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Development of passive design zones in China using bioclimatic approach

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Abstract

This paper presents the work on development of passive design zones for different climates in China. A total of 18 cities representing the five major climatic types, namely severe cold, cold, hot summer and cold winter, mild and hot summer and warm winter were selected for climatic analysis. Measured weather data were gathered and analysed. A bioclimatic approach was adopted in which the comfort zone and 12 monthly climatic lines were determined and plotted on the psychrometric chart for each city. From these bioclimatic charts, the potential use of passive design strategies such as solar heating, natural ventilation, thermal mass with/without night ventilation and evaporative cooling was assessed. A total of nine passive design strategy zones were identified, and appropriate design strategies suggested for both summer and winter consideration.

Keywords: Building energy; Climates; Bioclimatic approach; Passive design; China

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1. Introduction

Buildings, energy and the environment are key issues facing the building professions worldwide. There has been a steady increase in the use of energy in China since the adoption of the Policy of Reforming and Opening in the 1980s [1] and energy conservation is of vital importance both economically and environmentally [2]. Total energy use rose from 603 million tonnes of standard coal equivalent in 1980 to 1320 in 2001, representing an average annual increase of 3.8% during that 22 year period [3]. There is a growing concern about energy consumption in buildings and its likely adverse impacts on the environment. It was estimated that buildings stocks accounted for 27.6% of the total national energy use in mainland China in 1998 [4]. With rapid economic growth and improvement in people's living standard, the building sector will continue to be a key energy end user. One way to alleviate the ever growing demand for energy is to have more energy efficient building designs and proper building energy conservation programmes, especially those involved in the use of passive design strategies, which would greatly reduce the reliance on mechanical systems.

The primary aim of the present work is, therefore, to identify the different climate zones in China, where certain well established passive design strategies could have energy saving potential. It is envisaged that such passive climate zones would give architects and engineers an overall view of the appropriate design strategies that are conducive to making better use of the natural environment and resources during the initial conceptual design stage in the various regions of China.

2. General climates in China and climate classification

China is a large country with an area of about 9.6 million km^2. About 98% of the land area stretches between a latitude of 20°N to 50°N, from the subtropical zones in the south to the temperate zones (including warm-temperate and cool-temperate) in the north [5]. The maximum solar altitudes vary a great deal and there is a large diversity in climates, especially the temperature distributions during winters. China is situated between Eurasia, the largest continent and the Pacific Ocean, allowing the monsoons to be well developed. The monsoon climate, therefore, tends to be dominant, with a marked change of wind direction between winter and summer as well as seasonal variation of precipitation according to whether the maritime monsoon advances or retreats. Besides, characteristics associated with continental climates can be identified, with warmer summer, cooler winter and a larger annual temperature range than other parts of the world with similar latitudes. China also has a complex topography ranging from mountainous regions to flat plains. These diversities and complexities have led to many different regions with distinct climatic features.

There are various ways to classify climatic types or zones according to different criteria using different climatic variables and indices. This depends largely on the purpose of establishing such classification. Olgyay, in his work on the influence of climate on building design principles and architectural similarities around the world, has suggested four main climate types, namely cool, temperate, hot and arid and hot and humid in the early 1960s [6]. Later, also on a worldwide basis, Givoni specified four major climates, hot, warm-temperate, cool-temperate and cold with 11 sub-climatic types. The emphasis was on the influences of climatic characteristics on human comfort as well as the thermal response of buildings [7]. In China, there are, broadly speaking, two major climatic zones classifications. The first one is for the thermal design of buildings and is concerned mainly with conduction heat gain/loss and the corresponding thermal insulation issues. It has five climatic types, namely severe cold, cold, hot summer and cold winter, mild and hot summer and warm winter [8]. The zoning criteria (a summary of which is shown in Table 1) are mainly based on the average temperatures in the coldest and hottest months of the year. The numbers of days that the daily average temperature is below 5 °C or above 25 °C are counted as complementary indices for determining the zones. Fig. 1 shows an overall layout of the five major climates and their locations relative to Beijing, the capital. Because of the varying topology and hence elevations, there are nine regions, both the severe cold and cold climates have three regions. The second major climatic zone covers more general architecture and building designs [9]. Apart from temperature, other major climatic variables such as precipitation, relative humidity, daily diurnal temperature and wind speed are also considered. It has seven main categories, each of which is further divided into two to four sub-categories. The sub-categories have taken into account the daily diurnal temperature and maximum wind speed so as to categorize any distinct differences within each of the seven main categories.

To strike a balance between keeping the analysis manageable and achieving broad representation of the prevailing climate types in China, a total of 18 cities were selected for this study. Table 2 shows a summary of the relevant information on the 18 cities: five of which are in the severe cold climate region; four are in the cold climate region; five are in the hot summer and cold winter climate region; one is in the mild and three are in the hot summer and warm winter climate regions. The criteria of selection were based on:

(i) The cities selected must have local meteorological stations and measured weather data such as temperature, relative humidity, wind speed etc. are readily available.
(ii) The cities selected should cover the major climatic types/categories identified in the two major climate classifications mentioned above [8,9] and have a reasonably even geographical distribution.
(iii) Besides climates, the whole sample of cities should also be representative in terms of political and economic influences.

Table 1
Summary of climate classification criteria (Ref. [8])

Climatic type (Source [5])	Zoning criteria	
	Main criteria	Complementary criteria
Severe cold	ATCM $\leqslant -10$ °C	NDAT5 $\geqslant$ 145 days
Cold	ATCM = 0–10 °C	NDAT5 = 90–145 days
Hot summer and cold winter	ATCM = 0–10 °C ATHM = 25–30 °C	NDAT5 = 0–90 days, NDAT25 = 40–110 days
Mild	ATCM = 0–13 °C ATHM = 18–25 °C	NDAT5 = 0–90 days
Hot summer and warm winter	ATCM $\geqslant$ 10 °C ATHM = 25–29 °C	NDAT25 = 100–200 days

Remarks: ATCM = Average temperature in the coldest month; ATHM = Average temperature in the hottest month; NDAT5 = Number of days that average temperature is below 5 °C; NDAT25 = Number of days that average temperature is above 25 °C.

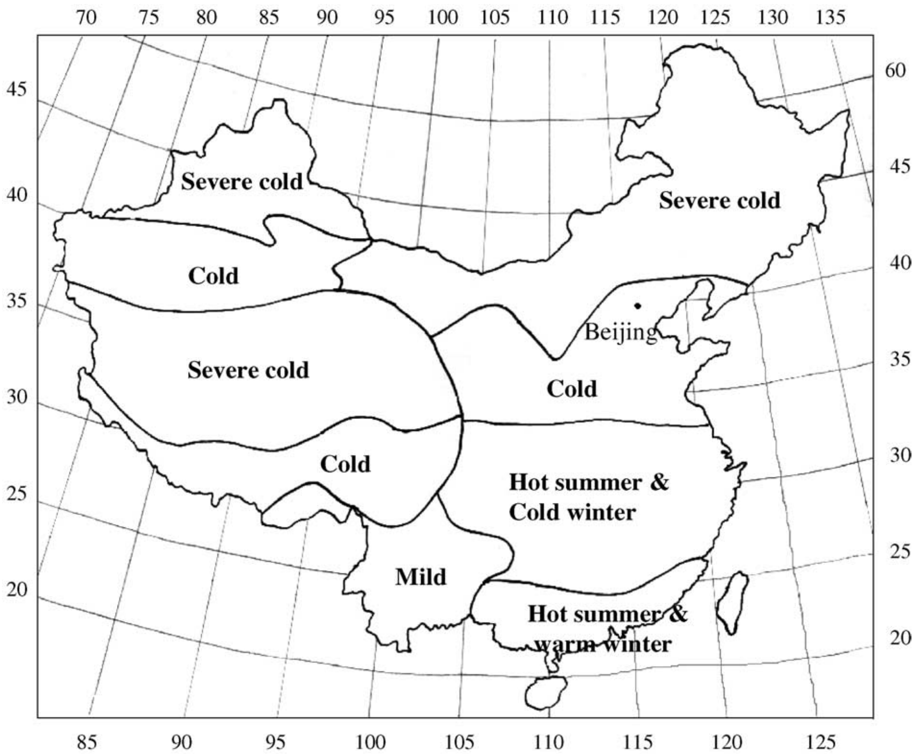

Fig. 1. The five major climates in nine geographical regions based on Ref. [8].

3. Bioclimatic approach

Over the past few decades, there have been several attempts to develop a systematic approach adapted to human requirements and prevailing climatic conditions during the early building design stage. The attempts aimed at defining the appropriate building design strategies for a certain region. This systematic approach of bioclimatic building design was first proposed by Olgyay [6] in the 1950s. His method was based on a ''bioclimatic chart'' showing the human comfort zone in relation to the dry bulb temperature (vertical axis) and relative humidity (horizontal axis). The effects of mean radiant temperature, wind speed and solar radiation were also considered. Later, Milne and Givoni [10] developed building bioclimatic charts based on typical psychrometric charts. More recent works included the control potential zones by Szokolay [11], and the graphical design tool involving comfort triangle charts [12]. There is, however, very little work on climatic analysis and bioclimatic design strategy suitable for the initial conceptual design stage for different climates in China, except a recent attempt by Yang et al. [13] to develop bioclimatic building design charts for five cities, namely Changchun, Beijing, Shanghai, Kunming and Guangzhou. This earlier work forms a basis for the present study to develop the passive design climate zones for China. The development process is as follows:

Table 2
Summary of general information on the 18 cities selected

No.	City	Latitude (N)	Longitude (E)	Altitude (m)	Annual mean temperature (°C)	Ref. [8]
1	Altay	47°44′	88°05′	735.3	4.6	Severe cold
2	Urumqi	43°47′	87°37′	917.9	7.1	Severe cold
3	Huhhot	40°49′	111°41′	1063.0	6.8	Severe cold
4	Changchun	43°53′	125°13′	236.8	5.7	Severe cold
5	Shenyang	41°44′	123°27′	44.7	8.5	Severe cold
6	Turpan	42°56′	89°12′	34.5	14.5	Cold
7	Beijing	39°48′	116°28′	31.3	12.3	Cold
8	Xi'an	34°18′	108°56′	397.5	13.7	Cold
9	Lhasa	29°40′	91°03′	3648.7	8.3	Cold
10	Nanjing	32°00′	118°48′	8.9	15.5	Hot summer and cold winter
11	Shanghai	31°10′	121°26′	2.6	16.2	Hot summer and cold winter
12	Chengdu	30°40′	104°01′	506.1	16.2	Hot summer and cold winter
13	Wuhan	30°37′	114°08′	23.1	16.7	Hot summer and cold winter
14	Nanchang	28°36′	115°55′	46.7	17.7	Hot summer and cold winter
15	Kunming	25°01′	102°41′	1892.4	14.9	Mild
16	Guangzhou	23°10′	113°19′	41.7	22.1	Hot summer and warm winter
17	Nanning	22°49′	108°21′	73.1	21.8	Hot summer and warm winter
18	Haikou	20°02′	110°21′	13.9	24.1	Hot summer and warm winter

(i) Identify prevailing passive design strategies and plot the application regions on a typical psychrometric chart.
(ii) For each of the 18 cities, overlay the 12 monthly climatic lines on the psychrometric chart. The two end points of each of the 12 climatic lines are given by the mean minimum temperature and mean minimum relative humidity and the mean maximum temperature and mean maximum relative humidity. The 30 year (1971–2000) long term measured daily temperature and corresponding relative humidity data base for each of the 18 cities were gathered from the National Meteorological Centre of China, from which the long term mean minimum and mean maximum outdoor temperatures and corresponding relative humidities were determined.
(iii) Assess the potential use of passive design strategies according to the positions of the monthly climatic lines in relation to the comfort zone and the different passive design regions shown on the psychrometric chart.
(iv) Develop passive design zones for different parts of China based on the application potentials identified for the 18 cities.

4. Analysis of the 18 cities

A total of five passive design strategies were identified. These include passive solar heating, natural ventilation, thermal mass, thermal mass with night ventilation and evaporative cooling.

These strategies and their application regions on the psychrometric chart were adopted based on the earlier works by Milne and Givoni [10]. In addition to the five passive design strategies, two active conventional means, conventional heating and air conditioning, were also considered.

The key issue of constructing the bioclimatic building design charts is to determine the comfort zone and boundaries of the different climatic design strategies. The ASHRAE definition of thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" [14]. The comfort zone is defined as the range of climatic conditions within which the majority of people would not feel thermal discomfort, either hot or cold. In defining conditions for thermal comfort, a total of six primary factors must be addressed, metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. For a particular metabolic rate, clothing insulation, air speed and humidity, a comfort zone may be determined. Such comfort zone is generally defined in terms of a range of operative temperatures or the combinations of air temperature and mean radiant temperature that would provide thermal conditions acceptable to most people. The two comfort zones specified in the latest ASHARE Standard 55-2004 [14] were chosen for this study, one for 0.5 clo of clothing insulation (1 clo = 0.155 m^2 °C/W) and the other for 1.0 clo. These clothing insulation levels are typical of clothing worn indoors when the external environment is warm/hot and cool/cold, respectively. The operative temperature range for each zone is for 80% occupant acceptability. This is based on a 10% dissatisfaction criterion for general thermal comfort based on the Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) index [15,16], plus an additional 10% dissatisfaction that may occur from local thermal discomfort. The comfort zones are intended primarily for sedentary or near sedentary physical activity levels. Table 3 shows a summary of the values used to generate the comfort zones.

Strictly speaking, for each city, there ought to be three comfort zones because people tend to wear different clothing during summer, mid-season (spring and autumn) and winter. However, the primary aim of the bioclimatic building design charts is to give architects and engineers a quick overview of the appropriate design strategies during the initial design stage where different conceptual building schemes are being considered. For simplicity, only one combined "annual" comfort zone was considered, which covered both the 0.5 clo and 1.0 clo comfort zones. The upper humidity limit is set at the 0.012 kg/kg moisture content, corresponding to a water vapour pressure of 1.91 kPa at standard pressure or a dew point temperature of 16.8 °C. There is no established lower humidity limit. However, to address other non-thermal considerations such

Table 3
Summary of data used to generate the comfort zone (Ref. [14])

Air temperature (°C)	RH (%)	Radiant temperature (°C)	Air speed (m/s)	Met.	CLO
19.6	86	19.6	0.10	1.1	1.0
23.9	66	23.9	0.10	1.1	1.0
25.7	15	25.7	0.10	1.1	1.0
21.2	20	21.2	0.10	1.1	1.0
23.6	67	23.6	0.10	1.1	0.5
26.8	56	26.8	0.10	1.1	0.5
27.9	13	27.9	0.10	1.1	0.5
24.7	16	24.7	0.10	1.1	0.5

as skin or eye dryness and electrostatics, a lower limit of 0.004 kg/kg moisture content was adopted for this study. This corresponds to a relative humidity of 20% or more for the range of acceptable operative temperatures within the combined "annual" comfort zone (e.g. see Fig. 2).

In order not to present too many illustrations, only the bioclimatic charts for five cities, namely Atlay (severe cold), Beijing (cold), Nanjing (hot summer and cold winter), Kunming (mild) and Haikou (hot summer and warm winter) are shown. Table 4 shows a summary of the potential use of passive design strategies for the 18 cities, and a brief description of the findings is outlined as follows:

Altay

Fig. 2 shows the bioclimatic building design chart for Atlay. The proportion of the monthly lines falling within a particular passive design strategy zone indicates (in terms of percentage) the potential use of that passive design. In determining the percentage of potential use, the 12 monthly climatic lines were grouped into the colder half (October–March) and warmer half (April–September) of the year. The former is for assessing the potential use of passive solar heating, and the latter is for assessing the other passive design strategies for summer cooling. To give a more holistic view, active design strategies, namely conventional/active solar heating and air conditioning are also shown on the bioclimatic chart. Altay is in the far northwest region within the severe cold climate zone and has an annual mean temperature of 4.6 °C. Most of the monthly lines

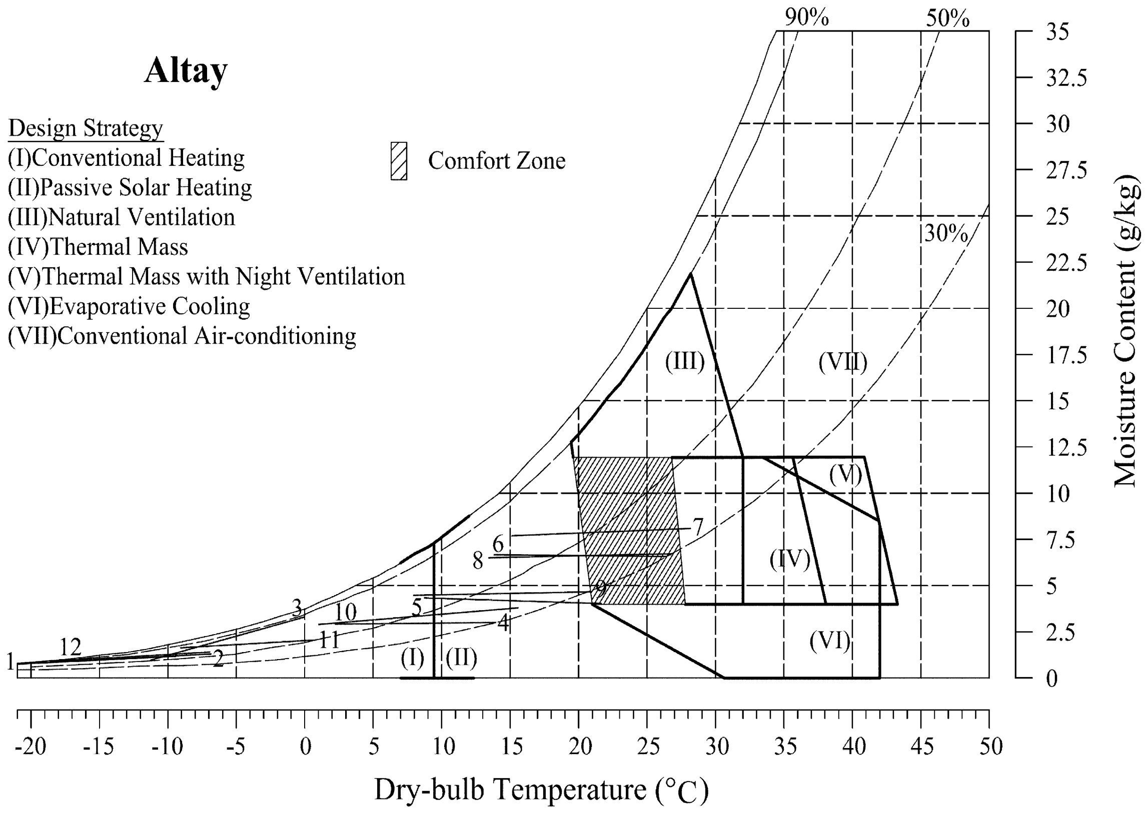

Fig. 2. Bioclimatic chart for Atlay.

Table 4
Summary of potential use of passive design strategies for the 18 cities

City	Colder half (October–March)			Warmer half (April–September)			
	Passive solar heating potential [a] (%)	Cooling requirement [b] (%)	Natural ventilation [c] (%)	Thermal mass [c] (%)	Thermal mass with night ventilation [c] (%)	Evaporative cooling [c] (%)	Air-conditioning [d] (%)
Altay	7	1	0	1	0	0	0
Urumqi	9	8	0	8	0	0	0
Huhhot	8	2	0	2	0	0	0
Changchun	8	28	28	0	0	0	0
Shenyang	13	30	30	0	0	0	0
Turpan	30	50	0	43	7	50 [e]	0
Beijing	26	40	35	5	0	0	0
Xi'an	50	45	37	6	0	0	2
Lhasa	39	0	0	0	0	0	0
Nanjing	58	57	47	0	0	0	10
Shanghai	65	58	48	0	0	0	10
Chengdu	83	54	54	0	0	0	0
Wuhan	68	76	61	0	0	0	15
Nanchang	75	79	61	0	0	0	18
Kunming	88	6	6	0	0	0	0
Guangzhou	100	86	61	0	0	0	25
Nanning	100	94	64	0	0	0	30
Haikou	100	100	50	0	0	0	50

[a] Percentage of heating requirement that can be provided by passive solar design during the six-month colder half of the year.
[b] Cooling requirement (i.e. percentage of monthly climatic lines falling outside the comfort zone) during the six-month warmer half of the year.
[c] Percentage of the time that passive cooling technique may be effective during the six-month warmer half of the year.
[d] Percentage of the time air-conditioning would be required during the six-month warmer half of the year.
[e] Alternative passive design strategy.

fall inside the conventional/active solar heating region. Only October falls partially within the passive solar design region, representing about 7% of the time during the colder half of the year. In fact, passive solar design plays a more significant role during the warmer half than the colder half. Between June and August, about half of the time, the outside conditions fall within the comfort zone, with a small extension into the thermal mass design region in July, accounting for just over 1% of the warmer half of the year. With some attention to proper building envelope design, in general, no air conditioning would be required during the short summer months. It should be pointed out that these figures only indicate the likely energy usage and saving potential, and the percentage would vary depending on the actual building envelope design, solar exposure and internal casual heat gain.

Urumqi

Climate-wise, Urumqi is similar to Altay, though with a higher annual mean temperature of 7.1 °C. The potential use of passive solar and thermal mass designs is 9% and 8%, respectively, with no air conditioning requirement.

Huhhot

In the north of the country, Huhhot is also in the severe cold climate zone. In general, its climate is similar to those of Altay and Urumqi. The annual mean temperature is 6.8 °C, and the potential use of passive solar and thermal mass designs is 8% and 2%, respectively, with no air conditioning requirement.

Changchun

Changchun is in the severe cold climate zone with an annual mean temperature of 5.7 °C. Because of the long, severe winter, most of the winter monthly lines fall within the conventional/active solar heating region. Only part of October falls inside the passive solar design zone, representing 8% of the colder half of the year. The summer months of July and August of the warmer half of the year tend to fall outside the comfort zone, but because of the short, mild summer, passive designs like natural ventilation would be able to lower the summer time temperature without any need for air conditioning. The potential use of natural ventilation is about 28% of the warmer half of the year, mainly occurring in July and August.

Shenyang

With an annual mean temperature of 8.5 °C, the climate in Shenyang is similar to that in Changchun. Both are in the severe cold climate region in the northeast. The potential use of passive solar design is 13%. The two peak summer months (July and August) tend to fall outside the comfort zone. Again, because of the generally cool summer condition, natural ventilation would be adequate to achieve indoor thermal comfort with no air conditioning, and the percentage use during the six-month warmer half of the year is 30%.

Turpan

Turpan is near Urumqi in the northwest, but having an annual mean temperature of 14.5 °C, it belongs to the cold climate region. About 30% of the colder half of the year, passive solar heating can be utilised. It has a rather hot and dry summer. Between June and August, over 80% of the time, the outdoor conditions fall outside the comfort zone, lying largely within the thermal mass with/without night ventilation and evaporative cooling design strategy regions. The potential use of either passive design is about 50% during the warmer half of the year. Again, with proper passive design, no air conditioning would be required to achieve thermal comfort.

Beijing

The capital city is in the cold climate zone and has an annual mean temperature of 12.3 °C (see Fig. 3). The potential of passive solar design is 26%, mainly in October and parts of March and November. Summer months can be hot and humid. About three-quarters of the time between June and August, the outside conditions fall beyond the comfort zone and lie within the natural ventilation and thermal mass design regions. The potential uses of these two passive design strategies are 35% and 5%, respectively, during the six-month warmer half of the year.

Xi'an

For thermal heating design purposes, Xi'an is within the cold climate zone [8] but very close to the boundary of the hot summer and cold winter climate region. It has distinct seasonal variations with hot summer and cold winter characteristics, thus requiring both heating and cooling. Its annual mean temperature is 13.7 °C, and its passive solar heating potential is 50% during the colder half of the year. Summer is hot and humid, especially in July and August. Passive cooling strategies such as natural ventilation and thermal mass could reduce the need for air conditioning. The potential uses of such passive techniques are 37% and 6%, respectively, during the six-month

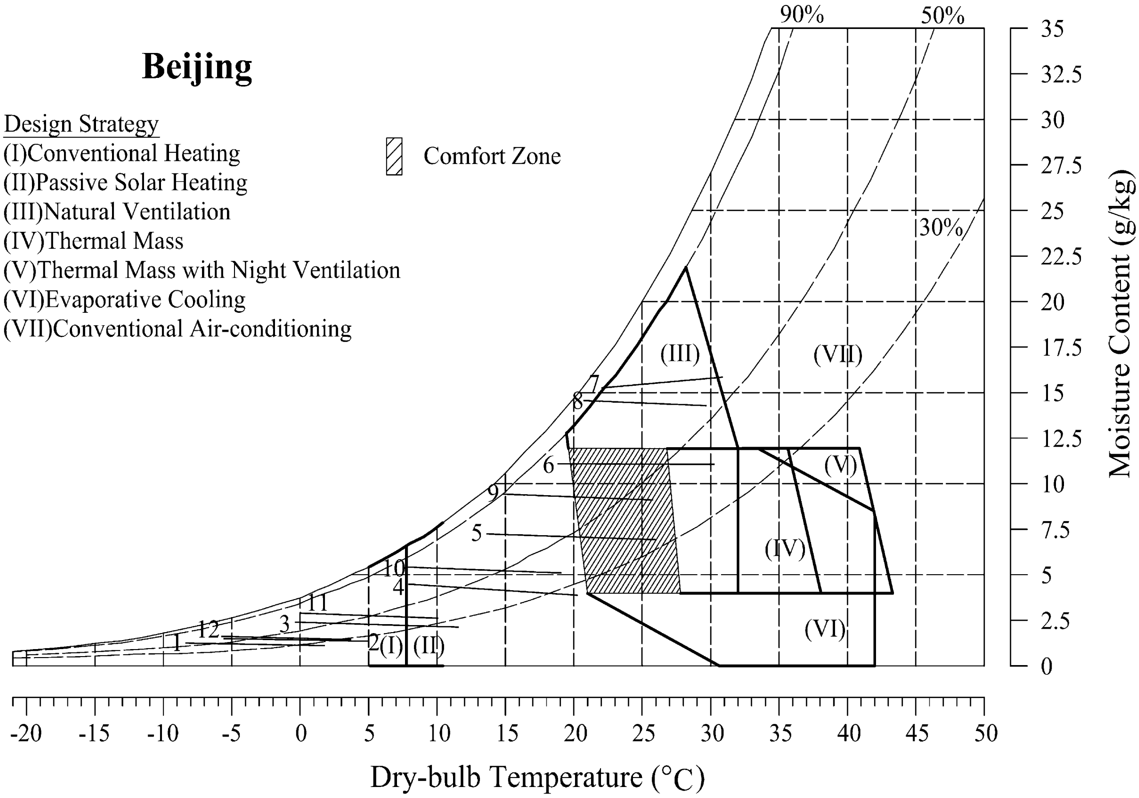

Fig. 3. Bioclimatic chart for Beijing.

warmer half of the year. A portion of the July climatic line lies outside the passive design strategy regions. This suggests that some conventional air conditioning would still be required.

Lhasa

Lhasa is also in the cold climate zone with an annual mean temperature of 8.3 °C. It has a long winter with short, rather cool, summer. In general, no cooling (passive and otherwise) would be required. Daily diurnal temperatures tend to be large, around 12–18 °C. Potential use of passive solar design is quite good, about 39% of the six-month colder half of the year.

Nanjing

Fig. 4 shows the bioclimatic chart for Nanjing. Although in a different climate zone (hot summer and cold winter), its climate is similar to that of Xi'an with an annual mean temperature of 15.5 °C. It has good passive design potential for both winter heating and summer cooling. Potential use of passive solar heating and natural ventilation is 58% and 47%, respectively. About 10% of the time during the warmer half of the year, air conditioning would still be required, mainly in July and August.

Shanghai

Shanghai is also in the hot summer and cold winter climate zone with an annual mean temperature of 16.2 °C. Its passive design potential and air conditioning requirement are very similar to those of Nanjing. The percentages of passive solar heating, natural ventilation and air conditioning

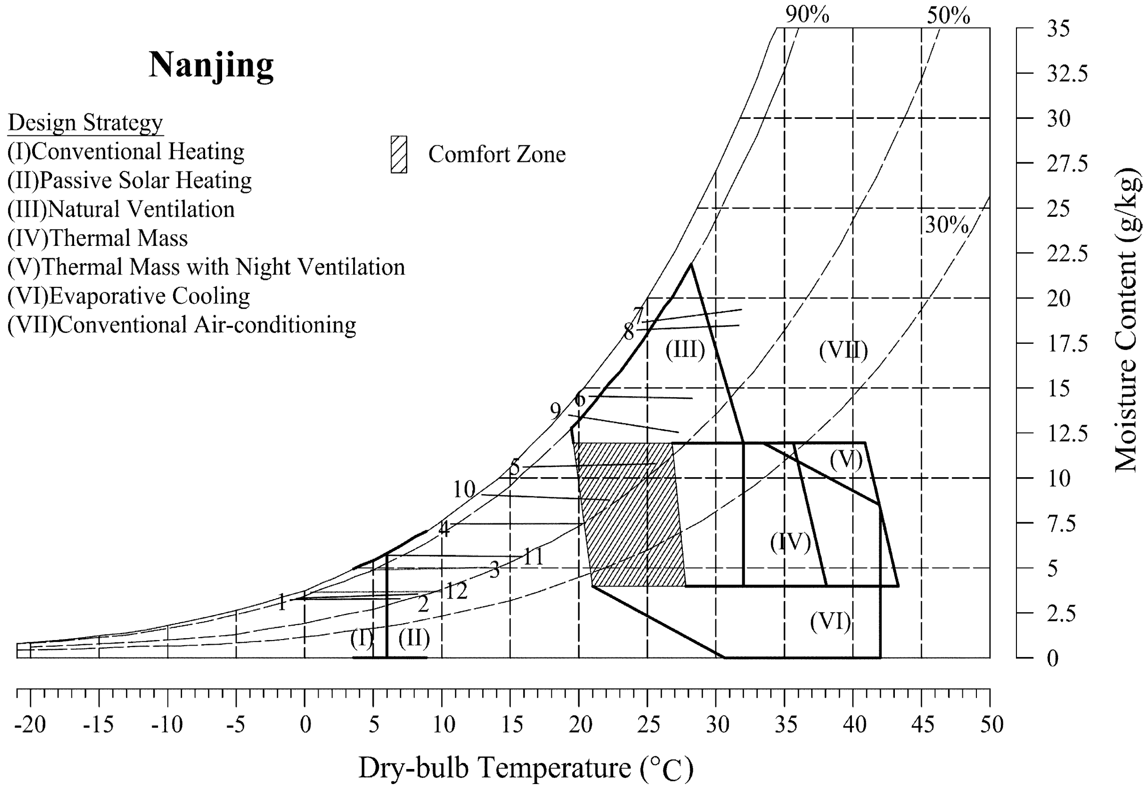

Fig. 4. Bioclimatic chart for Nanjing.

requirements are 65%, 48% and 10%, respectively. With rapid urbanisation and high rise building development in Shanghai, it is envisaged that the potential use of passive cooling techniques would be limited, resulting in more frequent use of air conditioning.

Chengdu

The climate of Chengdu is similar to that of Shanghai except with a higher potential use of natural ventilation (54%) and no air conditioning requirement. Chengdu has an annual mean temperature of 16.2 °C, and the percentage of passive solar heating usage during winter months is a high 83%.

Wuhan

Wuhan is another hot summer and cold winter city with an annual mean temperature of 16.7 °C, Wuhan has a good passive solar heating potential of 68%. Its summer months are hotter and slightly more humid than those of Chengdu, and the potential use of natural ventilation is 61%. About 15% of the time in the six-month warmer half of the year, air conditioning would be required.

Nanchang

Nanchang's climatic characteristics are very similar to those of Wuhan. Nanchang has an annual mean temperature of 17.7 °C. The percentage uses of passive solar heating, natural ventilation for summer cooling and air conditioning are 75%, 61% and 18%, respectively.

Kunming

This is the only city in this study that lies within the mild climate zone with an annual mean temperature of 14.9 °C. Fig. 5 shows the bioclimatic chart for Kunming. It has a cool winter with practically no hot summer months. Except for a short period in July, the six climatic lines for the warmer half of the year do not exceed either the temperature or the humidity limits of the comfort zone, thus requiring very little cooling (only 6% by natural ventilation). It has good passive solar heating potential of 88% during the six-month colder half of the year.

Guangzhou

Guangzhou is in the hot summer and warm winter zone, typical of subtropical climates. It has an annual mean temperature of 22.1 °C. Passive solar heat would be more than adequate for the short, mild winter. Summer is long, hot and humid. Some kinds of cooling would be required for at least five months from May to September. The percentages of natural ventilation and air conditioning are 61% and 25%, respectively, during the six-month warmer half of the year. Again, with rapid urbanisation and high rise building development in Guangzhou, it is envisaged that the potential use of passive cooling techniques would be limited, resulting in more frequent use of air conditioning.

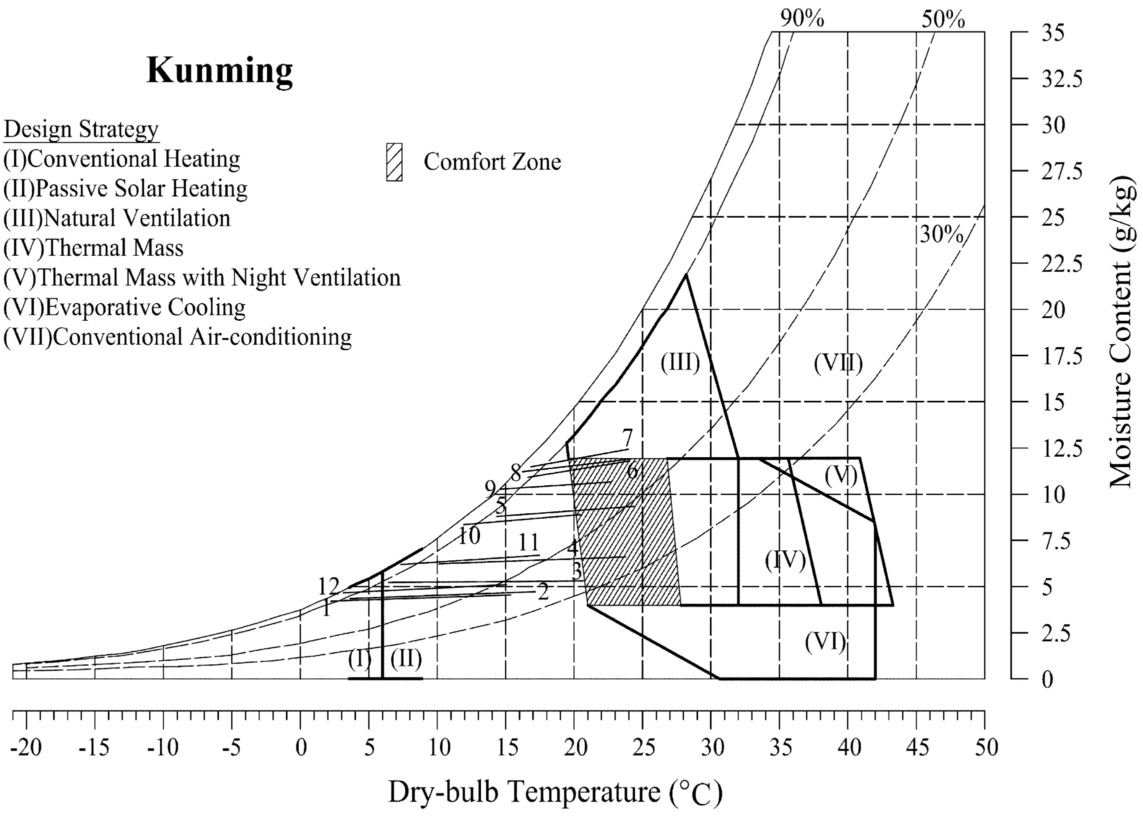

Fig. 5. Bioclimatic chart for Kunming.

Nanning

Nanning's climate is similar to that of Guangzhou but a lot more humid during the summer. Its annual mean temperature is 21.8 °C. All heating requirements could be provided by passive solar design. Passive cooling by natural ventilation is 64%. Because of the hot weather and high humidity, about 30% of the summer time would need air conditioning.

Haikou

Fig. 6 shows the bioclimatic chart for Haikou. Among the 18 cities, Haikou has the highest annual mean temperature of 24.1 °C. It can be seen that heating is needed only during the winter months (December–February), and the requirement is not substantial. Again, a passive solar heating technique would be adequate. In fact, parts of the colder half (i.e. March, October and November) of the year actually require cooling (mainly latent cooling). During the warmer half of the year, the six monthly climatic lines fall outside the comfort zone. About 50% of the time, cooling could be provided by natural ventilation and the remaining time would have to rely on air conditioning.

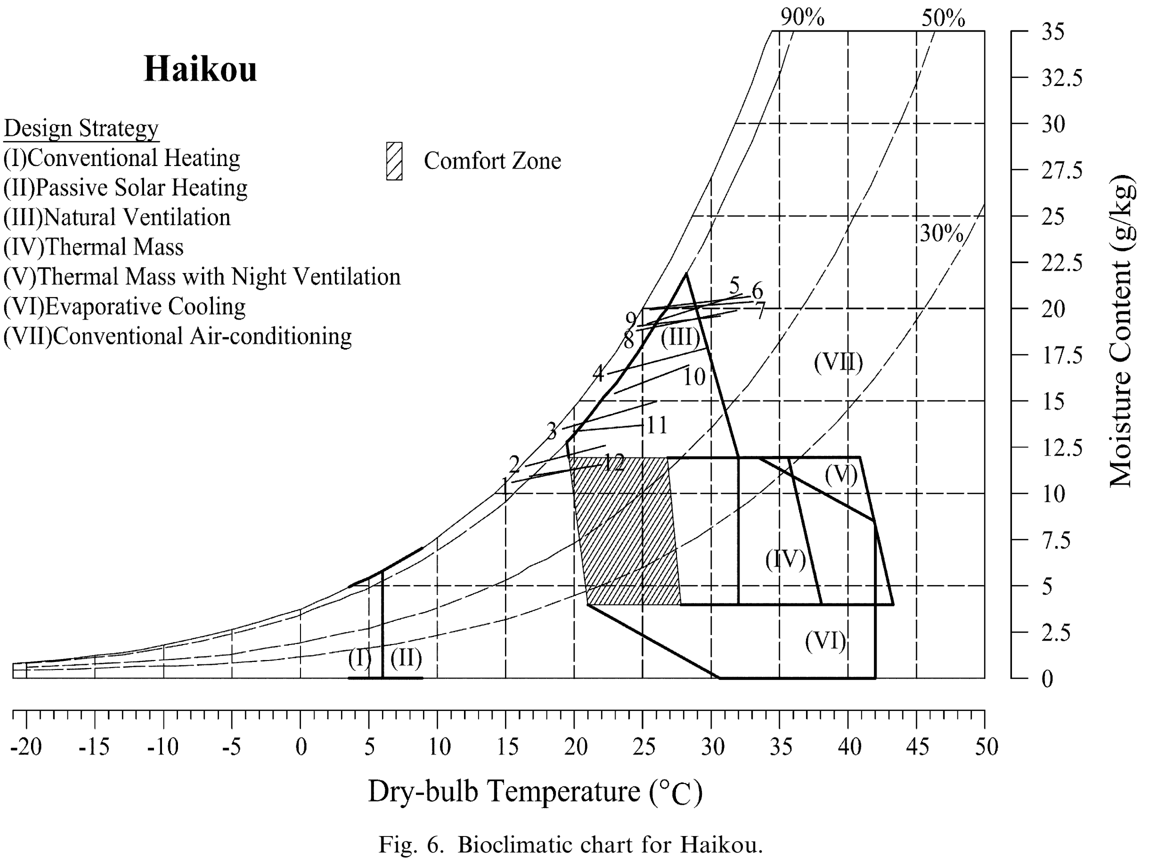

Fig. 6. Bioclimatic chart for Haikou.

5. Passive design zones

Since solar energy is by far the dominant environmental factor in passive building designs, the potential use of passive solar energy during the colder half of the year (i.e. six-month period from October to March) was adopted as a zoning criterion. A total of five zones were identified as follows:

- Zone I—passive solar energy use potential $\leqslant 20\%$.
- Zone II—$20\% <$ passive solar energy use potential $\leqslant 40\%$.
- Zone III—$40\% <$ passive solar energy use potential $\leqslant 65\%$.
- Zone IV—$65\% <$ passive solar energy use potential $\leqslant 90\%$.
- Zone V—$90\% <$ passive solar energy use potential.

To account for climatic differences in temperature and humidity within the same zone during the summer, two discomfort indices (hot and humid) were determined for the three month summer period from June to August and used as sub-zoning criteria. The discomfort indices were defined as follows:

$$\text{Hot Index} = L_{\text{at}}/L_{\text{total}} \tag{1}$$

$$\text{Humid Index} = L_{\text{ah}}/L_{\text{total}} \tag{2}$$

where L_{at} = length of the monthly climatic line above the neutral (comfort) temperature, L_{total} = total length of the monthly climatic line and L_{ah} = length of the monthly climatic line above the moisture content of 0.012 kg/kg.

Table 5 shows a summary of the zoning arrangement. It is interesting to see that zone I covers the five cities with severe cold climates. There is a distinct difference in humidity in the northeast and the northwest, requiring different passive cooling strategies. The northeast tends to be humid during the summer months, especially in July and August, whereas the northwest is usually within the humidity comfort level recommended by ASHRAE [14] (i.e. maximum moisture content of 0.012 kg/kg). Zone I was, therefore, divided into two sub-zones with the humid index as the sub-zoning criterion. Zone II covers mainly the cold climate regions where the potential use of passive solar heating could last for about two months. Because of the differences in temperature as well as the humidity, it was divided into three sub-zones with hot and humid indices as the sub-zoning criteria. Zone II A is neither hot nor humid, II B is relatively hot and humid and II C is hot and dry. Zone III covers the cooler parts of the hot summer and cold winter climate region. There are two sub-zones in Zone IV. IV A includes the warmer parts of the hot summer and cold winter climate region, and IV B covers the mild climates. Zone V covers the hot summer and warm winter climates. There are, altogether, nine passive design zones identified.

A summary of the geographical regions covered and the appropriate passive design techniques for summer and winter design consideration are also shown in Table 5. It can be seen that passive solar heating and thermal insulation is important to all regions except southern China. In fact, passive solar and thermal insulation design techniques could be a double edged sword, in that improper design may result in excessive solar heat gain and overheating during the summer months,

Table 5
Summary of passive design strategy zones

Zone	Passive solar heating potential during colder half (PSH) [a]	Sub-zone	Hot index (T) [b]	Humid index (H) [b]	Representative city	Geographical region	Passive design strategy	
							Winter	Summer
I	PSH $\leqslant$ 20%	I A	$1 \geqslant T \geqslant 0$	$1 \geqslant H > 0$	Changchun (0.04 [c], 0.67 [d]) Shenyang (0.18, 0.67)	Northwest	Passive solar thermal insulation	Natural ventilation
		I B	$1 \geqslant T \geqslant 0$	$H = 0$	Altay (0.02, 0) Huhhot (0.04, 0) Urumqi (0.16, 0)	Nei Mongol, North Xinjiang	Passive solar thermal insulation	Thermal mass
II	20% < PSH $\leqslant$ 40%	II A	$0.3 > T \geqslant 0$	$0.5 > H \geqslant 0$	Lhasa (0, 0)	Qinghai–Tibet Plateau	Passive solar thermal insulation	–
		II B	$0.6 > T \geqslant 0.3$	$1 > H \geqslant 0.5$	Beijing (0.39, 0.67)	Southern part of the North-west, North	Passive solar thermal insulation	Natural ventilation thermal mass
		II C	$1 \geqslant T > 0.6$	$0.5 > H \geqslant 0$	Turpan (0.76, 0)	Xinjiang Inland Basin	Passive solar thermal insulation	Thermal mass evaporative cooling
III	40% < PSH $\leqslant$ 65%	–	–	–	Nanjing (0.61, 1) Shanghai (0.63, 1) Xi'an (0.44, 0.67)	Yunnan–Guizhou Plateau	Passive solar thermal insulation	Natural ventilation
IV	65% < PSH $\leqslant$ 90%	IV A	$1 \geqslant T \geqslant 0.3$	$1 \geqslant H \geqslant 0.5$	Chengdu (0.36, 1) Nanchang (0.84, 1) Wuhan (0.75, 1)	Along Changjiang (Yangtze) River	Passive solar [e] thermal insulation	Natural ventilation solar shading
		IV B	$0.3 > T \geqslant 0$	$0.5 > H \geqslant 0$	Kunming (0, 0.11)	Central and eastern (30°–35°N latitude)	Passive solar [e] thermal insulation	Natural ventilation solar shading
V	90% < PSH	–	–	–	Guangzhou (0.91, 1) Haikou (0.91, 1) Nanning (0.91, 1)	Southern China	–	Natural ventilation solar shading

[a] Colder half = six months from October to March.
[b] Based on 3-month summer period from June to August.
[c] Hot discomfort index.
[d] Humid discomfort index.
[e] Solar shading devices are required to ensure no excessive solar heat gain during summer.

especially in the cooler parts of the hot summer and cold winter climate region (i.e. Zone IV A). Shading devices (preferably external) should be a major design consideration to achieve a proper balance between beneficial winter solar heating and unwanted summer solar heat gain. It is worth noting that nearly all the design zones (with the exception of Zone II A) would, to a greater or lesser extent, require cooling during the summer period. Given the rapid growth in the demand for air conditioning systems in China [17], passive cooling strategies should be considered carefully during the building design process. This could have far reaching implications for the energy use and environmental issues, especially in the warmer and more affluent southern and eastern parts of China.

6. Conclusions

There is a growing concern about energy use in China. With rapid building development programmes and rising living standards, the building sector is and will continue to be a major energy end user. Using a bioclimatic approach, the potential use of passive design techniques was examined. A total of 18 cities were investigated, covering the five major climatic types, namely severe cold, cold, hot summer and cold winter, mild and hot summer and warm winter. Five passive design strategies were considered, solar heating, natural ventilation, thermal mass, thermal mass with night ventilation and evaporative cooling. It has been found that for the severe cold and cold climate regions, the potential use of passive solar design ranges from 7% to 50% of the time during the colder half of the year (October–March). The remaining period would have to rely on conventional/active solar heating systems. In general, no air conditioning would be required if proper passive cooling techniques such as natural ventilation, thermal mass or evaporative cooling are adopted. In the hot summer and cold winter climate zone, passive solar application ranges from 58% to 83% in the winter, and passive cooling techniques range from 47% to 61% during the summer months. Periods requiring air conditioning vary within 10–18%. The mild climate region (represented by Kunming) shows good potential use of passive solar heating, covering 88% of the colder half of the year, with no cooling requirement (passive and otherwise) during the warmer half of the year. For the hot summer and warm winter climates, passive solar heating is more than adequate to provide any space heating required during the short, mild winter. Potential use of passive cooling techniques ranges from 50% to 64% during the warmer half of the year, and 25–50% of the time air conditioning would be required for thermal comfort.

A total of nine passive design strategy zones were identified with appropriate design techniques suggested for both summer and winter consideration. It is hoped that the work presented would enable architects and building designers to assess the appropriate passive design strategies, especially during the initial conceptual design stage when different building schemes are being considered. The present work has limitations though. For instance, only 18 cities were considered, and there could well be cities with distinct micro-climates that are not covered by the nine passive design zones. Moreover, surveys of clothing habits/patterns for the summer, mid-season and winter should also be conducted, so that more appropriate clothing insulation values and, hence, comfort zone boundaries could be established. More work is required.

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