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Linking human-biometeorological thermal conditions with the Köppen-Geiger climate classification updated – The Example of China

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Dated: 14 June 2015

1. Introduction

Human thermal comfort is an important human-biometeorological issue of growing importance. It indicates how satisfied human beings are with their thermal environment (Fanger 1970; Fanger 1973; ASHRAE 2001). In recent years, the study of outdoor human thermal comfort was assessed world widely due to its influence on human health care (Pappenberger et al. 2014), urban planning (Plumley 1977; Lin et al. 2010) and tourism (Matzarakis 2007; Lin and Matzarakis 2008). However, there is still a lack of information on thermal comfort on a world-scale.

World climate classifications have existed since the last century. Currently, based on the Köppen Climate classification (KCC) (Köppen 2011), there are several widely accepted versions: the Köppen-Geiger climate classification updated through Austria and Germany (KGC_{AG}) (Kottek et al. 2006), the updated Köppen-Geiger climate classification through Australia (KGC_{AU}) (Peel et al. 2007) and the Köppen-Trewartha climate classification (KTC) (Belda et al. 2014). KGC_{AG} has been selected as the reference climate classification in this study.

In KGC_{AG}, the characteristics of each climate type are mainly based on mean monthly surface air temperature and accumulated precipitation, which can effectively describe the distribution of vegetation. However, these two parameters hardly describe the human thermal comfort conditions. To describe and study human thermal comfort conditions, several thermal indices have been developed. Well known thermal indices are the predicted mean vote (PMV) (Fanger 1973), standard effective temperature (SET*) (Gagge et al. 1986), universal thermal climate index (UTCI) (Jendritzky et al. 2012) and physiologically equivalent temperature (PET) (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999). In this study, PET has been used, as it is based on the human energy balance. It has been commonly applied in previous studies and it uses the well known unit °C. Humid conditions are another important aspect for human thermal comfort. PET underestimates the influence of moisture. Therefore vapour pressure is considered separately as a second parameter.

Generally, all climate classifications are characterised by a set of letters. Each KGC_{AG} climate type is defined by 2 or 3 letters (compare to the legend in *Fig. 1*). It defines 31 climate types, 11 of which there are frequent in China (*Fig. 1*). The objective of this study is to develop a methodology which can link human-biometeorological thermal conditions with KGC_{AG}.

2. Data and Methods

2.1 Analysis of parameters in KGC_{AG}

In order to link thermal comfort conditions with KGC_{AG} in a corresponding form, parameters and time scales, which are utilised in KGC_{AG}, have been analysed. Air temperature (T_a) and precipitation (pp) are the two parameters used to indicate hot/cold climatic conditions and wet/dry climatic conditions, respectively. Due to the characteristics of PET (which indicates thermal conditions) and *VP* (which can indicate humid conditions), hot/cold thermal comfort conditions can be described by PET,

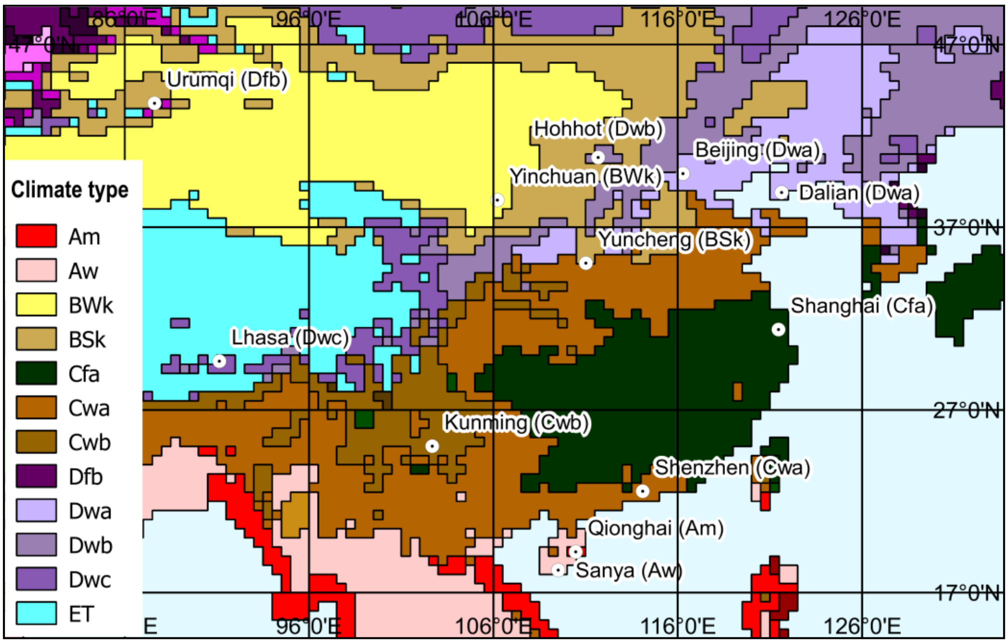

Fig. 1 Climate types in China according to Köppen–Geiger classification updated (KGC_{AG}) (modified after Kottek et al. 2006)

and wet/dry thermal comfort conditions can be described by *VP*. Meanwhile, the time scales in KGC_{AG} are mainly the annual period, the warmest month, the coldest month and the driest month. Therefore, the thermal comfort conditions can be organised with similar time scales, which are the annual period, the hottest month, the coldest month, the wettest month and the driest month.

2.2 Obtainment of data

In this study, 12 Chinese cities (*Fig. 1*) have been selected as the primary representations of 11 climate types, respectively. The digital map of KGC_{AG} (1976-2000) has been obtained from http://koeppen-geiger.vu-wien.ac.at/. The map has been modified by QGIS. The first reason for selecting cities in each climate type is the high density of population, as this theme is closely associated with human beings. The thermal comfort conditions of these climate types would roughly present in which kinds of thermal comfort conditions human beings could survive and reside permanently. Secondly, the importance of regional economy, culture and education has been taken into account, because it is also the reason for attracting human beings to remain there in modern society. 2 cities (Beijing and Dalian) have been selected for the climate type Dwa as comparisons, due to the complex geographical situation in this climate type in China. Thus the climate type Dwa has been represented by Dwa (Beijing) and Dwa (Dalian). Based on the primary represented cities, the data of 10 + 2 climate types has been obtained: Aw (Sanya), Am (Qionghai), Cwa (Shenzhen), Cwb (Kunming), Cfa (Shanghai), Dwa (Beijing), Dwa (Dalian), Dwb (Hohhot), Dwc (Lhasa), Dfb (Urumqi), BSk (Yuncheng) and BWk (Yinchuan).

3-hourly meteorological data in a long-term period (from 2000 to 2012) of 12 cities has been downloaded from http://www.ogimet.com/. Because the climatic station of Sanya (Aw) was relocated from an urban centre up to a hill in 2009, the 3-hour data from 2000 to 2008 has been utilised in this study. The points in time included in this dataset are 2:00, 5:00, 8:00, 11:00, 14:00, 17:00, 20:00 and 23:00 in Local Standard Time (LST). Four meteorological parameters – air temperature (T_a), wind velocity (*v*), vapour pressure (*VP*) and cloud cover (c) – have been utilised for further study.

The RayMan model (Matzarakis et al. 2007, 2010) has been applied to calculate the 3-hour PET values − the human thermal comfort index. Meteorological parameters (T_a, *VP*, *v* and c) have been used together with LST for this calculation. Currently, default values on thermo-physiological conditions (personal data, clothing and activity) in the RayMan model have been used.

2.3 Linking thermal comfort conditions with each climate type

Quantification of the thermal comfort conditions for each climate type is the key step in this study. According to the quantification of PET and *VP*, which correspond to T_a and pp, respectively, the thermal comfort conditions of each climate type will be described by concrete data. Data with 3-hour intervals in a long-term period for each climate type is one kind of big data. Frequencies can better present the actual distribution of the big data. Therefore, the linking phase will be achieved by adding specific frequencies of PET and *VP* to 10 + 2 climate types.

2.4 Categorisation of data

3-hour PET and *VP* of each climate type have been categorised by frequencies of 3-value and 4-value classes, respectively. The 3-value classes for PET are ≤ 8 °C, 8-35 °C, and > 35 °C. It is a modification of the classification of thermo–physiological stress for PET (Matzarakis and Mayer 1996). The 4-value classes for *VP* are ≤ 6 hPa, 6-12 hPa, 12-18 hPa, and > 18 hPa. This category is based on the previous data analysis.

Meanwhile, these frequencies have been grouped by 5 time scales: the annual period, the hottest month, the coldest month, the wettest month and the driest month. The annual period can present the entire thermal comfort conditions throughout the whole year. The last 4 time scales can present the extreme thermal comfort conditions (hottest, coldest, wettest and the driest) in one year for each climate type.

The final frequencies of PET and *VP* will be calculated according to the limitations from the value classes and the time scales. Therefore, 6 kinds of frequencies will be added to each climate type: (1) **annual** frequencies of **PET** within 3-value classes ($\mathbf{PET_a}$), (2) frequencies of **PET** in the **hottest** month within 3-value classes ($\mathbf{PET_h}$), (3) frequencies of **PET** in the **coldest** month within 3-value classes ($\mathbf{PET_c}$), (4) **annual** frequencies of ***VP*** within 4-value classes ($\mathbf{VP_a}$), (5) frequencies of ***VP*** in the **wettest** month within 4-value classes ($\mathbf{VP_w}$), and (6) frequencies of ***VP*** in the **driest** month within 4-value classes ($\mathbf{VP_d}$).

2.5 Visualisation of thermal comfort conditions

Visualisation of numeric information can always help readers to directly gain the key message. Therefore, in order to obtain a visual form of the thermal comfort conditions for each climate type, bar graphs have been used to present these frequencies. 12 groups of bar graphs have been created for Aw (Sanya), Am (Qionghai), Cwa (Shenzhen), Cwb (Kunming), Cfa (Shanghai), Dwa (Beijing), Dwa (Dalian), Dwb (Hohhot), Dwc (Lhasa), Dfb (Urumqi), BSk (Yuncheng) and BWk (Yinchuan), respectively. Each bar-graph group is composed of 6 horizontal bar graphs. These 6 bar graphs represent $\mathbf{PET_a}$, $\mathbf{PET_h}$, $\mathbf{PET_c}$, $\mathbf{VP_a}$, $\mathbf{VP_w}$ and $\mathbf{VP_d}$ in an order from top to bottom. Due to the 3-value classes of PET and the 4-value classes of *VP*, 3 colours have been implemented to display the frequencies of PET in bar graphs, and 4 colours have been implemented to display the frequencies of VP, respectively. Therefore, the quantification of human-biometeorological conditions has been displayed in a visual form.

3. Results

3.1 Thermal comfort conditions of each climate type in KGC_{AG}

Fig. 2 represents the thermal conditions of each climate type in KGC_{AG} through 12 groups of figures: Aw (Sanya), Am (Qionghai), Cwa (Shenzhen), Cwb (Kunming), Cfa (Shanghai), Dwa (Beijing), Dwa (Dalian), Dwb (Hohhot), Dwc (Lhasa), Dfb (Urumqi), BSk (Yuncheng) and BWk (Yinchuan). These figures are based on the frequencies of PET in 3-value classes and the frequencies of *VP* in 4-value classes. Each group consists of 6 bar graphs corresponding to the annual frequencies of PET (**PET_a**), frequencies in the hottest month of PET (**PET_h**),

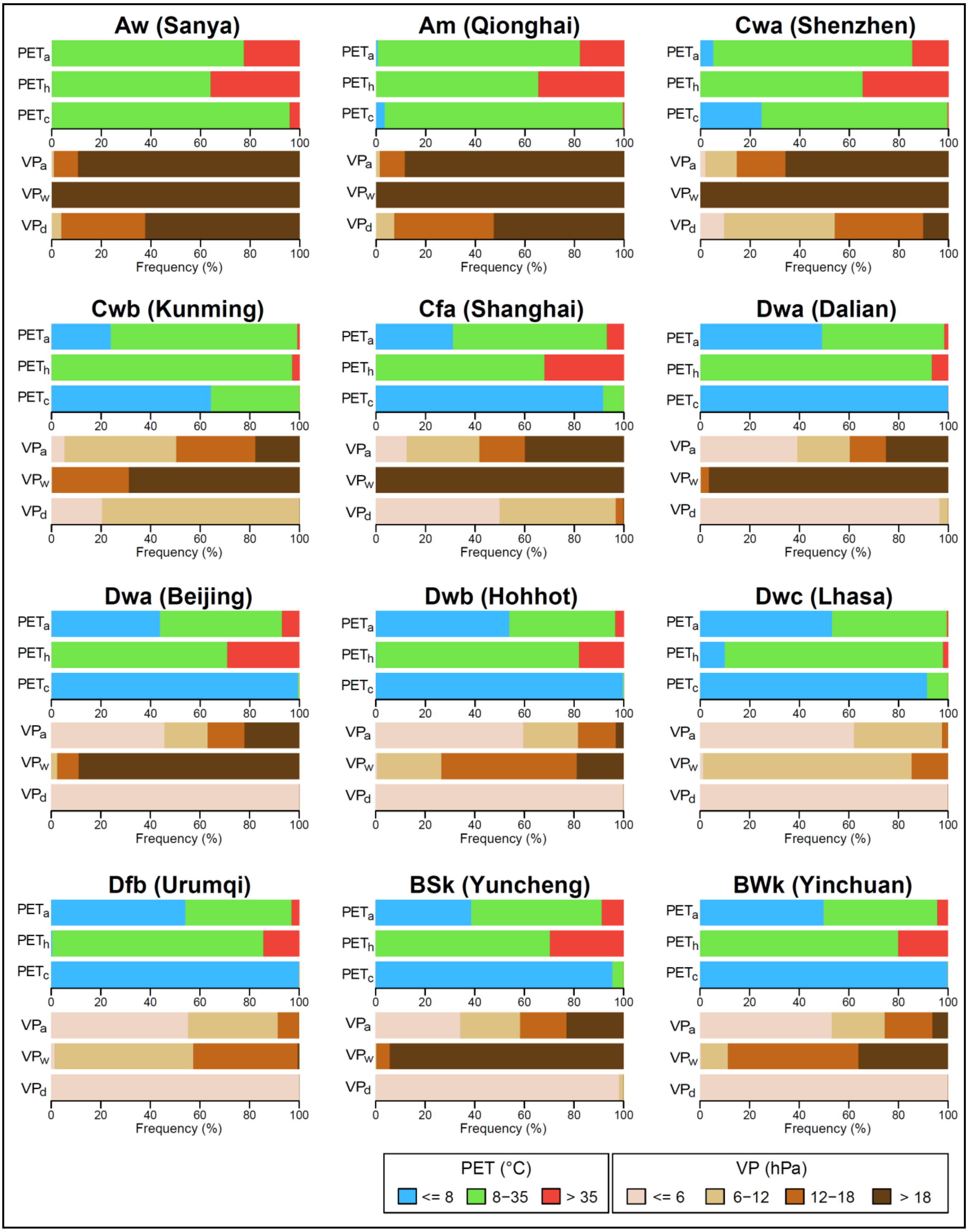

Fig. 2 The quantification of human-biometeorological conditions based on KGC_{AG}

frequencies in the coldest month of PET (**PET_c**), annual frequencies of *VP* (**VP_a**), frequencies in the wettest month of *VP* (**VP_w**) and frequencies in the driest month of *VP* (**VP_d**). PET is used to indicate the hot/cold conditions, and *VP* is used to indicate the wet/dry conditions.

In relation to the climate type **Cwa (Shenzehen)**, the results of the annual analysis show that the frequency of PET ≤ 8 °C is approx. 5% , while for approx. 80 % of the year PET is ranged between 8 °C and 35 °C and 15 % exceeds the 35 °C. In the hottest month, there are no conditions of PET ≤ 8 °C, but there are 65 % of the time with 8 °C < PET ≤ 35 °C, and approx. 35 % of the time with PET > 35 °C. During the coldest month, PET conditions ≤ 8 °C reach 25% , and approx. 75 % of the time are 8 °C < PET ≤ 35 °C. Finally, a frequency of 0.5 % depicts PET > 35 °C. The annual frequencies of *VP* in **Cwa (Shenzhen)** are approx. 2 %, 13 %, 20 % and 66 % for *VP* ≤ 6 hPa, 6 hPa < *VP* ≤ 12 hPa, 12 hPa < *VP* ≤ 18 hPa and *VP* > 18 hPa, respectively. The frequency of *VP* > 18 hPa dominates with 100 %, during the wettest month. The approx. frequencies in the driest month of *VP* are approx. 9 %, 45 %, 36 % and 10 % for ≤ 6 hPa, 6-12 hPa, 12-18 hPa and > 18 hPa, respectively. Assessment of each other climate type follows the same methodology as conducted for Cwa (Shenzhen).

3.2 Comparison of the entire thermal comfort conditions between climate types

According to the 12 bar graphs of **PET_a** that are depicted in *Fig. 2*, the climate type **Aw (Sanya)** has the warmest thermal comfort conditions: PET in 78 % of the year is ranged between 8 °C and 35 °C, while PET in 22 % of the year is higher than 35 °C. Climate types Dwa (Beijing), Dwb (Hohhot), Dwc (Lhasa) and Dfb (Urumqi) present similar annual frequencies of PET. However, in Dwc (Lhasa),due to the fact that the value class of PET > 35 °C rarely exists (less than 0.5 %), the climate type **Dwc (Lhasa)** has the coldest thermal comfort conditions.

In relation to **VP_a** in *Fig. 2*, the wettest thermal comfort conditions exist in the climate type **Aw (Sanya)**, where approx. 1 % of the year has *VP* between 6 hPa to 12 hPa, almost 10 % is between 12 hPa to 18 hPa and 89 %, which is the highest among the others, is presented with *VP* > 18 hPa. The driest thermal comfort conditions exist in the climate type **Dwc (Lhasa)** (where 62 % of the year *VP* is ≤ 6 hPa, and 36 % ranges between 6 hPa and 12 hPa) and **Dfb (Urumqi)** (where 55 % of the year *VP* is ≤ 6 hPa, and 36 % ranges between 6 hPa and 12 hPa).

3.3 Comparison between the oppositely extreme months

The oppositely extreme months refer to the hottest month versus the coldest month, and the wettest month versus the driest month. The hot/cold thermal comfort conditions of each climate type will shift between the conditions regarding to the hottest month and the coldest month. The wet/dry thermal comfort conditions of each climate type will shift between the conditions in the wettest month and the driest month. For example, in **Cwa (Shenzhen)** for 65 % of the time PET ranges between 8 °C < PET ≤ 35 °C, while for 35 % PET exceeds 35 °C, regarding the hottest month. On the other hand, during the coldest month, PET presents values lower than 8 °C for a frequency of 25 % , while 75 % of the month indicates by PET ranged between 8 °C < PET ≤ 35 °C. Thus, the frequency of PET > 35 °C in each other month will be equal to or less than 35 %, and the frequency of PET ≤ 8 °C in each other month will be equal to or less than 25 %. During the wettest month, the frequency of VP > 18 hPa reaches 100%. Additionally, during the driest month, approx. 9 % of the time is *VP* ≤ 6 hPa, approx. 45 % of the time is 6 hPa < *VP* ≤ 12 hPa, approx. 36 % of the time is 12 hPa < *VP* ≤ 18 hPa, and approx. 10 % of the time is *VP* > 18 hPa. Therefore, the frequency of *VP* > 18 hPa in each other month will be equal to or less than 100 %, while the frequency of *VP* ≤ 6 hPa in each other month will be equal to or less than 9 %.

3.4 Observed similarities in extreme months

According to the current value classes for PET and *VP*, similarities are shown regarding the thermal comfort conditions that exist in extreme months, in several climate types. In the climate types Dwa (Dalian), Dwb (Hohhot), Dfb (Urumqi) and BWk (Yinchuan), the frequency of PET that is presented with values equal to or less than 8 °C is **100 %**, regarding the coldest month. In the climate types Aw (Sanya), Am (Qionghai), Cwa (Shenzhen) and Cfa (Shanghai), the frequency of *VP* that is presented with values higher than 18 hPa is also **100 %,** corresponding to the wettest month. Furthermore, the frequency of VP that is presented with values ≤ 6 hPa is **100 %** for the driest month in the climate types Dwa (Beijing), Dwb (Hohhot), Dwc (Lhasa), Dfb (Urumqi) and BWk (Yinchuan).

Due to the fact that one month is approx. 1/12 of one year, the annual frequency of the single specific thermal comfort condition for the extreme month is 8 % (≈ 1/12). However, the annual frequency of this condition (**PET_a** or **VP_a**) is considerably higher than 8 %, due to the existence of the same conditions in the other 11 months. For instance, in **Cwa (Shenzhen)**, 100 % of the month is presented with a condition of *VP* > 18 hPa for the wettest month. Thus the annual frequency of this condition from the wettest month is 8%. From the bar graph of **VP_a** in **Cwa (Shenzhen)**, it is obvious that the annual frequency of *VP* > 18 hPa is 66 %. Therefore, the annual frequency of VP > 18 hPa for the other 11 months is 58 % (= 66 % - 8 %).

3.5 Differences in climate type Dwa

Although Dwa (Beijing) and Dwa (Dalian) have been temporarily marked as two climate types, they actually belong to the same climate type Dwa in KGC_{AG}. However, according to *Fig. 2*, the thermal comfort conditions of Dwa (Beijing) and Dwa (Dalian) are presented with some differentiations. For instance, the hottest month analysis presented the biggest differentiations. The annual frequencies of PET (**PET_a**) in Dwa (Beijing) are 71 % and 29 %

for 8-35 °C and > 35 °C, respectively. In contrast, the annual frequencies of PET (**PET$_a$**) in Dwa (Dalian) are 93 % and 7 % for 8-35 °C and > 35 °C, respectively. This can be explained due to the fact that Dalian is a coastal city, while Beijing is an inland city.

4. Discussion

Currently, a possible methodology on how to link human-biometeorological thermal conditions with KGC_{AG} has been created. The quantification of thermal comfort conditions has been added to 11 climate types based on the data from 12 Chinese cities. The key step of this methodology is to utilise the frequencies of PET and *VP* in specific time periods: annual period, the hottest month, the coldest month, the wettest month and the driest month.

In order to present the actual thermal comfort conditions with a stable dataset, the long-term meteorological data with 3-hour interval is necessary to be included in the current study. Through the utilisation of the frequency, the variation of data could be contained. Thus, frequencies of PET and *VP* can present more accurate thermal comfort conditions, compared to, for example, mean PET values and mean *VP* values.

Brief and visual information on thermal comfort conditions could be helpful to the reader. For example, people could gain the thermal comfort information of each climate type by scanning simple figures. Therefore, bar graphs can be a possible solution to fulfil this requirement. Meanwhile the data, which will be presented in the bar graphs, needs to be simplified and accurately represented. In the current study, the frequencies of PET and *VP* on an annual scale have been used to show the general thermal comfort conditions. Frequencies of PET and *VP* in the hottest & coldest months have been analysed in order to show the extreme hot/cold thermal comfort conditions during the year, for every climate type. Similarly, frequencies of PET and *VP* in the wettest & driest months have been analysed in order to show the extreme wet/dry thermal comfort conditions during the year. Finally, the visual form of thermal comfort conditions in each climate type has been achieved through the 6 bar graphs.

This methodology can be applied not only in China, but also in other regions. It is of great importance for future research to extend into other sample cities or even worldwide, in order to improve and quantify the current methodology, as well as validate the results of the frequencies of the thermal comfort conditions.

Due to the similar results that appear in several climate types (result 3.4), it is also possible to adjust the value classes of PET and *VP*, in order to obtain more variant thermal comfort conditions between each climate type.

As there are differences of the thermal comfort conditions between Dwa (Beijing) and Dwa (Dalian), the parameters that were used for the human thermal comfort conditions may have more sensitive qualities than T_a and pp. Therefore, the variations of PET and *VP* are more obvious than that of T_a and pp, respectively. These differences between Dwa (Beijing) and Dwa (Dalian) may also lead to two considerations: (1) How large of differences in thermal comfort conditions should be classified in one climate type? (2) Is it necessary to classify other new biometeorological types in the future?

Additionally, although BSk (Yuncheng) and BWk (Yinchuan) are the arid climate types in KGC_{AG} (Kottek et al. 2006), the current study shows that the driest thermal comfort conditions exist in Dwc (Lhasa) and Dfb (Urumqi). This can demonstrate that the traditional climate classification cannot indicate the wet/dry thermal comfort conditions for human beings directly through pp.

Based on future global human-biometeorological information, more suitable building styles could be selected, more precise energy consumption (heating /cooling) could be budgeted, possible disease periods could be predicted and the most suitable tourism season could be estimated in every type. Therefore, the fields of architecture, urban planning, public health and tourism could benefit from the global human-biometeorological information.

5. Conclusion

According to the analysis of 12 cities' data in a long-term period, the possible methodology of linking human-biometeorological thermal comfort conditions with KGC_{AG} has been obtained. The current study will provide a helping hand towards the understanding of the human-biometeorological thermal conditions on a largely regional scale. The results of the current study regarding the influence of the human-biometeorological conditions can be useful to architects, urban planners, public health services, the tourism industry and all the various stakeholders.

Acknowledgment

This study is sponsored by the China Scholarship Council (No. 201206990020).

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