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A comparison of global bioclimates in the 20th and 21st centuries and building energy consumption implications

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ABSTRACT

Summer and winter thermal discomforts in the major climate zones and sub-zones of the Köppen–Geiger world climate classifications during the 21st century were investigated and compared with those in the 20th century. Compared with the 20th century, frequency of distribution of the comfort index for the 21st century shows a distinct decrease in winter thermal discomfort and increase in summer thermal discomfort under the low and medium forcing emissions scenarios. Based on zone-average analysis, decreasing trends of cumulative cold stress and increasing trends of cumulative heat stress have been observed in all the major climate zones and sub-zones. There is an overall increase in energy use for space conditioning for all the sub-zones in equatorial climates, and an overall reduction in all the snow and polar climates sub-zones. In arid and warm temperate climates, the hot sub-zones have an increase in the overall energy requirements whereas the cold/warm sub-zones have a reduction. Locations within the hot summer sub-zones in warm temperate climates will become much more cooling-dominated, and there are significant increases in cumulative heat and proportional stresses in the hot summer sub-zones in snow climates. Implications for energy use and carbon emissions are discussed and mitigation/adaptation measures suggested.

1. Introduction

There is a growing concern about energy use in buildings and its likely adverse effects on the environment. The building sector, one of the largest energy end-users, often accounts for a larger proportion of the total primary energy requirement (PER) than the industry and transportation sectors in many developed economies. In 2004 for instance, building sector accounted for 40%, 39% and 37% of the total PER in the US, the UK and the European Union [1]. In China, building stocks accounted for about 24.1% of total national energy use in 1996, rising to 27.5% in 2001, and is projected to increase to about 35% in 2020 [2]. Globally, buildings account for about 40% of the total PER and contribute to more than 30% of CO_2 emissions [3]. In their work on the energy performance of nine large commercial buildings in Shanghai and Beijing, Jiang and Tovey [4] found that total annual CO_2 emissions were 119 kg CO_2/m^2 and 178 kg CO_2/m^2 in Shanghai and Beijing respectively. In addition to the energy used for operation, buildings embody the energy used in the mining, processing, manufacturing and transporting of the building materials, and the energy consumed in the construction and decommissioning of the buildings. This embodied energy, together with the energy used during the life span of a building constitutes the life-cycle energy and emissions footprint [5,6].

It is generally agreed that our climates are changing and the average temperature will rise gradually. In response to this, there have been a number of studies on the impact of climate change on energy consumption and potential adaptation strategies in the built environment (e.g. residential and office buildings in Australia [7–10], residential buildings in Sweden [11,12] and the United Arab Emirates [13], and office buildings in Burkina Faso [14], China [15,16] and Greece [17]). An increase in temperature has varying degrees of influences on the energy demand depending on the geographical spread of the major climate regions and role of different energy resources for heating and cooling in the built environment. The extent of reduction in heating and increase in

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cooling differs from one region/climate to another, depending on the prevailing local climatic conditions and energy efficient measures adopted. The greatest impacts will certainly be felt in low latitude regions, especially in cooling-dominated buildings with large internal heat gains such as people, electric lighting and equipment/appliances.

Building designs and energy use in the built environment are directly related to the prevailing climates and their impact on people's perception and acceptance of their surrounding environment. There have been attempts to investigate the long-term trends of outdoor human bioclimates (a combination of human responses and the prevailing climates) in terms of thermal heat and cold stresses in the different climate zones across China [18–20]. Outdoor human bioclimates have direct influences on the indoor built environment in terms design strategies and subsequent energy consumption. It has been found that thermal heat stress shows an increasing trend and thermal cold stress a decreasing trend. A reduction in thermal cold stress would lead to less space heating requirements in winter; whereas an increase in thermal heat stress would increase the risk of summer overheating in naturally ventilated buildings and result in more space cooling requirements in air-conditioned buildings during the hot summer months. Space heating is usually provided by gas- or oil-fired boiler plants whereas cooling relies mainly on electricity. There would be a shift towards greater demand for electricity supply. Because of its relative abundance in many energy-consuming nations such as Australia, China, India, the US and parts of Europe, coal would remain the main fuel for power generation in the foreseeable future. From a global perspective, this can have significant implications for energy and environmental policy in the built environment in the 21st century because electricity from coal-fired power plants tends to have a much higher carbon footprint than other fuels. For example, in China in 2007 carbon footprint of electricity was 1.073 kg CO_2e per kWh based on approximately 80% coal in the fuel mix compared to an average of 0.184 kg CO_2e per kWh for natural gas [21].

The primary aim of the present work is, therefore, to investigate the prevailing human bioclimates under different future climate scenarios in different climate zones across the world in the 21st century (2001–2100), and compare the long-term thermal heat and cold stresses with those found in the 20th century (1901–2000) [22] to ascertain whether there will indeed be any underlying trends in changes to human bioclimates in future years. This study is not intended to be a comprehensive thermal comfort analysis, in which other factors (such as clothing, activity, etc.) would be considered. From a global perspective, this is an attempt to achieve an areal expression of the feelings of human beings in relation to the prevailing physio-climatic regions. Based on these findings, implications for the built environment (in terms of energy consumption and carbon emissions and future research work required) are discussed.

2. World climate classifications and major regions

Climate determines to a large extent the type of soil and natural vegetation in a given region and exerts influences over the use of the land. It also dictates how buildings are designed and constructed and affects energy use in the built environment. In this study, the new digital Köppen–Geiger map on climate classification developed by the Biometeorology Group at the University of Veterinary Medicine Vienne [23,24] was adopted. Table 1 shows a summary of the classification. It has five major climate types – equatorial, arid, warm temperate, snow and polar – which are further sub-divided into hot/cold steppe/desert, fully humid, dry summer/winter, hot/warm summer, and cool summer and cold winter. Altogether, there are 31 climate classes. Fig. 1 shows an overview of the geographical layout

Table 1
Summary of the 5 major climates and 31 sub-types within the Köppen-Geiger climate classification (Refs. [22,23]).

Major climates	Sub types	Criteria
Equatorial (A)		$T_{min} \geq +18$ °C
	Fully humid (Af)	$P_{min} \geq 60$ mm
	Monsoon (Am)	$P_{ann} \geq 25(100-P_{min})$
	Savannah with dry summer (As)	$P_{min} < 60$ mm in summer
	Savannah with dry winter (Aw)	$P_{min} < 60$ mm in winter
Arid (B)		$P_{ann} < 10\ P_{th}$
	Desert climate (BW)	$P_{ann} \leq 5\ P_{th}$
	Cold desert (BWk)	$T_{ann} < +18$ °C
	Hot desert (BWh)	$T_{ann} \geq +18$ °C
	Steppe climate (BS)	$P_{ann} > 5\ P_{th}$
	Cold steppe (BSk)	$T_{ann} < +18$ °C
	Hot steppe (BSh)	$T_{ann} \geq +18$ °C
Warm temperate (C)		-3 °C $< T_{min} < +18$ °C
	Fully humid (Cf)	Not (Cs) or (Cw)
	Hot summer (Cfa)	$T_{max} \geq +22$ °C
	Warm summer (Cfb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Cfc)	Not (b) and $T_{min} > -38$ °C
	Dry summer (Cs)	$P_{smin} < P_{wmin}$, $P_{wmax} >$ 3 P_{smin} and $P_{smin} < 40$ mm
	Hot summer (Csa)	$T_{max} \geq +22$ °C
	Warm summer (Csb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Csc)	Not (b) and $T_{min} > -38$ °C
	Dry winter (Cw)	$P_{wmin} < P_{smin}$ and $P_{smax} >$ 10 P_{wmin}
	Hot summer (Cwa)	$T_{max} \geq +22$ °C
	Warm summer (Cwb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Cwc)	Not (b) and $T_{min} > -38$ °C
Snow (D)		$T_{min} \leq -3$ °C
	Fully humid (Df)	Not (Ds) or (Dw)
	Hot summer (Dfa)	$T_{max} \geq +22$ °C
	Warm summer (Dfb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Dfc)	Not (b) and $T_{min} > -38$ °C
	Extremely continental (Dfd)	Like (c) but $T_{min} \leq -38$ °C
	Dry summer (Ds)	$P_{smin} < P_{wmin}$, $P_{wmax} >$ 3 P_{smin} and $P_{smin} < 40$ mm
	Hot summer (Dsa)	$T_{max} \geq +22$ °C
	Warm summer (Dsb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Dsc)	Not (b) and $T_{min} > -38$ °C
	Extremely continental (Dsd)	Like (c) but $T_{min} \leq -38$ °C
	Dry winter (Dw)	$P_{wmin} < P_{smin}$ and $P_{smax} >$ 10 P_{wmin}
	Hot summer (Dwa)	$T_{max} \geq +22$ °C
	Warm summer (Dwb)	Not (a) and at least 4 $T_{mon} \geq +10$ °C
	Cool summer and cold winter (Dwc)	Not (b) and $T_{min} > -38$ °C
	Extremely continental (Dwd)	Like (c) but $T_{min} \leq -38$ °C
Polar (E)		$T_{max} < +10$ °C
	Frost climate (EF)	$T_{max} < 0$ °C
	Tundra climate (ET)	0 °C $\leq T_{max} < +10$ °C