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The optimal period of record for air-conditioning outdoor design conditions

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ABSTRACT

The outdoor design conditions should not only regularly update, but also reflect the effects of climate change. In this study, a new method of calculating the optimal period of record (POR) for air-conditioning outdoor design conditions was put forward. Firstly, the M–K test was used to prove the significantly change of outdoor temperatures in air-conditioning season. Secondly, the generalized Pareto distribution (GPD) model was adopted to fit the distribution of the high temperature and the model was verified by the P–P and Q–Q plot. Empirical distribution functions with different PORs were calculated by defining the meteorological impact factor. Finally, the optimal POR was determined by comparing the empirical distribution functions with the GPD model. The new method for determining the optimal POR of outdoor design conditions was examined and the case for Tianjin was studied. The result shows that the optimal POR for Tianjin is 17 years.

1. Introduction

Outdoor design conditions are weather information for design purposes showing characteristic features of the climate at a particular location. They are basic data for the load calculation and equipment selection of HVAC systems. The researches of outdoor design conditions are mainly focused on the method or updating data, rarely on the period of record (POR) [1–3]. However, a fundamental premise of outdoor design conditions is an appropriate POR. Generally speaking, the period of record (POR) refers to the years of meteorological data. In order to get appropriate outdoor design conditions, the POR should not only reflect the local climatic normal but also the trend of climate change [4]. The climatic normal is defined by the World Meteorological Organization as "period averages of a climatic element computed for a uniform and relatively long period comprising at least three consecutive ten-year periods" [5,6]. It is considered all the time that the outdoor design conditions can more accurately reflect the climatic normal with longer POR.

But in recent years, more and more scholars believe that the concept of 30-year climate normal may no longer be suitable due to the influence of climate change. Livezey et al. [7] found that the 30-year POR only applied to a relatively stable climate sequence by analyzing prediction errors of four climate prediction models. So the 30-year POR was no longer applicable to engineering design as recent temperatures showed a rapid changing trend. Huang et al. [8] indicated that it was more accurate to predict the climate with shorter POR compare with 30 years. Kunkel et al. [9] also analyzed the optimal climate normal and their research pointed out it would improve the prediction with shorter POR. Snelling et al. [10] calculated the outdoor design conditions respectively with 15-year POR and the maximum possible POR. Then, they compared the "not-guaranteed" hours and maximum "not-guaranteed" duration. Their research also indicated that it was more suitable to calculate the outdoor design conditions with shorter POR. The above studies showed that the 30-year POR was too long to reflect the trend of climate change.

The POR of meteorological data cannot be too short, or it is impossible to filter out the fluctuation of the climate system. Hubbard and Kunkel [11] used meteorological data over 33 years to calculate the outdoor design conditions with $\mathrm{POR} = 1, 2, \ldots, 33$. Then, they discussed the minimum POR by using standard deviation of 1 °C. Colliver and Gates [12] also used the deviation and standard deviation to study the minimum POR of dry-bulb temperature, wet-bulb temperature and dew-point temperature.

Regulations including ASHRAE [13] and the Chinese specification [14] recommend the POR of outdoor design conditions to be 30-year because of the climate normal. But in CIBSE [15], the POR is recommended to be 20-year. The difference between ASHRAE and

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CIBSE indicates that further studies are needed to get an appropriate POR which can not only filter out the fluctuation of climate system, but also reflect the trend of climate change. The purpose of this study is to get a method of the optimal POR for air-conditioning outdoor design conditions on the background of climate change. In the first procedure, M–K test was adopted to verify the significant change of outdoor temperatures in air-conditioning season. Then, the generalized Pareto distribution (GPD) model was adopted to fit the distribution of high temperature. The empirical distribution functions with different PORs were determined by defining meteorological impact factor. Finally, the optimal POR considering climate change was determined by comparing the empirical distribution functions with the GPD model. The influence of climate change is mainly focus on the dry bulb temperature, rarely to the humidity [16]. So the change of dry-bulb temperatures was only analyzed in this research to determine the optimal POR with the climate change. Hourly dry-bulb temperatures of Tianjin from 1961 to 2010 were used in this study to analyze the optimal POR for air-conditioning outdoor design conditions in Tianjin.

2. Mathematical methods

2.1. GPD model

Mathematical model can be established to describe the distribution of temperatures as meteorology research has proved that the temperatures in a region are stable time series [17,18]. Generally speaking, outdoor design conditions are used for the design load calculation, and the design load reflects the risk decision of HVAC system. That means more attention should be paid to the extreme temperature rather than normal temperature for the air-conditioning outdoor design conditions. So the generalized Pareto distribution (GPD) model in the extreme value statistics was introduced in this paper. The GPD model is usually used to describe the distribution of values which exceed a certain number. The model has been widely used in the field of climate diagnostics, reliability research and financial risk management [19,20].

Let X_i ($i = 1, 2, \ldots, n$) be independent and identically distributed random variables. For the natural number n, let $M_n = \max\{X_1, X_2, \ldots, X_n\}$. If there are constant columns $\{a_n > 0\}$ and $\{b_n\}$ meet

$$\lim_{n\to\infty} P\left(\frac{M_n - b_n}{a_n} \le x\right) = H(x) \tag{1}$$

where

$$H(x;\mu,\sigma,\xi) = \exp\left\{-\left(1+\left(\frac{x-\mu}{\sigma}\right)\right)^{-1/\xi}\right\}, \quad 1+\xi\left(\frac{x-\mu}{\sigma}\right) > 0$$

For sufficiently large threshold value μ, $X-\mu$ would approximately obey GPD model, i.e.

$$G(y;\tilde{\sigma},\xi) = 1-\left(1+\frac{\xi y}{\tilde{\sigma}}\right)^{-1/\xi}, \quad y>0, \quad 1+\frac{\xi y}{\tilde{\sigma}} > 0 \tag{2}$$

With $\tilde{\sigma} = \sigma + \xi(u-\mu)$, σ, ξ, μ are the parameters of the distribution.

2.2. P–P plot and Q–Q plot

To verify the accuracy of GPD model for high temperature, P–P plot and Q–Q plot were used in this study. P–P plot is the abbreviation of probability plot and Q–Q plot is the abbreviation of quantile–quantile plot. These plots can be used to determine whether the sample data obey a certain distribution. The P–P plot compares an empirical cumulative distribution function of a variable with a specific theoretical cumulative distribution function. Similarly, the Q–Q plot compares ordered values of a variable with quantiles of a specific theoretical distribution. They are both theory-driven graphical methods for model test and the sample can satisfy the distribution if most points of the P–P and Q–Q plot are on the diagonal [21]. In this paper, P–P plot and Q–Q plot were drawn by the SPSS software.

2.3. Empirical distribution function

To get the approximate distribution of high temperature with different PORs, the empirical distribution function was used in this study. Empirical distribution function is a method to estimate the probability of sample by the frequency. Let x be a continuous random variable with empirical distribution function $F_n(x)$ and $x_{(1)}, \ldots, x_{(n)}$ be the order statistics from x. The empirical distribution function $F_n(x)$ can be calculated from the sample as

$$F_n(x) = \begin{cases} 0, & x \le x_{(1)} \\ \dfrac{k}{n}, & x_{(k)} < x \le x_{(k+1)}, \quad k = 1, \ldots, n-1 \\ 1, & x > x_{(n)} \end{cases} \tag{3}$$

where $x_{(1)}$ is the minimum of the sample, $x_{(n)}$ is the maximum of the sample, $x_{(k)}$ is the kth order statistics of the sample, n is the total number of the sample.

According to the Glivenko–Cantelli theorem [22], for any real x, empirical distribution function $F_n(x)$ and common distribution function $F(x)$ will almost have no differences when n is sufficiently large. Therefore, the empirical distribution function of the sample approximately equals to the common distribution function when the number of the sample is sufficiently large.

2.4. M–K test

The fact of climate change has been proved by many meteorologists [23,24]. However, further studies are still needed to study the influence of climate change on the distribution of outdoor temperatures in air-conditioning season. To analyze the significant influence on outdoor temperatures, the M–K test was used in this study. The rank-based non-parametric Mann–Kendall (M–K) statistical test (Mann, 1945 and Kendall, 1975) has been commonly used to assess the significance of trends in hydro-meteorological time series such as water quality, temperature, and precipitation [25,26]. The M–K test is based on the correlation between the ranks of a time series and their time order. For a time series $X = \{x_1, x_2, \ldots, x_n\}$, the test statistic is given by

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{4}$$

where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$) and $\mathrm{sgn}(x_j - x_i)$ is the sign function as

$$sgn(x_j - x_i) = \begin{cases} 1 & x_i < x_j \\ 0 & x_i = x_j \\ 1 & x_i < x_j \end{cases} \tag{5}$$

The variance is computed as

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{6}$$