

Supplementary materials

S1. The three climate zones and their representative cities

S1.1. The climate zones

There are five climate zones in China according to the Chinese National Standard GB 50178-93: *Standard of Climatic Regionalization for Architecture*, consisting of severe cold, cold, hot summer/cold winter, temperate and hot summer/warm winter regions. This climate zoning is primarily based on the mean temperature in the hottest and coldest months of the year. According to the climatic map, three major climate regions - cold, hot summer/cold winter and hot summer/warm winter – occupy more than one-third of the whole territory [1].

The *hot summer / warm winter zone* is located in southern China, where the rapid development of high-rise buildings, with an extremely small space between buildings, has become a particular characteristic. Summer is hot and long while the winter is warm and short. The hot summer lasts from around May to October, with a mean temperature over 26°C. Around half the year is sunny but its average relative humidity is around 71-85%. There is a big demand for space cooling in summer but there is almost no need for space heating in winter as the average temperature in cold months is over 10°C. Most existing buildings have no building envelope insulation [1].

The *hot summer / cold winter zone* is located in central China and it is well known for its high population density. The average temperature is usually 25-30°C in the hottest month and to 2-7°C in the coldest season. In extreme weather, the temperature can be below -10°C. The summer incorporates June, July, August and September but the cold winter is restricted to December, January and February. The annual mean humidity of up to 70-80% is much higher than other parts of China. The annual sunshine rate is below 50% and less than 30% in the cold season. The annual wind speed is around 1-3 m/s and has little impact on space cooling and heating demand. As with southern China, the building design standard has no requirement for building envelope insulation in this region [2]. Space cooling and heating are necessary in summer and winter respectively to provide a comfortable indoor environment.

The *cold climatic zone* covers most areas of northern China, having a typically dry, cold and long winter usually lasting from November to March with a mean temperature of -10 to 0°C and lowest temperature less than -20°C. The summer months of June, July and August are mild, with an average temperature of 18-28°C in the hottest month. Strongly windy days, with a wind speed higher than 5 m/s, are quite common in winter [1]. It is quite dry in winter, and its mean relative moisture is approximately 44%. Even in summer, its average maximum humidity is only 77% and thus its relative moisture is far less than that of other two climatic zones. Although recent construction codes require new buildings to use insulation, most existing old buildings built in 20 or more years ago have no envelope insulation and no consideration about energy-efficiency of window glazing.

S1.2. The cities

According to Waugh [3], the vast majority of the population lives in major cities in the eastern part of China with the highest population density. This region traverses hot summer/warm winter, hot summer/cold winter and cold climates, and it covers many important metropolises that contain an abundance of high-rise residential buildings to meet the accommodation demands of their dramatically

increasing population. The key characteristics of the three representative cities are summarized in Table S1.

Table S1. Key characteristics of the cities.

Climatic zones Heating and cooling period		Hong Kong	Shanghai	Beijing
Location		Latitude 22.3°, longitude 114.17°	Latitude 29.58°, longitude 106.47°	Latitude 39.93°, longitude 116.28°
Winter and summer weather data	Outside design temperature (°C)	In winter: 17°C In summer: max temperature 33°C, min temperature 27°C	In winter: 4°C In summer: max temperature 32°C, min temperature 26°C	In winter: -9°C In summer: max temperature 31°C, min temperature 22°C
	Wind speed (m/s)	In winter: 3 m/s In summer: 3 m/s	In winter: 3.5 m/s In summer: 3 m/s	In winter: 3.5 m/s In summer: 1.5 m/s
Summer (months of cooling needed)		May to October	June to September	June to early September
Winter (months of heating needed)		None	December to February	November to March
Population density (people/km ²)		More than 6,544	More than 3,800	More than 13,000 in urban area
Ratio of high-rise residential buildings		More than 90% of population live in high-rise buildings	Around 44%	Over 50%

Hong Kong is located in the region with the highest population density in a *hot summer/warm winter* climate. The fast increasing population, together with the limited amount of land available, has resulted in a ‘street canyon’ urban morphology [4] of closely packed high-rise buildings on both sides of narrow streets [5-6]. More than 90% of the total population live in high-rise buildings of 10-40 stories that have been broadly developed for more than 40 years [7]. The high-density of these buildings plays an important role in their thermal performance, with approximately 60% of electricity energy being consumed by space cooling in the hot season [8]. There is almost no residential space heating demand and most air conditioners have no capacity for heating because of the warm winter. The humidity can reach 80% in hot months. The annual sunshine ratio is more than 42% with considerable solar heat gain through windows. The average wind speed of 3 m/s encourages open windows in the nighttime to increase natural ventilation.

Shanghai is the largest city in southern China, with a population of over 24 million in 2016, and the density that is the highest in Mainland China, and is located in the *hot summer/cold winter* region. As with many Chinese cities, its rapid population growth and limited available land has resulted in an increasing preponderance of high-density high-rise residential buildings – accounting for around 44% of the total residential blocks in this area [9]. It is a typical subtropical monsoon city, with four distinct seasons and abundant sunshine throughout the year. The hot four-month summer is matched by a cold three-month winter. The mean maximum temperature in the hottest month is similar to Hong Kong, with a mean minimum temperature of 4°C in the coldest month. Therefore, both cooling in summer and heating in winter are needed to maintain a comfortable indoor environment. Residential buildings over 20 years old have no insulation requirements, which leads to excessive heat loss in winter and heat gain in summer.

Consequently, the average indoor temperature is usually higher than 30°C in summer but often lower than 3°C in winter. In addition, the wind speed is affected in the monsoon season and it is therefore necessary to consider this when evaluating building performance.

Beijing, with a population of approximately 22 million in 2016, and the highest population density in cold climatic zone, is in the northern part of China's northern plain. About 62% of its administrative area is mountainous, which has resulted in intensive development on the restricted lowland. Almost all apartments in Beijing are concentrated in high-rise buildings [10], of which there are thousands, with some being built more than 20 years. As with Shanghai, most of these have no construction envelope insulation and their single glazed windows considerably exacerbate building energy performance in this type of climatic region [11]. The daily average temperature in coldest month is around -3.7°C, and 26°C in the hottest month. The cold winter usually lasts from November to March, while the summer period of is much shorter from June to August which, together with the strong winter wind, means that heating demand is concentrated at first and the cooling requirement accounts for only a small portion of the whole energy consumption.

References

1. MOC, GB50178-1993 Standard of Climatic Regionalization for Architecture. Ministry of Construction, 1994, Beijing, People's Republic of China.
2. Yu, J.; Yang, C.; Tian, L.; Liao, D. Evaluation on energy and thermal performance for residential envelopes in hot summer and cold winter zone of China. *Appl. Energy* **2009**, *86*, 1970-1985.
- [3] Waugh, D. Geography: An Integrated Approach. 2014, Oxford University Press, Oxford, United Kingdom.
- [4] Ng, E.; Yuan, C.; Chen, L.; Ren, C.; Fung, J.C. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong. *Lands. Urban Plan.* **2011**, *101*, 59-74.
- [5] Chen, L.; Ng, E.; An, X.; Ren, C.; Lee M.; Wang, U.; He, Z. Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach. *Intl. J. Climatol.* **2012**, *32*, 121-136.
- [6] Ng, E.; Chen, L.; Wang, Y.; Yuan, C. A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. *Build. Environ.* **2012**, *47*, 256-271.
- [7] Lai, L.W.C.; Ho, D.C.W. Unauthorized structures in a high-rise high-density environment – the case of Hong Kong. *Proper. Manage.* **2001**, *19*, 112-123.
- [8] EMSD. Hong Kong Energy End-use Data 2014, Electrical and Mechanical Services Department (EMSD), The Government of Hong Kong Special Administrative Region, Hong Kong, 2014.
- [9] Yang, F.; Lau, S.S.Y.; Qian, F. Summer time heat island intensities in three high-rise housing quarters in inner-city Shanghai China: building layout, density and greenery. *Build. Environ.* **2010**, *45*, 115-134.
- [10] Ekblad, S.; Werne, F. Housing and health in Beijing: implications of high-rise housing on children and the aged. *J. Sociol. Social Wel.* **2015**, *17*, 51-77.
- [11] Yang, L.; Lam, J.C.; Tsang, C.L. Energy performance of building envelopes in different climate zones in China. *Appl. Energy* **2008**, *85*, 800-817.