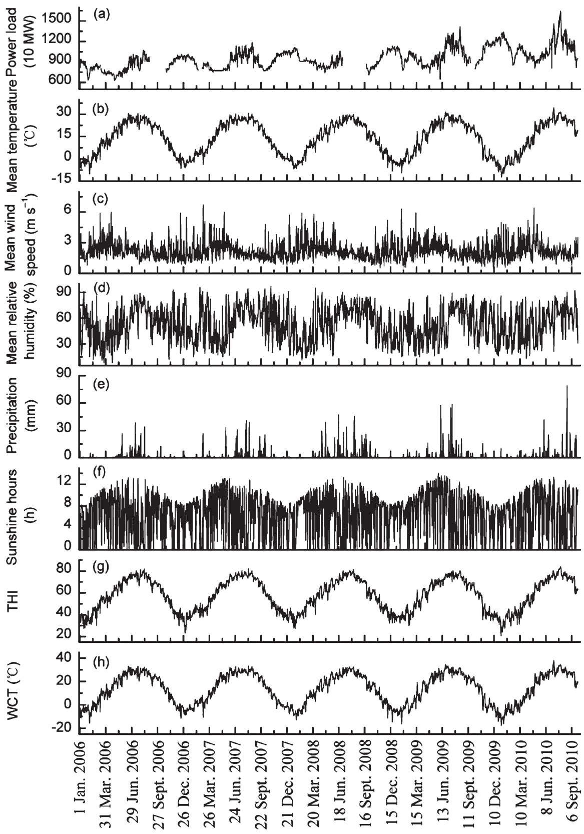

Figure 2. Daily maximum power load (a) and meteorological factors (b–f), temperature-humidity index (g) and wind-chill temperature index (h).

the daily maximum power load, the daily mean temperature is characterized by a single peak in the annual cycle. The two peaks in the daily maximum power load correspond to winter and summer. Moreover, the other factors, such as the wind speed, relative humidity, precipitation and sunshine hours also contain a single peak in their annual cycles. In this study, the relationships between the power load and the temperature, precipitation, wind speed and other factors over the winter (1 November to 31 March) and the summer (1 May to 30 September) were studied, respectively, and moreover, the temperature humidity index in the summer and the wind chill temperature index in the winter were also analysed.

4. The daily variability of the power load and its relationships with meteorological factors

4.1. Summer

The correlation co-efficients of the daily maximum power load and the daily mean temperature (marked as T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), wind speed (W_s), relative humidity (H_r), precipitation amount (P), sunshine hours (S_h), THI and WCT over the summer and winter are shown in Table 1. The $r1$ term in Table 1 denotes the raw correlation of each time series, while the $r2$ term denotes the high-frequency ($<$10 days) of each time series after high-pass filtered to reveal the day-to-day correspondence of the power load and meteorological factors without any influence from the long term signals.

As shown in Table 1, the temperature is most closely correlated with the daily fluctuations in the power load in the summertime in Beijing as evidenced by the significant positive correlation. The correlation co-efficients of the maximum power and the daily mean, maximum and minimum temperatures are 0.63, 0.51 and 0.65 respectively. Of these values, the daily minimum temperature had the largest correlation with the power load variability. The high-frequency correlation co-efficients of the maximum power load and the mean, maximum and minimum temperatures are 0.32, 0.23 and 0.28, respectively; these values are also statistically significant at the 0.1% level. The correspondence between the raw and high-frequency correlations suggests a stable relationship between the maximum power load and the temperature, and the significant positive correlation is a reflection of their physical response mechanisms. As a result of the rapid economic development in China, the urban and rural living standards have greatly improved. The installation and use of air conditioning in factory workshops, markets, office buildings and residential buildings has increased rapidly in the past few decades, especially in Beijing. It is likely that the extensive use of air conditioning and other cooling equipment has caused the maximum power load to rise sharply in the summer. The high positive correlations reflect the response of the power load to the temperature. However, it is still unclear why the daily minimum temperature is most closely correlated with the maximum power load. One possible explanation is that in summer the daily minimum temperature is high and the heat often endures throughout the day, causing people to suffer from continuously high temperatures. These conditions spur electricity demand as people turn up their air conditioning or other cooling equipments to stay cool. Thus, the maximum power load is more dependent on the daily minimum temperature in the summer.

The curve displayed in Figure 3(a) compares the daily maximum power load in the summer averaged over the last 5 years with the daily minimum temperature averaged over the same period (Figure 3(b)). The smooth lines denote the cubic polynomial fitting curve for each time series in Figure 3. The two curves share the same general parabolic variation: they both rise in the early summer, peak in the mid-summer, and decrease in the late summer. They have a correlation co-efficient of 0.90 at the 0.1% significance level, which indicates that the variation in the daily maximum power load is highly dependent on the daily minimum temperature in Beijing during the summer. The possible physical mechanisms of the power load response to the variations in temperature have been discussed previously: namely, the sharp increase in the maximum power load may be

Table 1. Correlation co-efficients of the power load and meteorological factors in the summer and winter.

		T_{mean}	T_{max}	T_{min}	W_s	H_r	P	S_h	THI	WCT
Summer	$r1$	0.63[a]	0.51[a]	0.65[a]	−0.19[b]	0.19[b]	0.02	−0.01	0.67[a]	–
	$r2$	0.32[a]	0.23[a]	0.28[a]	−0.02	−0.05	−0.10	0.01	0.32[a]	–
Winter	$r1$	−0.47[a]	−0.48[a]	−0.40[a]	−0.06	0.04	0.00	−0.13	–	−0.45[a]
	$r2$	−0.27[a]	−0.29[a]	−0.10	0.06	−0.01	0.05	−0.08	–	−0.18[b]

[a] Significant at the 0.1% level. [b] Significant at the 1% level. The $r1$ and $r2$ terms indicate the raw correlation and high-frequency (<10 days) correlation, respectively.

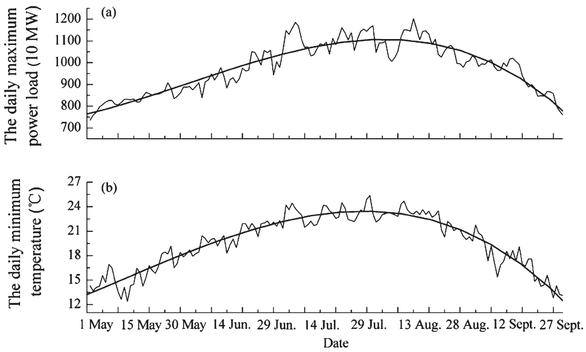

Figure 3. Comparisons of the daily maximum power load (a) and the daily minimum temperature (b) in Beijing during the summer averaged over the past 5 years.

caused by the heavy use of air conditioning and other cooling equipments to withstand the hot weather.

Furthermore, the relationships between the daily maximum power load and other meteorological factors, such as the wind speed, relative humidity, precipitation and sunshine duration (sunshine hours) were also examined. The correlation co-efficients for these relationships are also listed in Table 1. The correlation co-efficients between the maximum power load and precipitation and sunshine are close to 0, which indicates that the variability in precipitation and sunshine had little effect on the maximum power load during the summertime in Beijing. Although the correlation co-efficients for the wind speed and relative humidity factors are much less than that for the temperature, they are still significant at the 1% confidence level. The significant negative correlation with wind speed shows that the peak power load consumption will decrease on a windy day and increase on a windless day in the summer. The significant positive correlation with the relative humidity shows that the daily maximum power load will increase with humidity in the summer because of greater cooling energy consumption due to the fact that high humidity is not favourable for human body heat emission. However, the high-frequency correlation co-efficients of the wind speed and relative humidity with the maximum power load are relatively low compared with that of temperature and do not reach the significance level of 5% (Table 1). Although the daily mean wind speed and relative humidity also exert some effects on the daily maximum power load variability, temperature is a greater determinant of the maximum power load fluctuations in the summer.

The temperature humidity index is a comprehensive indicator that reflects the temperature and relative humidity simultaneously; subsequently, this index can better reflect the human somatosensory comfort in the summer. The THI is positively correlated with the daily maximum power load, with a correlation co-efficient of 0.67 and a high-frequency correlation co-efficient of 0.32 at the 0.1% confidence level. These strong positive correlations suggest that more power consumption will occur on a day characterized by a high THI. This correlation can be explained by the observation that a high THI indicates a high temperature coupled with a high relative humidity, producing muggy weather that is popularly called sauna-like weather in Beijing. High temperatures, high humidity, low pressure and a low diurnal temperature range are the dominant features on the muggy days. These conditions suppress the evaporation of sweat from the body, producing discomfort and increasing the possibility of sunstroke when walking or working outside. The final outcome is that most people choose to remain in a room with air conditioning in order to stay cool. Consequently, the power load increases on days with a high THI, and the variability in the electricity demand can be explained by the variability in this index during the summer. Thus, a high THI value can be seen as a predictor of a higher demand for electricity in the summer.

4.2. Winter

A similar analysis has been implemented to study the relationships between the power load and meteorological factors in the winter: the raw and high-frequency correlation co-efficients are also shown in Table 1. During winter, there are significant negative correlations between the daily maximum power load and the temperature. The correlation co-efficients of the maximum power load and the mean, maximum and minimum temperatures are −0.47, −0.48 and −0.40, respectively, all of which are significant at the 0.1% level. The high-frequency components of these factors (mean, maximum and minimum temperature) are also negatively correlated: the corresponding co-efficients are −0.27, −0.29 and −0.10, respectively, and, except for the minimum temperature, these values are significant at the 0.1% level. The significant negative correlations suggest that the power load will increase as the temperature falls. This increase in the power load may be attributed to increased heating energy consumption in response to the severe winter. Although gas and coal central heating supply systems dominate in Beijing city (coverage was approximately 80% in 2010), central heating is scarce in the suburbs and rural areas. Also, many old buildings in the city lack heating pipes, meaning that most residents in those areas rely on electric heating during the chilly winter. At the same time, as living standards improve and consumer attitudes change, some residents will use electric heat sources to strengthen the heating during winter. All of the factors mentioned here would result in an augmentation of the Beijing power load in the winter. For the raw correlations and the high-frequency correlations, the daily maximum temperature had the greatest association with the daily power load variations in the winter. This relationship can be explained by the observation that, in the winter, when the daily maximum temperature is low, the cold persists throughout the day, causing people to supplement the heating with electric heat sources or other heaters, especially in buildings without central heating.

Table 2. Correlation co-efficients of power load and meteorological factors during the central heating period and its pre- and post-heating periods.

		T_{mean}	T_{max}	T_{min}	W_s	H_r	P	S_h	WCT
Pre-heating	$r1$	−0.77[a]	−0.72[a]	−0.72[a]	−0.01	0.24	0.23	−0.38[b]	−0.76[a]
	$r2$	−0.49[a]	−0.37[b]	−0.50[a]	0.16	−0.12	−0.02	−0.06	−0.40[b]
Central heating	$r1$	−0.38[a]	−0.39[a]	−0.30[a]	−0.01	−0.01	−0.03	−0.07	−0.33[a]
	$r2$	−0.33[a]	−0.37[a]	−0.11[a]	0.22[b]	−0.02	0.01	−0.08	−0.21[b]
Post-heating	$r1$	−0.51[a]	−0.49[a]	−0.35[b]	−0.14	0.24[c]	0.15	−0.24[c]	−0.46[a]
	$r2$	−0.25[c]	−0.26[c]	0.06	0.02	0.12	0.28[b]	−0.16	−0.21

[a] Significant at the 0.1% level. [b] Significant at the 1% level. [c] Significant at the 5% level.

Whether the daily maximum power load is correlated significantly with other meteorological factors was also investigated, such as the wind speed, relative humidity, precipitation and sunshine duration (sunshine hours) in the winter. Unlike in the summer, the daily mean wind speed and the daily mean relative humidity are only weakly correlated with the daily maximum power load in the winter. Although the raw and high-frequency correlation co-efficients of the maximum power load and the WCT index are −0.45 (significant at the 0.1% level) and −0.18 (significant at the 1% level), respectively, the correlations for these factors are lower than those observed for the temperature factors, which suggests that the combined effects of wind and temperature do not explain more of the variability in the power load than a single temperature factor does. This observation arises from the fact that the WCT is an index for calculating the danger from winds and freezing temperatures outdoors in the winter. A lower WCT means colder and more dangerous outdoor conditions, but it does not suggest that indoor conditions are affected. Thus, power consumption is not very sensitive to the WCT index in Beijing during the winter. However, the variability in the sunshine duration does appear to be correlated with the maximum power load variability: the raw and high-frequency correlation co-efficients of sunshine hours and power load are −0.13 (significant at the 10% level) and −0.08, respectively.

As previously mentioned, the coverage of the central heating supply in Beijing city has reached approximately 80%. It would be interesting to know whether there are any differences in the relationships between the power load and meteorological factors during the central heating period (15 November to 15 March) and its pre- and post-periods in Beijing in the winter. The correlation co-efficients between the maximum power load and the main meteorological factors over the three periods are shown in Table 2; the $r1$ and $r2$ terms denote the raw and high-frequency co-efficients, respectively. During the three periods, the highest correlation co-efficients ($|r1| \geq 0.72$) between the daily maximum power load and the temperature factors occur in the pre-heating period. In the post-heating period, the correlation co-efficients between the maximum power load and the temperature are close to −0.50 and are significant at the 0.1% confidence level. However, the correlations between the power load and the temperature factors are relatively weak during the central heating period with $|r1| < 0.4$ (Table 2). The differences in the correlations between the temperature and the power load in the pre-heating, central heating and post-heating periods indicate that the correspondence between the daily maximum power load and temperature factors are not stable over the entire winter in Beijing. This inconsistency could be explained by the observation that people depend mainly on gas- or coal-based heating systems and not electric heating during the central heating period. The other meteorological factors, such as the wind speed, relative humidity, precipitation and sunshine hours, are also somewhat correlated with energy consumption in the winter. The WCT is also significantly correlated with the maximum power load in the pre-heating, central heating and post-heating periods in accordance with the other temperature factors.

The variation in the power load is characterized by a more complex relationship with the meteorological factors in the wintertime compared to the summertime. Figure 4 displays the curves (a) of the daily maximum power load in the winter averaged over the last 4 years and the curves (b) of the daily maximum temperature averaged over the same time. The smooth lines denote the cubic polynomial fitting for each time series in Figure 4. Similar to the summer, the daily temperature in Beijing in the winter is characterized by a parabolic variation: generally, it decreased in early winter, reached a minimum in mid-winter and rose in late winter. However, the fluctuations in the winter maximum power load did not correspond strongly with the temperature and instead could be roughly summarized as five distinct stages, marked as 1 to 5 on curve (a) in Figure 4. In stage 1, a gradual increase in the maximum power load corresponded to a reduction in the daily maximum temperature, which indicated that the increasing power load in the pre-heating period could be mainly attributed to the use of air conditioning in the early winter. In stage 2, which corresponded to the first few days during the central heating period, the temperature was still decreasing, but the power load reached a plateau during a transitional phase. In stage 3, the power load increase again corresponded to the continual decrease in the temperature, which could reflect the use of electric heat or other heating technology to supplement the central heat supply during the severe mid-winter. In stage 4, which

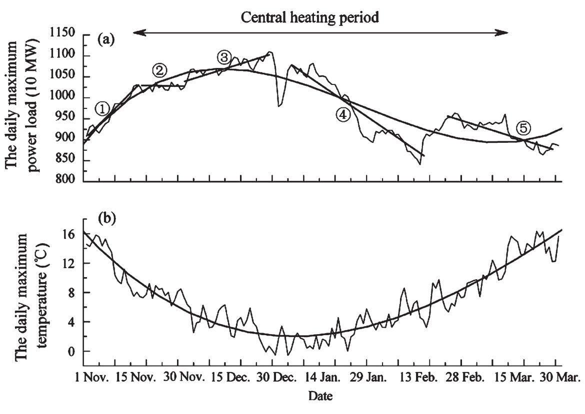

Figure 4. Comparisons of the daily maximum power load (a) and the daily maximum temperature (b) in Beijing winter averaged over the past 5 years.

corresponded to a transitional period from mid-winter to late winter, the daily maximum power load decreased sharply as the temperature increased, but there is an obvious asymmetry to this relationship. The sharp reductions in the maximum power load during this stage could be attributed to two factors: the warming period after mid-winter or the fact that many factories, enterprises, schools and institutions are on holiday during the Chinese New Year (approximately 12 January to 15 February). In stage 5, the gradual reduction in the power load corresponds to a gradual increase in the temperature during late winter. There is a power increase in the interval period between stages 3 and 4, which may have been caused by the fact that many factories and enterprises resume production after the Chinese New Year holiday. Furthermore, there is an anomalous fluctuation in the power load during stages 4 and 5 that could be explained by obtaining additional data.

4.3. The primary effect of temperature on the power load in the summer and winter

The relationship between the temperature and the power load also can be derived intuitively from the scatter diagram (Figure 5), which features a 'U'-shaped structure with a flat valley. In general, the power load decreases as the temperature rises and, subsequently, increases gradually as the temperature rises. The power load varies little when the mean temperature is between approximately 12 and 20 °C. In other words, power consumption increases as the temperature rises during the summer and as the temperature falls during the winter. Although the daily maximum power load is more closely affected by the temperature-humidity index in the summer, it is simpler to use a single factor in the forecasting and monitoring process. Although the mean temperature is

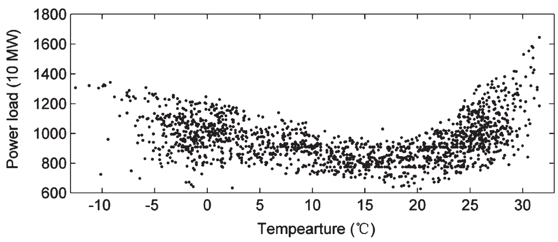

Figure 5. Scatter diagram of the daily maximum power load and the daily mean temperature.

highly consistent with the maximum or minimum temperature, the mean temperature is not a measurable variable in actual operations. Therefore, the minimum temperature and the maximum temperature, not the mean temperature, have been used to generate the power load forecast in this research trial.

A series of linear regressions has been implemented, and the results are listed in Table 3. In the equations, x is the daily minimum temperature in the summer and the daily maximum temperature in the winter, respectively, and y is the maximum power load estimated from the regression equation. The physical meaning of the regression co-efficient in the regression model is the primary effect of temperature on the maximum power load. For example, the regression co-efficient in one regression equation for the summer is 39.7 (in the unit of 10 MW °C^{-1}), which means that the maximum power load will increase (decrease) 397 MW when the minimum temperature increases (decreases) by 1 °C in the summer. In order to examine the possible differences in the primary effect at different statistical thresholds, the daily minimum temperature thresholds were set from 16 to 25 °C in the summer and the daily maximum temperature thresholds were set from 9 to 0 °C in the winter. The primary effect ranges from 376 to 858 MW °C^{-1}, and this effect increases sharply when the daily minimum temperature reaches 24 °C. It can be seen clearly from the histogram in Figure 6(a), the primary effect increases gradually as the daily minimum temperature rises in the summer. The daily minimum temperature is typically greater than or equal to 24 °C (the daily maximum temperature is about 32 °C) during the period from late July to early August, which is usually characterized by muggy weather. When enduring long periods of hot weather, people are more likely to use air conditioning or fans. Thus, a high T_{min} often equates a substantial increase in the power demand in Beijing during the summer.

In the winter, the primary effect increases clearly as the daily maximum temperature falls (Figure 6(b)), and it varies from 109 to 391 MW °C^{-1}. When the daily maximum temperature is below 10 or 9 °C (the daily minimum temperature is about 0 °C), the primary effect is greater than 100 MW °C^{-1}. However, when the daily maximum temperature drops to 0 °C (the daily minimum temperature is approximately −7 °C), the primary effect can reach 391 MW °C^{-1}. In general, the statistical regression models can roughly estimate the maximum power load fluctuations and

Table 3. Regression models at the different statistical thresholds.

Summer				Winter			
T_{min} (°C)	N	Regression equation	Primary effect (MW °C^{-1})	T_{max} (°C)	N	Regression equation	Primary effect (MW °C^{-1})
16	524	$y = 202.0 + 38.1x$	376	9	446	$y = 1049 - 10.9x$	109
17	493	$y = 170.2 + 39.6x$	393	8	417	$y = 1050.3 - 12.0x$	120
18	449	$y = 166.4 + 39.7x$	397	7	376	$y = 1051.3 - 13.4x$	134
19	398	$y = 82.8 + 43.3x$	433	6	334	$y = 1052.0 - 14.6x$	146
20	341	$y = 41.2 + 45.1x$	451	5	287	$y = 1052.1 - 15.3x$	153
21	284	$y = -133.9 + 52.3x$	523	4	244	$y = 1050.0 - 18.5x$	185
22	209	$y = -282.1 + 58.3x$	592	3	191	$y = 1044.2 - 22.7x$	227
23	141	$y = -237.1 + 56.6x$	566	2	145	$y = 1041.5 - 24.5x$	245
24	77	$y = -602.7 + 71.0x$	710	1	104	$y = 1024.4 - 31.1x$	311
25	38	$y = -994.7 + 85.8x$	858	0	72	$y = 993.8 - 39.1x$	391

x is the daily minimum temperature in the summer and the daily maximum temperature in the winter respectively, y is the maximum power load estimated from the regression equation; T_{min} and T_{max} mean the daily minimum and the daily maximum temperature threshold respectively; N denotes the number of samples.

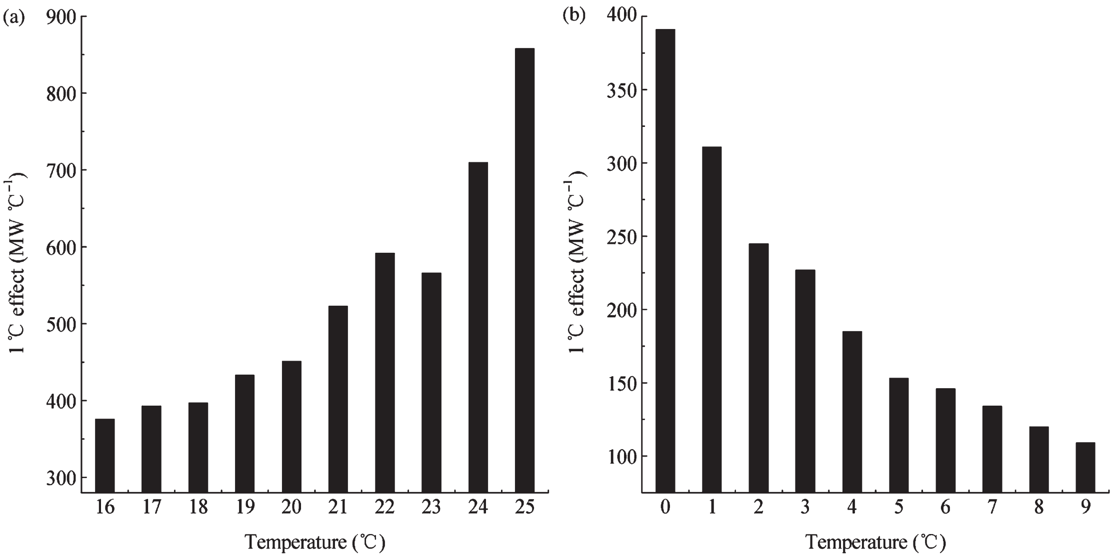

Figure 6. Histograms of the primary effect at the different statistical thresholds for the summer (a) and the winter (b).

Table 4. Regression models from the different years.

Year	Summer			Winter		
	N	Regression equation	Primary effect (MW °C^{-1})	*N*	Regression equation	Primary effect (MW °C^{-1})
2006	91	$y = 433.0 + 20.9x$	209	131	$y = 886.1–3.6x$	36
2007	117	$y = 285.1 + 31.9x$	319	131	$y = 1012.9–9.2x$	92
2008	29[a]	$y = 197.3 + 36.2x$	362	123	$y = 1049.5–8.7x$	87
2009	103	$y = 201.1 + 40.8x$	408	142	$y = 1124.1–12.0x$	120
2010	109[a]	$y = 59.6 + 50.6x$	506	88[a]	$y = 1150.4–12.1x$	121
All case	458	$y = 165.5 + 39.7x$	397	615	$y = 1048.3–10.6x$	106

[a] There are many data points missing from the data sets for summer 2008 and winter 2010; therefore, the sample sizes for these periods are comparatively smaller. In the equations, y represents the daily maximum power load in the unit of 10 MW, and x represents either the daily minimum temperature in the summer or the daily maximum temperature in the winter.

thus provide references for advance decisions about power allocation.

In Section 3, it was mentioned that power consumption has increased considerably in Beijing over the last 5 years. To determine whether this increase has influenced the relationships between the power load and temperature, the primary effect of temperature on the power load in each year were examined in Table 4. In the summers of 2006, 2007, 2008, 2009 and 2010, the primary effects are 209, 319, 362, 408 and 506 MW °C^{-1}, respectively, and the average of the 5 years is 397 MW °C^{-1}. This analysis revealed an increasing trend. In the winter, the primary effects in each year are 36, 92, 87, 120 and 121 MW °C^{-1}, respectively, and the average of the 5 years is 106 MW °C^{-1}. Although it is weaker than in the summer, the increasing trend of the primary effect also exists in the winter. The increase in the primary effect is a direct reflection of the annual growth in electricity consumption, which can be primarily attributed to the rapid urbanization of Beijing in recent years. Thus, the regression model should be updated regularly to produce an accurate estimate of daily power consumption.

5. Conclusions and discussion

The variability in the daily power load in Beijing was described in terms of its relationship with meteorological factors during the winter and summer using correlation and regression analysis methods. Three meteorological factors were significantly correlated with the daily maximum power load in the summer: temperature, wind speed and relative humidity. The daily minimum temperature had the highest correlation co-efficient (0.65, significant at the 0.1% confidence level) with the daily maximum power load. In contrast, in the winter, the temperature and sunshine duration factors were significantly correlated with the variability in the electric power load: the daily maximum temperature was most closely correlated with a correlation coefficient of −0.45 that was significant at the 0.1% confidence level. The significant positive and negative correlations of temperature with the power load in the summer and winter, respectively, can plausibly be explained by the expected increase in energy consumption necessary to stay cool in the summer and warm in the winter. The temperature humidity index (THI) was more significantly correlated with the power load than any single temperature factor in the summer, which suggests that there is a greater power demand during muggy days in Beijing. In the winter, however, the wind-chill temperature index (WCT) did not improve the impact on the variation of the power load.

In the summer, the primary effect of temperature on the maximum power load varied widely from 376 to 858 MW °C^{-1}, and it increased dramatically when the daily minimum temperature was higher than 24 °C or when the daily maximum temperature was higher than 32 °C, which usually occurred on muggy days in late July to early August in Beijing. In the winter, the primary effect of temperature on the maximum power load varied from 109 to 391 MW $^{\circ}C^{-1}$, and it reached a peak of 391 MW $^{\circ}C^{-1}$ when the daily maximum temperature dropped to 0 °C or the daily minimum temperature dropped to −7 °C. Additionally, the relationship between the power load and the temperature varied among the central heating period and its pre- and post-periods.

The power load increased substantially over the last 5 years, and the primary effect also increased year by year, especially in the summer. The primary effect varied from 209 MW $^{\circ}C^{-1}$ in 2006 to 506 MW $^{\circ}C^{-1}$ in 2010. The rapid growth in power demand and the primary effect reflect the accelerated urbanization that has occurred in Beijing in recent years. It is worth noting that, although air conditioning ownership has increased quickly over the last decades as the national economy has grown, it is not installed widely in most rural households, with an estimated 5 million people living around Beijing city and, moreover, there is a number of dormitories without air conditioning which accommodate more than 2 million college students in Beijing city. If these buildings are all equipped with air conditioning in future there is no doubt that power consumption will increase, and at the same time the variability of power load will be much closer to meteorological conditions. Thus, more attention should be paid to the role of socioeconomic development when developing a statistical model to estimate the daily power demand.

Acknowledgements

This research was supported by the State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant No 2010-KF-06), the National High Technology Research and Development Program of China (Grant No. 2010CB428506), the National Science Foundation of China (Grant No. 40975064) and the Climate Change Special Fund of CMA (Grant No. CCSF201204).

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