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Proposal of a new climate classification based on Köppen and Trewartha

Lirongtuo Xin

Independent researcher, graduated from University of Melbourne with a master's degree in 2021

Email: xinlirongtuo@gmail.com

Abstract

A new and detailed climate classification based on Köppen-Geiger and Trewartha schemes is proposed, which uses four components (thermal zone, continentality, humidity, and seasonal distribution of precipitation) to determine a location's climate type. It specifies thermal zones into nine types by subdividing tropical, subtropical, temperate, and polar zones, which are based on original Trewartha classification. Continentality classification (continental, oceanic, and transitional) is based on modified Ivanov's equation considering diurnal and annual temperature range. Humidity zone is based on the smoothed formula of Köppen's approach, and this classification adds a 'semi-humid' zone to distinguish dry and wet forest climate zones. Monsoonal and Mediterranean climate are specified by seasonal distribution of precipitation.

This study explores climate types in major global cities, and found that there are 82 different climate types among them. Cities tend to be in areas with mild to warm thermal conditions, oceanic climate (low annual and diurnal temperature ranges), high precipitation, and uniform seasonal distribution of precipitation, with the climate type C_1oaf (warm-temperate oceanic humid climate with uniform precipitation) most common among global cities. Cities in subpolar and polar climate zones are extremely rare.

An important improvement of this classification compared to Köppen and Trewartha climate schemes is its inclusion of arid and semi-arid climate zone into thermal zones and seasonal distribution of precipitation types. Compared to Thornthwaite and Holdridge climate classifications, the classification only uses temperature and precipitation instead of other meteorological elements, making data more accessible for mapping and research.

Keywords: climate classification, Köppen, Trewartha, semi-humid, continentality

1. Introduction

Climate is the long-term pattern of different meteorological elements in a location, and the most important meteorological elements are temperature and precipitation. A moderate temperature, not too hot or too cold, is the optimal condition for plants and animals to live. Enough precipitation is necessary for vegetation to grow, providing nutrition to other kinds of species. Even though many places in the world have similar annual mean temperature and total precipitation, the seasonal distribution of the two factors can have significant influence on comfortability. Therefore, a systematic climate classification is beneficial for scientists and other sectors in society to determine the most suitable regions for their interests.

German climatologist Wladimir Köppen's work on global climate is currently the most widely accepted version, which divides the world into five zones (A, B, C, D and E) and then subdivides these zones according to the seasonal distribution of temperature and precipitation. In the tropical zone (A), the average temperature of the coldest month is ≥ 18°C; The average temperature of the coldest month in temperate zone (C) is between 0 °C ~ 18 °C (Peel et al. 2007) (or -3 °C ~ 18 °C by Kottek et al. (2006)), and the average temperature of the hottest month is above 10 °C; The average temperature of the coldest month in cold zone (D) is below 0°C (or -3°C), and the average temperature of the hottest month is above 10°C; The average temperature in all months in the polar zone (E) is below 10°C. If the precipitation does not meet the minimum criteria in a location, the climate is classified into dry zone (B), regardless of temperature distribution according to Peel et al. (2007). In Kottek et al. (2006), polar zone (E) is firstly determined.

There are several shortcomings in the well-known Köppen classification. Firstly, the temperate zone and cold zone are too broad because the criteria mainly consider the mean temperature of the coldest month. For example, Hanoi and Hong Kong (both are Cfa) are classified into temperate zone as well as London (Cfb), New York City (C/Dfa) and even Reykjavík (C/Dfc). Cities that are classified into cold zone such as Beijing and Seoul (Dwa) are actually less 'colder' than many cities in temperate and subpolar oceanic climate zones. In fact, there is no reference of 'subtropical' and 'subpolar' climate in the Köppen scheme. Secondly, when considering the threshold of arid and semi-arid climate, there is a discontinuity when the percentage of precipitation in the six high-sun months is just 30% or 70%. Thirdly, some sources like Brugger and Rubel (2013) use 'continental climate' to refer to D type, which is not rigorous because regions in arid zone (B) and temperate zone (C) can also be highly continental regarding annual and diurnal temperature range.

Trewartha climate classification is an improvement on the Köppen climate classification (Belda et al., 2014). It introduces the subtropical and boreal (subpolar/subarctic) zones, based on the number of months with mean temperature ≥ 10 °C. 8-12 months are above 10 °C in subtropical zone, 4-7 months are above 10 °C in temperate zone, and 1-3 months are above 10 °C in boreal zone. The criteria for tropical and polar climate have not been changed. De Castro et al. (2007) uses the equation (1) as the threshold to determine the boundary of arid climate, in which R denotes the mean annual precipitation threshold in cm, T denotes mean annual temperature in °C, and Pw denotes percentage of annual precipitation concentrated in the winter half. A location falls into semi-arid zone when the mean annual precipitation is lower than R but higher than R/2, and arid zone when it is lower than R/2. In temperate and boreal climate zones, mean temperature of the coldest month determines the difference between continental and oceanic climate, with the former below 0°C and the latter above 0°C.

$$R = 2.3T - 0.64Pw + 41 \quad (1)$$

However, it is noticeable that temperate oceanic zone by Trewartha classification includes some regions which show continental-like temperature range, like Xuzhou, Belgrade, and Louisville, just because the mean temperature of January is above 0°C and only 7 months are above 10°C. Another problem is Trewartha classification neglects monsoon climate.

Furthermore, there are three issues which can be further improved in future climate classification. The first issue is the subdivision of thermal zone. Areas in the outer part and inner part of tropics are different when cold wave affects these areas. The record low of Miami is -2.8°C in February 1917 (https://www.weather.gov/media/mfl/climate/Daily_Records_Miami.pdf), which is impossible in cities like Singapore (http://www.weather.gov.sg/climate-historical-extremes-temperature/). The mean annual temperature in warmer subtropical zone (like New Delhi and Hong Kong) is much higher than cooler subtropical zone (like Shanghai and Tokyo), and the length of hot season (mean temperature over 22°C) and distinction of 'four season' is very different in the two typical zones within subtropics (Yiqi et al., 2022), with cooler subtropical areas facing snow and frost while warmer subtropical areas not (Corlett, 2013; Wen et al., 2009). There is a 'hemi-boreal' region located in the colder part of temperate region, near boreal climate zone, with mixture of coniferous and broadleaf species (Bourtsoukidis et al., 2014).

The second issue is, although the arid climate is characterized by desert or steppe regardless of thermal variance, it is still meaningful to investiagte the temperature variation in these regions to analyse synoptic systems influencing these regions. Also, an arid location can show monsoonal precipitation type when summer monsoon takes moisture into areas like Arizona (Adang & Gall, 1989; Balling Jr & Brazel, 1987), or Mediterranean precipitation type when westerlies produce mild rainfall or snowfall in winter (Ghasemi & Khalili, 2008; Kheiri et al., 2022).

The third issue is the necessity to define 'semi-humid' zone which can be separated from humid zone. Semi-humid zone is generally located on the periphery of humid zone and near the semi-arid zone, which is more susceptible to droughts caused by annual climate variabilities (like northern China) (Yin et al., 2017; Zhang et al., 2019). Sometimes its precipitation pattern is more monsoonal than areas with humid condition all the year round

(Tan et al., 2011), but it is not always the case. The vegetation type of these areas is more likely to be a mixture between forest and steppe (Erdős et al., 2018; Zakh et al., 2010), like tropical savanna climate.

According to Sanderson (1999), it is necessary to prepare for a new climate classification following the development of meteorological instruments. Now climate models are well-developed, and people’s understanding of climate has gradually diverted from vegetation to weather systems, comfortability, and future climate change, so climate classifications also need to fit these demands.

2. Data and methodology

This paper focuses on the theoretical methods of dividing the global climate into specific zones according to the average level and temporal deviation of two basic meteorological elements: temperature and precipitation. One feature of this approach is to make resultant four components mutually independent. For example, Riyadh can be arid regarding humidity, subtropical thermally, and highly continental, with precipitation concentrated in winter like Mediterranean climate zone. Another feature is to integrate some concepts (like monsoon, Mediterranean, continental, oceanic, highland, and alpine) into these subdivisions. Due to the limitations of time and length, no mapping is conducted in this paper, and this study only preliminarily provides a framework for further climate classification studies.

This paper will provide climate classification of notable global cities. The database used for calculating climate values is https://en.climate-data.org/, based on ECMWF data between 1991-2021. In this website, mean temperature and precipitation in each month are provided in a table, and the annual mean temperature and total precipitation are also provided in a graph. In this study, annual mean daily maximum and minimum temperature are derived by averaging the corresponding temperature data of the 12 months. The list of global cities used for climate classification comes from the latest version of Globalization and World Cities Research Network (GAWC) (https://www.lboro.ac.uk/microsites/geography/gawc/world2020t.html), and the full list is in the appendix. The region of a city is based on the United Nations geoscheme (https://unstats.un.org/unsd/methodology/m49/). Sources of cities' latitudes are from the World Cities Database (https://simplemaps.com/data/world-cities).

The full list of climate types of 392 global cities is in Supporting Information, which includes five tables (S1, S2, S3, S4, and S5), corresponding to alpha, beta, gamma, highly sufficient, and sufficient level cities, respectively.

3. Classification scheme

3.1 Thermal zone classification

As mentioned earlier, the Trewartha climate classification divides the world into five temperature zones: tropical, subtropical, temperate, boreal (subpolar) and polar. Thermal zone classification in this paper will be based on this methodology, and further divide tropical, subtropical, and temperate zone into two subtypes.

For tropical zone, there is a distinction between outer tropical region with warm winter (mean temperature of the coldest month between 18-22°C) and inner tropical region with hot winter (mean temperature of the coldest month above 22°C). Outer tropics are generally located not far from Tropic of Cancer/Capricorn and are more susceptible to cold wave (Guo et al., 2012; Malik et al., 2020; Shrestha et al., 2017). Cities like Kaohsiung, Miami, Dhaka, Chiang Mai, Dubai, and Rio de Janeiro fall into this type. Some equatorial cities with higher altitude may also have outer tropical climate, like Caracas and San Jose (Costa Rica). Low-sun season is generally cooler than high-sun season due to the winter monsoon (Dimri et al., 2016), but hot weather may happen in spring. Inner tropics are more near the equator and have a low elevation. Most of Southeast Asian capitals are in inner tropics and have a hot weather all the year round with negligible difference of temperature during wet and dry season.

Subtropical zone is broad, and there is a gap between cooler subtropical areas where coldest months are below 10°C (cool-winter type), and warmer subtropical areas where coldest months are above 10°C (mild-winter type). In China, the former type is typical in cities of Yangtze River valley (like Shanghai), and the latter type is typical in cities of Pearl River valley (like Guangzhou). Due to more frequent influence by cold air due to higher latitude and more continental climate, cool subtropics can be snowy and frosty in winter, while winter is the most pleasant season in warm subtropics. The 'four-season' style (Yiqi et al., 2022) is more typical in cool subtropics with mild weather in spring and autumn, while in warm subtropics there are typically only 'cool' and 'hot' season in different length. For example, cities like Auckland, Lisbon, and Cape Town are comfortable almost around the year, while New Delhi, Riyadh, and Phoenix is mild only in winter, although both kinds are within the warm subtropics.

Temperate zone is in the middle latitude and controlled by synoptic systems of various characteristics in different seasons. Regions with mean temperature above 10°C in only 4-5 months are cold-temperate (or hemi-boreal), while regions with mean temperature above 10°C in 6-7 months are warm-temperate. In China, the former type is typical in Heilongjiang River valley, while the latter type is typical in Yellow River valley. Cold-temperate zone has a longer winter than summer by Yiqi et al. (2022) standards, and the mean temperature of the hottest month is rarely above 22°C. By contrast, warm-temperate zone has a more balanced length of winter and summer, which may be not very different from cool-subtropical zone. Mean annual temperature are below 10°C in cold-temperate zone (like Moscow and Montreal) and around (like Chicago) or slightly above 10°C (like Paris and New York City) in warm-temperate zone.

Like Trewartha classification, subpolar climate zone (also called boreal/subarctic climate in northern hemisphere) has a mean temperature above 10°C in only 1-3 months, combining continental subarctic climate (Dfc/Dwc/Dsc/Dfd/Dwd/Dsd) and subpolar oceanic climate (Cfc/Cwc/Csc) in Köppen classification. This climate type is characterized by very short warm season in summer, allowing it to support taiga (Viereck et al., 1986), although in oceanic subpolar zone the dominant flora is not far from oceanic tundra zone because the mean temperature of the hottest month is just slightly above 10°C (Elmarsdottir et al., 2003). Subpolar zone is controlled either by subarctic winter high (like Siberia and Canada) or subpolar low (like Iceland, Aleutian Islands, and subantarctic).

When no month has a mean temperature above 10°C, an area is classified as polar climate, and is further subdivided into tundra and ice-cap climate with the same scheme as Köppen and Trewartha classifications. Not all places classified as polar climate are in the polar circle. In subantarctic region, many islands have an average annual temperature around 0-10°C, as well as the mean temperature of both hottest and coldest month. The mean annual temperature is similar to cold-temperate climate area in northern hemisphere, but due to the lack of heat in summer, trees cannot grow in these areas.

The classification of temperature bands is shown in Table 1:

Table 1. Classification of thermal zones

Type	Description	Criteria
A_1	Inner-tropical climate	Mean temperature ≥ 22.0°C in the coldest month
A_2	Outer-tropical climate	Mean temperature in the coldest month is 18.0-21.9°C
B_1	Warm-subtropical climate	Mean temperature in the coldest month is 10.0-17.9°C
B_2	Cool-subtropical climate	Mean temperature ≥10°C for 8-11 months of the year
C_1	Warm-temperate climate	Mean temperature ≥10°C for 6-7 months of the year
C_2	Cold-temperate climate	Mean temperature ≥10°C for 4-5 months of the year
D	Subpolar climate	Mean temperature ≥10°C for only 1-3 months of the year
E_1	Polar tundra climate	Mean temperature in the hottest month is 0.1-9.9°C
E_2	Polar ice cap climate	Mean temperature of the hottest month ≤0.0°C

The term '**highland climate**' can be used if the colder thermal zone in one location compared to surrounding areas is due to higher elevation instead of higher latitudes. High-altitude Polar climate can be called '**alpine climate**', and high-altitude subpolar climate can be called '**subalpine climate**'. For example, Bogota and Quito can be regarded as warm-subtropical highland climate, and Lhasa has a subalpine climate.

3.2 Continental and oceanic climate

The concept of continentality is based on the law that air-land interface has much lower heat conductive capacities than air-water interface, making the annual and diurnal temperature range inland higher than it in oceanic areas. Also, in continental areas, spring is generally warmer than autumn, while in oceanic areas autumn is typically warmer than spring. To measure the continentality of an area, an index taken both annual temperature range and latitude into account is most frequently used, because higher latitudes have more significant difference in radiation receiving between summer and winter (Driscoll & Fong, 1992). Polish climatologist Gorczynski (1920) used this index to measure continentality:

$$K = \frac{1.7A}{\sin\varphi} - 20.4 \qquad (2)$$

where K is the climate continentality, A is the annual difference in temperature in °C, and ϕ is latitude. Although this index is widely accepted, it has two problems. Firstly, when the latitude is near zero, K is toward infinity, which is not suitable if tropical continentality also needs to be investigated; secondly, in many highlands, annual range of temperature is low (Kopec, 1965), but they cannot be considered fully oceanic because diurnal range of temperature is still high.

To solve these problems, Ivanov's formula (as cited in Badescu, 1999) can be adopted:

$$I = \frac{E + E_g + 0.25(100 - u)}{0.36\varphi + 14} * 100 \quad (3)$$

In the formula, E represents the annual temperature range in °C, E_g represents the diurnal temperature range in °C, u (%) represents the yearly average value of the air relative humidity, and ϕ represents latitude. Although the annual temperature difference in the plateau area is small, due to the strong sunlight, sunny and dry climate, and thin air, the daily temperature difference is large, so the increase of the diurnal temperature range can effectively distinguish the plateau from areas with a truly oceanic climate (Ding et al., 2015; Zhou et al., 2010). In addition, the latitude denominator is added with a constant term 14, which avoids abnormal deviations in the calculation results due to a denominator of 0 in the equatorial region.

Considering that the data of relative humidity is less common than temperature and precipitation in general climate data, this item could be omitted. The **sum of the first two items in the above equation is the definition of "continentality" in this climate classification,**

denoted by i.

$$\boldsymbol{i} = \frac{E+E_g}{0.36\,\varphi+14} * \mathbf{100} \quad \textbf{(4)}$$

Table 2 shows classification of areas based on continentality.

Table 2. Continentality classification of areas

Type	Description	Criteria
c	Continental climate	i>100
t	Transitional climate	80≤i≤100
o	Oceanic climate	i<80

Continental climate zones are generally located in the interior of continents (mainly Eurasia and North America), of which the middle and high latitudes of Eurasia and the subtropical desert are the most continental. The climate is generally relatively dry, and the annual and diurnal temperature ranges are relatively large. Both extreme high and low temperatures of the world occur in highly continental regions. The East Asian monsoon region also belongs to the continental climate zone due to its cold winter and hot summer, and the annual temperature difference is large, although it is under the control of marine air masses in summer.

Oceanic climate zones are generally located in tropical ocean areas, mid-latitude oceans and continental west coasts, as well as some small islands in the Pacific Ocean, with a relatively humid climate, and relatively small annual and diurnal temperature ranges. However, the mid-latitude oceanic climate zone may still be hit by cold snaps and heat waves, with occasionally extreme high and low temperatures. Because in oceanic zones, abilities to resist extreme temperatures are weaker than in continental climate regions due to insufficient protection and equipment like air-conditioning systems, when there is an extreme weather event, it may cause more serious consequences (García-Herrera et al., 2010).

The transitional zone between the two is called transitional climate, which is characteristic in the Central and Mediterranean European regions and some tropical-subtropical highlands. Transitional zones may show moderate temperature range in a large timescale as well as more extreme temperatures during some synoptic weather events (Demirtaş 2017; Demirtaş, 2022).

3.3 Humidity zone classification

Humidity zone is contributed by annual total precipitation and distribution of precipitation in different seasons. Köppen climate classification and Trewartha climate classification uses different methods to calculate a baseline level of precipitation to distinguish arid (desert), semi-arid (steppe), as well as humid (forest) climate. Semi-arid zone in Trewartha climate classification is larger than Köppen climate classification. For example, North China regions like Hebei, Shanxi, Tianjin, and Beijing are largely considered as humid region in Köppen classification but semi-arid in Trewartha classification (Belda et al., 2014). However, in many Chinese geographical studies, North China is generally considered as 'semi-humid' climate, compared to humid climate in Southern China (Yangtze and Pearl River valley) (Liu et al., 2019; Yin et al., 2017; Zhang et al., 2019). Another point to distinguish semi-humid climate from humid climate, is the difference between tropical savanna, characterized by the grasslands with sparse trees, and the more prosperous tropical monsoon rainforests (Baker et al., 2005; Lü et al., 2010; Murphy & Bowman, 2012; Sano et al., 2010).

As mentioned in introduction, in Trewartha classification, the threshold to classify the aridity of one location is a continuous function of annual mean temperature and the percentage of annual precipitation during the winter half of a year. This method is an improvement compared to the criteria used in Köppen classification where there is a discontinuity on the boundary of dry-winter, no-dry-season, and dry-summer types of precipitation. However, if 'semi-humid' area is taken into account, a modified version of Köppen criteria is better, which subdivides non-arid climate zones into semi-humid and humid zones and smooths the criteria into one equation similar to Trewartha's.

By multiplying the average annual temperature by 20 and adding a value linearly related to the seasonal distribution of precipitation, a threshold is then obtained. Next, divide the annual precipitation by this indicator, the outcome is the coefficient to characterize the degree of wetness. It is named as "humidity coefficient".

Define the formula

$$T * 20 + 2.8P \quad (5)$$

where T is the mean annual temperature (unit: °C) of a certain place, and P is the percentage of precipitation in the six high-sun months (i.e. April-September in the northern hemisphere and October-March in the southern hemisphere).

The defined "humidity coefficient" is the result of dividing the annual precipitation by the value obtained by this formula. Table 3 shows the classification of humidity zone based on humidity coefficient.

Table 3. Classification of humidity zones

Type	Description	Criteria
a	Humid climate	Humidity coefficient ≥ 1.75
b	Semi-humid climate	Humidity coefficient between 1.0 and 1.75
c	Semi-arid climate	Humidity coefficient between 0.5 to 1.0
d	Arid climate	Humidity coefficient < 0.5

The natural zone corresponding to the arid climate is desert, so it can also be called ‘desert climate’; the natural zone corresponding to semi-arid climate is dry grassland, so it can be called ‘steppe climate’. Semi-humid and humid climates generally correspond to forests, with semi-humid climates also corresponding to dry forest, forest-steppe, or savanna zones, while humid climates correspond to moist forest climates (for the tropics, rainforests or seasonal forests, depending on the presence or absence of significant dry rainy seasons). The exception is the polar zone, which cannot be replaced by these natural belts due to the lack of vegetation.

The arid climate zone is typically located in the mid-latitude continental interior where terrain barrier makes water vapor from the oceans difficult to enter, or warm-subtropical to outer-tropical regions where subtropical high and trade wind belt control the climate all the year round. The harsh environment is not suitable for the survival of vegetation, so the typical natural landscape is desert. Only a few places where water sources exist oases appear, and settlements are often distributed in these oases.

The semi-arid climate zone is located in the periphery of the arid zone, and is often affected by certain precipitation systems in specific seasons (for example, the southern edge of the subtropical desert is affected by the monsoon trough or Intertropical Convergence Zone (ITCZ) in summer, the northern edge of the subtropical desert is affected by frontal systems in winter, and the semi-arid area of China is affected by the summer monsoon) producing a certain amount of precipitation, which is enough to support the growth of herbs, so the natural landscape is mainly grassland (HilleRisLambers et al., 2001).

The climatic conditions in the semi-humid climate zone are more conducive to plant survival. The rainy season is longer, and the precipitation is more abundant, which is enough to sustain trees, but the forest is often not very luxuriant, belonging to the transition zone from grassland to forest.

Humid climate zones are generally located in the tropical convergence zone, the mid-latitude oceanic zones, the subpolar low-pressure zone, as well as the monsoonal area on the east coast of continents. It can be rainy throughout the year, or there is a short dry season. Precipitation is very abundant during the wet season, so it is very conducive to vegetation growth and often can develop wet forests.

3.4 Seasonal distribution of precipitation

Köppen's scheme has specifically investigated the seasonal distribution of precipitation in tropics and temperate-continental areas in different methods, but the commonality is that areas with uniform level of precipitation in all seasons are denoted by 'f', areas with dry-summer characteristics are denoted by 's', and areas with dry-winter characteristics are denoted by 'w'. In tropics, an additional type of 'Am' (tropical monsoon climate) differentiates from tropical savanna climate ('Aw' or 'As' depending on its rainy season, but 'As' is not strictly defined) by more affluent dry season precipitation (Kottek et al., 2006). In Trewartha's scheme, the dry season is only considered in tropical and subtropical climate zones, and the zone of both ‘s’ and ‘w’ is much narrower than Köppen’s scheme due to the stricter requirements (Belda et al., 2014). For climate categorization itself, it is feasible to classify seasonal distribution of precipitation in arid zones, because they can also be influenced by precipitation in different seasons, especially in semi-arid zone.

Table 4 shows the classification of seasonal distribution of precipitation.

Table 4. Seasonal distribution of precipitation type

Type	Description	Criteria
s	Dry summer	the six high-sun months account for less than 30% of annual precipitation
w	Dry winter	the six high-sun months account for over 70% of annual precipitation
f	Uniform distribution	the six high-sun months account for 30-70% of annual precipitation

Dry-summer type of precipitation distribution is similar to ‘Mediterranean climate’ in subtropical and temperate areas. However, the mechanism resulting to dry summer is different by latitude. In the tropics, dry-summer and wet-winter precipitation pattern is typically caused by orographic effect. They are located to the poleward side of a mountain and the equatorward side of the sea, so winter monsoon or trade winds contribute more moisture than summer monsoon. Subtropical dry-summer climate is caused by the movement of synoptic weather systems, with westerlies and frontal systems dominating the winter and subtropical ridges dominating the summer. Temperate dry-summer climate can happen in some continental areas like northern Iran and Central Asia, where westerlies can contribute some rainfall during winter, but tropical summer monsoon cannot reach due to orographic effect (Gao et al., 2022; Ghasemi & Khalili, 2008; Kheiri et al., 2022). ‘Subpolar’ and ‘polar’ dry-summer climate zones are generally located at higher elevations within tropical or temperate zones, with similar mechanisms to their lower-altitude counterparts.

Dry-winter type of precipitation distribution can also be called 'monsoon climate' because most areas of this climate type are heavily influenced by summer monsoon, transporting tropical moisture into these areas. In tropics, dry-winter climate is highly related to savanna and monsoon climates because both types have a significant gap between wet and dry season, as well as semi-arid zone to the equatorward side of subtropical deserts. They are influenced by tropical low-pressure systems like ITCZ in summer, and subtropical/continental ridges or trade winds in winter (Gadgil, 2003; Safarova et al., 2022). In subtropical and temperate zones, dry-winter precipitation pattern is caused by the thermodynamical properties gap between the continent and sea. During summer, air pressure is lower inland, and summer monsoon transports warm and moist air from tropical oceans to the continent; during winter, air pressure is highest in subpolar continental zones, and it blows cold and dry air into lower-latitude areas (Wang, 2006). Topographic influence can still be considered, as some areas in colder thermal zones are influenced by monsoon schemes within their latitudes, only higher elevation making them fall into colder thermal zones.

Uniform distribution of precipitation typically shows no sign of monsoon, Mediterranean, or orographic influence. For humid areas, in tropics, regions with uniform precipitation are influenced by tropical systems all the year round, or they are in the passage of a warm current and susceptible to precipitation even in winter. In subtropics, regions can be influenced by tropical systems in the summer and mid-latitude systems in the winter, with frequent tropical-extratropical interactions in different seasons. In mid to high latitudes, regions with the uniform precipitation pattern are mostly controlled by westerlies, subpolar low-pressure systems, or polar systems, with no preference of precipitation during different seasons. Also, uniform distribution of precipitation can happen in dry areas in tropical and subtropical deserts where precipitation in all seasons is rare. Some regions falling into uniform type can show tendencies to relatively drier summer (six high-sun months account for 30-40% of annual precipitation) or relatively drier winter (six high-sun months account for 60-70% of annual precipitation), or there are wet and dry seasons but the wettest period is during spring, autumn, or both.

4. Results and discussions (climate type distribution among global cities)

Theoretically, there are 324 climate types based on random combinations of the four components, but many climate types do not exist in the real world. There are only 82 climate types in the 392 global cities. This section will discuss the distribution of climate zones, as well as the dominant climate types globally and regionally. The full list of climate types of 392 global cities is in Supporting Information, which includes five tables (S1, S2, S3, S4, and S5), corresponding to alpha, beta, gamma, highly sufficient, and sufficient level cities, respectively.

Figure 1 shows the number of major cities in eight thermal zones. There are 77 cities within the tropics (46 inner-tropics and 31 outer-tropics), 149 cities within the subtropics (85 warm-subtropics and 64 cool-subtropics), 163 cities within the temperate zone (116 warm-temperate and 47 cold-temperate), 2 cities within the subpolar zone, and 1 city within the polar zone (La Paz, which can also be classified as alpine climate due to high elevation). Almost all major cities are in tropics, subtropics, and temperate zone, with warm-subtropics to warm-temperate zone accounting for around 2/3 of all cities. Warm-temperate climate is the group with the largest number of cities, including some metropolises in northern hemisphere (like New York City, London, and Beijing). The number of cities in the cooler subtype is generally smaller than cities in the warmer subtype within the same main type (tropics, subtropics, and temperate zone). There are no cities in ice cap climate zone.

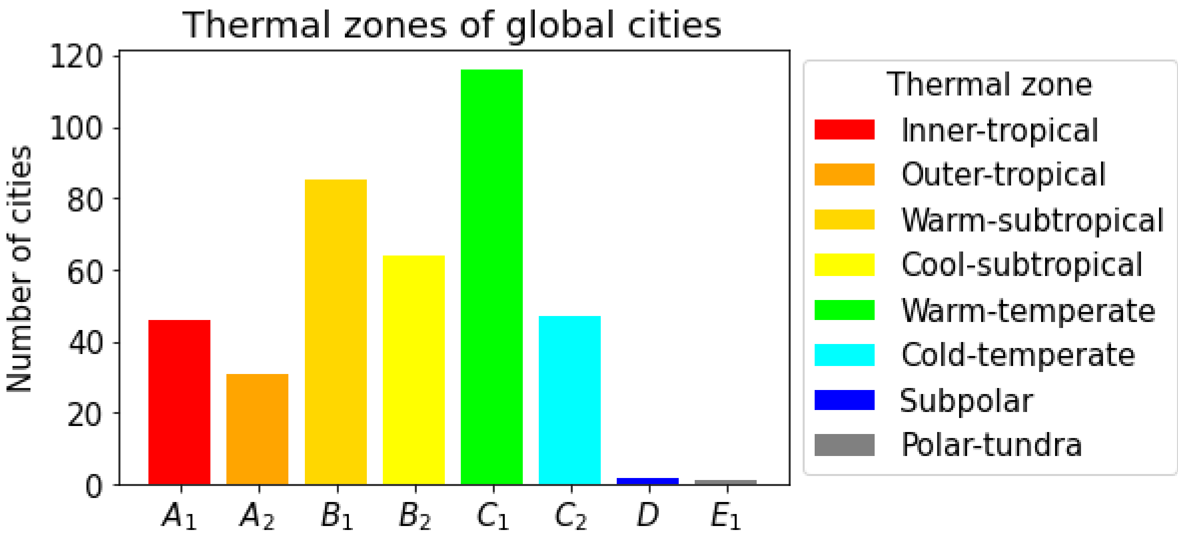

Figure 1. Thermal zone distribution among 392 global cities

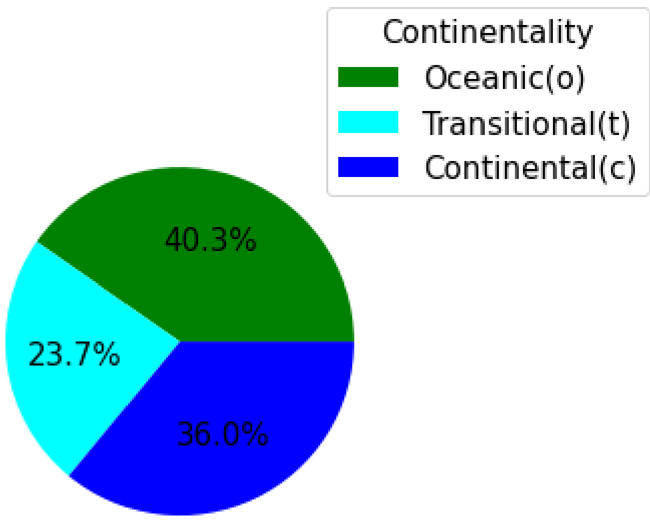

Figure 2. Percentage of three continentality zones among 392 global cities

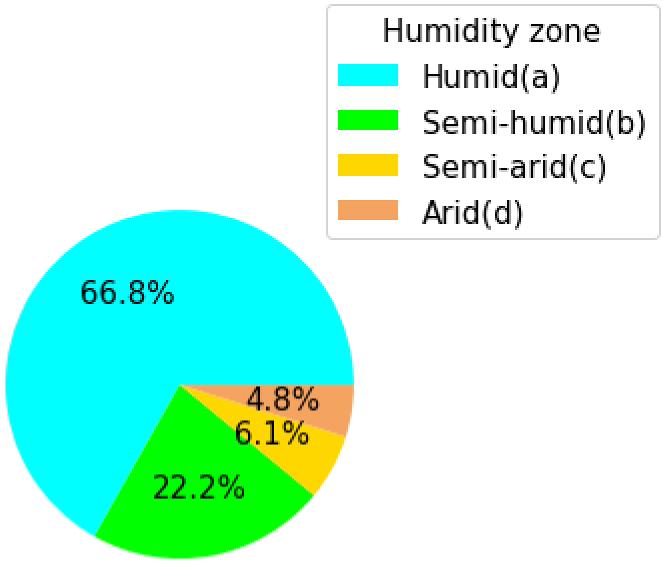

Figure 3. Percentage of four humidity zones among 392 global cities

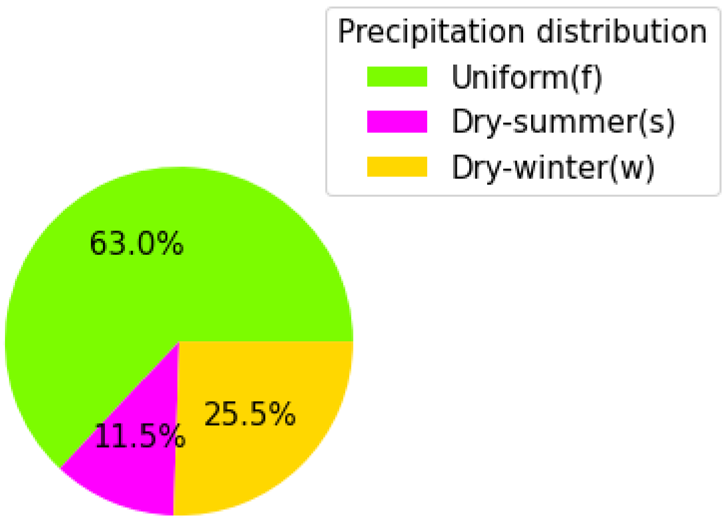

Figure 4. Percentage of the three types of precipitation seasonal distribution among 392 global cities

Figure 2, figure 3, and figure 4 show the percentage of cities within different continentality, humidity, and seasonal distribution of precipitation zones, respectively. Among the 392 global cities, 158 have an oceanic climate, 93 are in the transitional zone, and 141 have a continental climate; 262 are humid, 87 are semi-humid, 24 are semi-arid, and 19 are arid; 247 cities do not show significant differences of precipitation level between summer and winter (or the annual maximum precipitation periods are in spring or autumn), 45 cities are drier during summer (Mediterranean-type precipitation), and 100 cities are drier during winter (monsoonal-type precipitation). Most cities are within humid zone, and show a relatively uniform seasonal precipitation distribution, and a plurality of cities have oceanic climate, while there are also a large number of continental cities. The number of cities with dry winter doubles the number of dry-summer cities. Overall, major global cities tend to lie in areas with mild temperatures, lower annual and diurnal temperature range, and abundant and uniform precipitation.

Table 5. The most common climate type of 21 global regions

Region	Dominant type
Africa	
Northern Africa	B_1tcs
Eastern Africa	A_2obw/B_1tbw (tied)
Middle Africa	A_1oaf/A_1obw (tied)
Southern Africa	B_1obf/B_1ccw (tied)
Western Africa	A_1oaf
Americas	
Caribbean	A_1obf
Central America	B_1tbw
South America	B_1oaf
Northern America	C_1caf
Asia	
Central Asia	C_1caf
Eastern Asia	B_2caf
South-eastern Asia	A_1oaf
Southern Asia	A_2tbw
Western Asia	B_1cds
Europe	
Eastern Europe	C_2taf

Northern Europe (UK & Ireland excluded)	C_2oaf
UK & Ireland	C_1oaf
Southern Europe	C_1taf
Western Europe	C_1oaf
Oceania	
Australia and New Zealand	B_1oaf/B_1obf (tied)
Melanesia	A_1oaw/A_1oaf (tied)

Table 5 presents the dominant climate type of 21 global regions. Due to the low latitudes, Africa is dominated by tropical and subtropical climate. In Northern African cities, the most typical climate type is B_1tcs, representing a warm-subtropical climate with mild winter and moderate continentality. They show typical Mediterranean type of precipitation, with rainfall generally happens in winter, and the overall precipitation is relatively low. The tied two most common climate types in Eastern Africa are A_2obw and B_1tbw. Although Eastern Africa is near the equator, higher altitude in major cities makes the temperature lower, and in plateau the diurnal range of temperature is high, although the annual range is low due to its latitudes. The rainfall is moderately high and concentrates in summer, which is typical in tropical savanna zones. Western and Central Africa show the typical pattern of tropical rainforest climate, with hot weather all the year round and oceanic temperature ranges, as well as humid climate all the year round. However, inland Central Africa may be inclined to savanna climate, with semi-humid climate and dry winters. Cities in Southern Africa are mainly characterized by two dominant groups: one is more oceanic, with higher and more uniform precipitation, due to the influence of westerlies (like Durban), and the other is more continental, with lower and more seasonal precipitation (like Gaborone). Both types are warm-subtropical due to its latitudes.

In the Americas, climate is more diversified. Northern America (Mexico not included) is dominated by C_1caf, a warm-temperate continental climate with distinctive four seasons and abundant uniform precipitation. This characteristic is common in cities in Northeastern and Mid-western United States (New York City, Chicago, Boston) and Southeastern Canada (Toronto), which is the economic hub of Northern America. Climate in Central America is similar to Eastern Africa's, with plateau-influenced warm-subtropical semi-humid savanna climate. Caribbean region is similar to Western Africa, but the rainfall is lower due to its leeward location (Granger, 1985). The most common climate type of South America is B_1oaf, showing a warm-subtropical humid oceanic climate influenced by South Atlantic Ocean, which is typical in Platine Region.

Asia is the largest continent in the world, so the climate is typically more continental than other continents, even in some coastal areas. The dominant climate type in Central Asian major cities is the same as Northern America (C_1caf), which is not typical in most of Central Asian land considering the general aridity in this area. In fact, only Bishkek and Dushanbe share this climate type, which may be due to the effect of windward slope (Xu et al., 2022). The dominant thermal zone of East Asia is cool-subtropics, which is common in Yangtze River basin in China, the southern end of South Korea, and central Japan, and is the belt of most populated and economically developed areas in East Asia. Although it is 'subtropical', winter is chilly and sometimes snowy, and the four-season feature is distinctive, which is very different from other subtropical regions in the world where winter is mild. Precipitation is abundant and relatively uniform, but summer rainfall is still a bit higher than winter, due to the influence of summer monsoon (Yihui & Chan, 2005). Most commonly, South-eastern Asia has typical tropical rainforest climate, concentrated in the Malay Archipelago. Cities in Southern Asia are mainly on the edge of tropics, with occasional cold waves during winter (Malik et al., 2020), and moderate range of temperature; its precipitation regime is also typical semi-humid savanna type. The dominant climate type of Western Asia is common in Gulf States, which have mild winter and extremely hot summer, making it highly continental; interestingly, although it is arid and far from the Mediterranean basin, the seasonal distribution of precipitation is still Mediterranean (over 90% precipitation happens in the winter half of a year).

The UN classifies UK and Ireland into Northern Europe instead of Western Europe and divides Central Europe into Western and Eastern along the boundary between German-speaking and Visegrád countries. Because British Isles have numerous world-class cities and their locations are far from traditional Nordic Europe, it is necessary to exclude them from the group of Northern Europe (including Nordic and Baltic countries). Cities in British Isles tend to have the same climate characteristics as continental Western European countries (C_1oaf), with a mild temperature with low annual and diurnal range, and humid conditions around the year. Nordic and Baltic Europe features a colder temperate climate (C_2oaf), but it is still generally oceanic due to the influence of Gulf Stream. Eastern Europe is dominated by colder and more continental climate compared to Northwestern Europe, but its continentality is actually not as high as Asia and Northern America. An interesting point is Southern Europe, which is often characterized as having a typical 'Mediterranean climate', is neither subtropical nor extremely dry-summer, but still within the temperate range with a slightly lower precipitation during summer than winter. Cities in Southern Europe tend to be within the transitional zone between oceanic and continental climate.

Climate in Australasia features a typical warm-subtropical oceanic climate with relatively uniform precipitation (except Perth). Cities in Australia tend to be semi-humid, while cities in New Zealand tend to be humid. Melanesia's climate is dominated by equatorial oceanic humid climate, and the length of rainy season depends on the latitude of different cities.

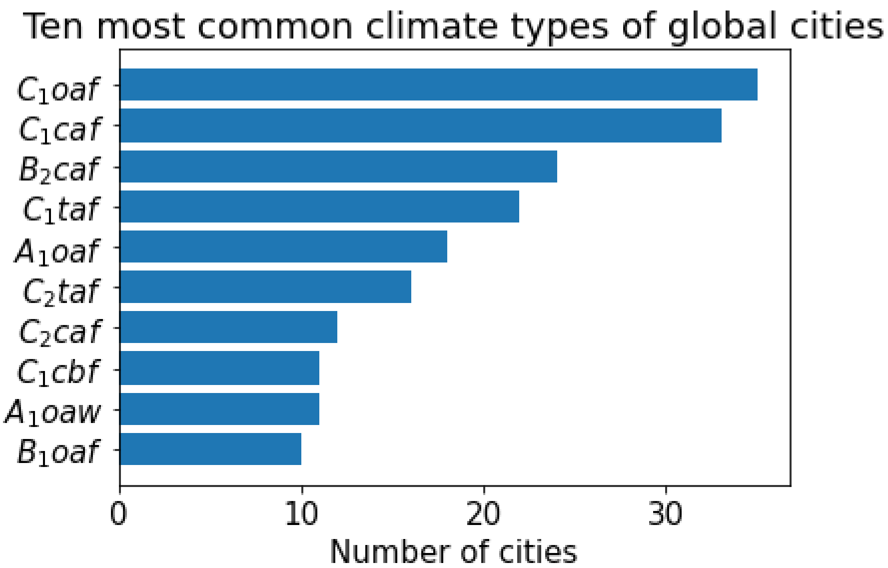

Figure 5. The ten most common climate types among 392 global cities

Globally dominant climate types reflect the locations of megalopolis controlling world economies. The two most frequent climate types—C_1oaf (35 cities) and C_1caf (33 cities), are typical warm-temperate humid oceanic and continentality climates respectively, and correspond to major cities in Western Europe and mid-eastern Northern America. They are followed by B_2caf (24 cities), which is typical in East Asia as well as inland Southern USA. Other common climate types include C_1taf (22, typical in Central Europe), A_1oaf (18, typical in equatorial regions), C_2taf (16, typical in Northeastern Europe), C_2caf (12, typical in former Soviet states and Canada), C_1cbf (11, typical in Southeastern Europe to Central Asia), A_1oaw (11, typical in tropical monsoonal zone in Southeastern Asia), and B_1oaf (10, typical in subtropical areas influenced by warm currents). The ten types account for 48.6% of all global cities.

5. Conclusions

This climate classification is based on four independent components of climate: thermal zone, continentality, humidity, and seasonal distribution of precipitation. The former two are related to temperature, and the latter two are related to precipitation; two consider the average/total level of temperature and precipitation, and the other two consider the seasonal difference of the two basic meteorological elements. No other factors (like evaporation, wind, or air pressure) are directly considered due to the lack of data in many climate stations, which is inconvenient. There are nine types of thermal zone: inner-tropical (A_1), outer-tropical (A_2), warm-subtropical (B_1), cool-subtropical (B_2), warm-temperate (C_1), cold-temperate (C_2), subpolar (D), tundra (E_1), and ice cap (E_2). There are three types of zones related to continentality: continental (c), transitional (t), and oceanic (o). There are four types of humidity zone: humid (a), semi-humid (b), semi-arid (c), and arid (d). There are three types of seasonal precipitation distribution: uniform (f), dry-summer (s), and dry-winter (w). Theoretically, there are 324 climate types based on random combinations of the four components, but many climate types do not exist in the real world.

This classification has several important functions. Firstly, it can be used for climate modelling of future climate change. Because arid regions are included in thermal zones, their tendencies to temperature change among global warming scenarios are clearer. Seasonal distribution of temperature (represented by continentality) (Vilček et al., 2016) and precipitation (Konapala et al., 2020; Vera et al., 2006) can also change due to climate change, and the change of each type's percentage is important to understand the trends of regional climate change. Secondly, seasonal distribution of meteorological elements is a meaningful measure of synoptic analysis because shift of weather systems during different seasons contributes to climatic difference between summer and winter. Also, in this classification researchers can have some knowledge about which parts of arid zones are more susceptible to cold waves during winter. Thirdly, specified classification of thermal and humidity zones can encourage local policymakers to formulate more specific plans to combat extreme weather events (incl. heat and cold waves, drought, and flood). For example, cool-subtropical climate zone should consider the effect of blizzard, while warm-subtropical climate zone is generally free from it (Wen et al., 2009).

Although most of climate-related studies use Köppen-Geiger or Trewartha climate classification to analyse global and regional climate and predict climate change, there are other climate classification systems which are more meticulous, such as Thornthwaite climate classification (Feddema, 2005), Holdridge life zones (Lugo et al., 1999), and Hardiness zone (Daly et al., 2012). Hardiness zone is fully determined by average annual minimum temperature, which is important to determine the kinds of vegetation. Both Thornthwaite and Holdridge climate classifications have more factors than temperature and precipitation, like potential evapotranspiration (PET), but the access of data is limited. By only considering temperature and precipitation in this new climate classification, data is more accessible to explore climate in the world in detail.

Supporting information

The full list of climate types of 392 global cities is in the appendix, which includes five tables (S1, S2, S3, S4, and S5), corresponding to alpha, beta, gamma, highly sufficient, and sufficient level cities, respectively. Geographic regions of these cities are also presented.

References

Adang, T. C., & Gall, R. L. (1989). Structure and dynamics of the Arizona monsoon boundary. *Monthly Weather Review*, *117*(7), 1423-1438. https://doi.org/10.1175/1520-0493(1989)117%3C1423:SADOTA%3E2.0.CO;2

Badescu, V. (1999). Correlations to estimate monthly mean daily solar global irradiation: application to Romania. *Energy*, *24*(10), 883-893. https://doi.org/10.1016/S0360-5442(99)00027-4

Baker, P. J., Bunyavejchewin, S., Oliver, C. D., & Ashton, P. S. (2005). Disturbance history and historical stand dynamics of a seasonal tropical forest in western Thailand. *Ecological Monographs*, *75*(3), 317-343. https://doi.org/10.1890/04-0488

Balling Jr, R. C., & Brazel, S. W. (1987). Diurnal variations in Arizona monsoon precipitation frequencies. *Monthly Weather Review*, *115*(1), 342-346. https://doi.org/10.1175/1520-0493(1987)115%3C0342:DVIAMP%3E2.0.CO;2

Belda, M., Holtanová, E., Halenka, T., & Kalvová, J. (2014). Climate classification revisited: from Köppen to Trewartha. *Climate research*, *59*(1), 1-13. https://doi.org/10.3354/cr01204

Bourtsoukidis, E., Bonn, B., & Noe, S. M. (2014). On-line field measurements of BVOC emissions from Norway spruce (Picea abies) at the hemiboreal SMEAR-Estonia site under autumn conditions. *Boreal Environment Research*, *19*(3), 153-167. https://helda.helsinki.fi/bitstream/handle/10138/228543/ber19-3-153.pdf?sequence=1

Brugger, K., & Rubel, F. (2013). Characterizing the species composition of European Culicoides vectors by means of the Köppen-Geiger climate classification. *Parasites & vectors*, *6*(1), 1-6. https://doi.org/10.1186/1756-3305-6-333

Corlett, R. T. (2013). Where are the Subtropics?. *Biotropica*, *45*(3), 273-275. https://doi.org/10.1111/btp.12028

Daly, C., Widrlechner, M. P., Halbleib, M. D., Smith, J. I., & Gibson, W. P. (2012). Development of a new USDA plant hardiness zone map for the United States. *Journal of Applied Meteorology and Climatology*, *51*(2), 242-264. https://doi.org/10.1175/2010JAMC2536.1

De Castro, M., Gallardo, C., Jylha, K., & Tuomenvirta, H. (2007). The use of a climate-type classification for assessing climate change effects in Europe from an ensemble of nine regional climate models. *Climatic Change*, *81*(Suppl 1), 329-341. https://doi.org/10.1007/s10584-006-9224-1

Demirtaş, M. (2017). The large-scale environment of the European 2012 high-impact cold wave: prolonged upstream and downstream atmospheric blocking. *Weather*, *72*(10), 297-301. https://doi.org/10.1002/wea.3020

Demirtaş, M. (2022). The anomalously cold January 2017 in the south-eastern Europe in a warming climate. *International Journal of Climatology*, *42*(11), 6018-6026. https://doi.org/10.1002/joc.7574

Dimri, A. P., Yasunari, T., Kotlia, B. S., Mohanty, U. C., & Sikka, D. R. (2016). Indian winter monsoon: Present and past. *Earth-science reviews*, *163*, 297-322. https://doi.org/10.1016/j.earscirev.2016.10.008

Ding, Z., Guo, P., Xie, F., Chu, H., Li, K., Pu, J., Pang, S., Dong, H., Liu, Y., Pi, F., & Zhang, Q. (2015). Impact of diurnal temperature range on mortality in a high plateau area in southwest China: a time series analysis. *Science of the Total Environment*, *526*, 358-365. https://doi.org/10.1016/j.scitotenv.2015.05.012

Driscoll, D. M., & Fong, J. M. Y. (1992). Continentality: A basic climatic parameter re-examined. *International Journal of Climatology*, *12*(2), 185-192. https://doi.org/10.1002/joc.3370120207

Elmarsdottir, A., Ingimarsdottir, M., Hansen, I., Olafsson, J. S., & Olafsson, E. (2003, September). *Vegetation and invertebrates in three geothermal areas in Iceland.* International Geothermal Conference, Reykjavík, Iceland. https://www.researchgate.net/profile/Asrun-Elmarsdottir/publication/239799864_Vegetation_and_invertebrates_in_three_geothermal_areas_in_Iceland/links/0c96052ea49939827d000000/Vegetation-and-invertebrates-in-three-geothermal-areas-in-Iceland.pdf

Erdős, L., Ambarlı, D., Anenkhonov, O. A., Bátori, Z., Cserhalmi, D., Kiss, M., Kröel-Dulay, G., Liu, H., Magnes, M., Molnár, Z., Naqinezhad, A., Semenishchenkov, Y. A., Tölgyesi, C., & Török, P. (2018). The edge of two worlds: A new review and synthesis on Eurasian forest-steppes. *Applied Vegetation Science*, *21*(3), 345-362. https://doi.org/10.1111/avsc.12382

Feddema, J. J. (2005). A revised Thornthwaite-type global climate classification. *Physical Geography*, *26*(6), 442-466. https://doi.org/10.2747/0272-3646.26.6.442

Gadgil, S. (2003). The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, *31*(1), 429-467. https://doi.org/10.1146/annurev.earth.31.100901.141251

Gao, X., Zhao, D., Chen, Z., & Zhu, Y. (2022). Changes in abrupt alternations between wet and dry over the Great Lakes Region of Central Asia during the period 1976–2015. *Journal of Hydrology*, *613*, 128333. https://doi.org/10.1016/j.jhydrol.2022.128333

García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., & Fischer, E. M. (2010). A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, *40*(4), 267-306. https://doi.org/10.1080/10643380802238137

Ghasemi, A. R., & Khalili, D. (2008). The association between regional and global atmospheric patterns and winter precipitation in Iran. *Atmospheric Research*, *88*(2), 116-133. https://doi.org/10.1016/j.atmosres.2007.10.009

Gorczyński, L. (1920). Sur le calcul du degré du continentalisme et son application dans la climatologie. *Geografiska Annaler*, *2*(4), 324-331. https://doi.org/10.1080/20014422.1920.11880778

Granger, O. E. (1985). Caribbean climates. *Progress in Physical Geography*, *9*(1), 16-43. https://doi.org/10.1177/030913338500900102

Guo, Y., Punnasiri, K., & Tong, S. (2012). Effects of temperature on mortality in Chiang Mai city, Thailand: a time series study. *Environmental health*, *11*(1), 1-9. https://doi.org/10.1186/1476-069X-11-36

HilleRisLambers, R., Rietkerk, M., van den Bosch, F., Prins, H. H., & de Kroon, H. (2001).

Vegetation pattern formation in semi-arid grazing systems. *Ecology*, *82*(1), 50-61. https://doi.org/10.1890/0012-9658(2001)082[0050:VPFISA]2.0.CO;2

Kheiri, M., Deihimfard, R., Kambouzia, J., Moghaddam, S. M., Rahimi-Moghaddam, S., & Azadi, H. (2022). Impact of Heat Stress on Rainfed Wheat Growth and Yield Under Semi-arid, Semi-humid and Mediterranean Climates in Iran Condition. *International Journal of Plant Production*, *16*, 1-12. https://doi.org/10.1007/s42106-021-00179-9

Konapala, G., Mishra, A. K., Wada, Y., & Mann, M. E. (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature communications*, *11*(1), 3044. https://doi.org/10.1038/s41467-020-16757-w

Kopec, R. J. (1965). continentality around the Great Lakes. *Bulletin of the American Meteorological Society*, *46*(2), 54-57. https://www.jstor.org/stable/26247810

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift,* *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Liu, S., Huang, S., Xie, Y., Wang, H., Huang, Q., Leng, G., Li, P., & Wang, L. (2019). Spatial-temporal changes in vegetation cover in a typical semi-humid and semi-arid region in China: Changing patterns, causes and implications. *Ecological indicators*, *98*, 462-475. https://doi.org/10.1016/j.ecolind.2018.11.037

Lugo, A. E., Brown, S. L., Dodson, R., Smith, T. S., & Shugart, H. H. (1999). The Holdridge life zones of the conterminous United States in relation to ecosystem mapping. *Journal of biogeography*, *26*(5), 1025-1038. https://doi.org/10.1046/j.1365-2699.1999.00329.x

Lü, X. T., Yin, J. X., & Tang, J. W. (2010). Structure, tree species diversity and composition of tropical seasonal rainforests in Xishuangbanna, south-west China. *Journal of Tropical Forest Science*, *22*(3), 260-270. https://jtfs.frim.gov.my/jtfs/article/view/927

Malik, P., Bhardwaj, P., & Singh, O. (2020). Distribution of cold wave mortalities over India: 1978–2014. *International Journal of Disaster Risk Reduction*, *51*, 101841. https://doi.org/10.1016/j.ijdrr.2020.101841

Murphy, B. P., & Bowman, D. M. (2012). What controls the distribution of tropical forest and savanna?. *Ecology letters*, *15*(7), 748-758. https://doi.org/10.1111/j.1461-0248.2012.01771.x

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences*, *11*(5), 1633-1644. https://doi.org/10.5194/hess-11-1633-2007

Safarova, S., van Hoof, J., Law, L., Zander, K. K., & Garnett, S. T. (2022). Thermal comfort in a tropical savanna climate: The case of home occupants in Darwin, Australia. *Energy and Buildings*, *266*, 112074. https://doi.org/10.1016/j.enbuild.2022.112074

Sanderson, M. (1999). The classification of climates from Pythagoras to Koeppen. *Bulletin of the American Meteorological Society*, *80*(4), 669-674. https://doi.org/10.1175/1520-0477(1999)080%3C0669:TCOCFP%3E2.0.CO;2

Sano, E. E., Rosa, R., Brito, J. L., & Ferreira, L. G. (2010). Land cover mapping of the tropical savanna region in Brazil. *Environmental Monitoring and Assessment*, *1*(166), 113-124. https://doi.org/10.1007/s10661-009-0988-4

Shrestha, R. P., Chaweewan, N., & Arunyawat, S. (2017). Adaptation to climate change by rural ethnic communities of Northern Thailand. *Climate*, *5*(3), 57. https://doi.org/10.3390/cli5030057

Tan, L., Cai, Y., An, Z., Edwards, R. L., Cheng, H., Shen, C. C., & Zhang, H. (2011). Centennial-to decadal-scale monsoon precipitation variability in the semi-humid region, northern China during the last 1860 years: Records from stalagmites in Huangye Cave. *The Holocene*, *21*(2), 287-296. https://doi.org/10.1177/0959683610378880

Vera, C., Silvestri, G., Liebmann, B., & González, P. (2006). Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. *Geophysical research letters*, *33*(13). https://doi.org/10.1029/2006GL025759

Viereck, L. A., Van Cleve, K., & Dyrness, C. T. (1986). Forest ecosystem distribution in the taiga environment. *Forest ecosystems in the Alaskan taiga: a synthesis of structure and function*, (pp. 22-43). https://doi.org/10.1007/978-1-4612-4902-3_3

Vilček, J., Škvarenina, J., Vido, J., Nalevanková, P., Kandrík, R., & Škvareninová, J. (2016). Minimal change of thermal continentality in Slovakia within the period 1961–2013. *Earth System Dynamics*, *7*(3), 735-744. https://doi.org/10.5194/esd-7-735-2016

Wang, B. (2006). *The asian monsoon*. Springer Science & Business Media. https://doi.org/10.1007/3-540-37722-0

Wen, M., Yang, S., Kumar, A., & Zhang, P. (2009). An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. *Monthly weather review*, *137*(3), 1111-1131. https://doi.org/10.1175/2008MWR2638.1

Xu, P., Wang, L., & Ming, J. (2022). Central Asian precipitation extremes affected by an intraseasonal planetary wave pattern. *Journal of Climate*, *35*(8), 2603-2616. https://doi.org/10.1175/JCLI-D-21-0657.1

Yihui, D., & Chan, J. C. (2005). The East Asian summer monsoon: an overview. *Meteorology and Atmospheric Physics*, *89*(1-4), 117-142. https://doi.org/10.1007/s00703-005-0125-z

Yin, J., He, F., Xiong, Y. J., & Qiu, G. Y. (2017). Effects of land use/land cover and climate changes on surface runoff in a semi-humid and semi-arid transition zone in northwest China. *Hydrology and Earth System Sciences*, *21*(1), 183-196. https://doi.org/10.5194/hess-21-183-2017

Yiqi, C., Yuanjie, Z., Yubin, L., & Shugang, S. (2022). Changes in lengths of the four seasons in China and the relationship with changing climate during 1961–2020. *International Journal of Climatology*, 1-18. https://doi.org/10.1002/joc.7919

Zakh, V. A., Ryabogina, N. E., & Chlachula, J. (2010). Climate and environmental dynamics of the mid-to late Holocene settlement in the Tobol–Ishim forest-steppe region, West Siberia. *Quaternary International*, *220*(1-2), 95-101. https://doi.org/10.1016/j.quaint.2009.09.010

Zhang, K., Wang, Q., Chao, L., Ye, J., Li, Z., Yu, Z., Yang, T., & Ju, Q. (2019). Ground observation-based analysis of soil moisture spatiotemporal variability across a humid to semi-humid transitional zone in China. *Journal of Hydrology*, *574*, 903-914. https://doi.org/10.1016/j.jhydrol.2019.04.087

Zhou, X., Wang, F., Fan, J., & Ochieng, R. M. (2010). Performance of solar chimney power plant in Qinghai-Tibet Plateau. *Renewable and Sustainable energy reviews*, *14*(8), 2249-2255. https://doi.org/10.1016/j.rser.2010.04.017

Appendix—List of GaWC global cities by this climate classification

Table S1-Alpha level cities

City	Level	Geographic region	Climate type
London	Alpha ++	Northern Europe	C_1oaf
New York	Alpha ++	Northern America	C_1caf
Hong Kong	Alpha +	Eastern Asia	B_1oaw
Singapore	Alpha +	Southeastern Asia	A_1oaf
Shanghai	Alpha +	Eastern Asia	B_2caw
Beijing	Alpha +	Eastern Asia	C_1cbw
Dubai	Alpha +	Western Asia	A_2cds
Paris	Alpha +	Western Europe	C_1oaf
Tokyo	Alpha +	Eastern Asia	B_2caf
Sydney	Alpha	Australia and New Zealand	B_1oaf
Los Angeles	Alpha	Northern America	B_1tcs
Toronto	Alpha	Northern America	C_1caf
Mumbai	Alpha	Southern Asia	A_1oaw
Amsterdam	Alpha	Western Europe	C_1oaf
Milan	Alpha	Southern Europe	C_1caf
Frankfurt	Alpha	Western Europe	C_1taf
Mexico City	Alpha	Central America	B_1taw
Sao Paulo	Alpha	South America	B_1oaw
Chicago	Alpha	Northern America	C_1caf
Kuala Lumpur	Alpha	Southeastern Asia	A_1oaf
Madrid	Alpha	Southern Europe	C_1cbf

Moscow	Alpha	Eastern Europe	C_2caf
Jakarta	Alpha	Southeastern Asia	A_1oaw
Brussels	Alpha	Western Europe	C_1oaf
Warsaw	Alpha -	Eastern Europe	C_2taf
Seoul	Alpha -	Eastern Asia	C_1caw
Johannesburg	Alpha -	Southern Africa	B_2tbw
Zurich	Alpha -	Western Europe	C_1taf
Melbourne	Alpha -	Australia and New Zealand	B_2obf
Istanbul	Alpha -	Western Asia	B_2taf
Bangkok	Alpha -	Southeastern Asia	A_1obw
Stockholm	Alpha -	Northern Europe	C_2oaf
Vienna	Alpha -	Western Europe	C_1taf
Guangzhou	Alpha -	Eastern Asia	B_1taw
Dublin	Alpha -	Northern Europe	C_1oaf
Taipei	Alpha -	Eastern Asia	B_1oaf
Buenos Aires	Alpha -	South America	B_1oaf
San Francisco	Alpha -	Northern America	B_2oas
Luxembourg	Alpha -	Western Europe	C_1oaf
Montreal	Alpha -	Northern America	C_2caf
Munich	Alpha -	Western Europe	C_2taf
Delhi	Alpha -	Southern Asia	B_1ccw
Santiago	Alpha -	South America	B_2tbs
Boston	Alpha -	Northern America	C_1caf
Manila	Alpha -	Southeastern Asia	A_1oaw
Shenzhen	Alpha -	Eastern Asia	B_1taw
Riyadh	Alpha -	Western Asia	B_1cds
Lisbon	Alpha -	Southern Europe	B_1obs
Prague	Alpha -	Eastern Europe	C_2taf
Banglore	Alpha -	Southern Asia	A_2tbw

Table S2-Beta level cities

City	Level	Geographic region	Climate type
Washington DC	Beta +	Northern America	C_1caf
Dallas	Beta +	Northern America	B_2caf
Bogota	Beta +	South America	B_1oaf
Miami	Beta +	Northern America	A_2obf
Rome	Beta +	Southern Europe	B_2taf
Hamburg	Beta +	Western Europe	C_1oaf
Houston	Beta +	Northern America	B_1caf
Berlin	Beta +	Western Europe	C_1taf
Chengdu	Beta +	Eastern Asia	B_2caw
Dusseldorf	Beta +	Western Europe	C_1oaf
Tel Aviv	Beta +	Western Asia	B_1tcs
Barcelona	Beta +	Southern Europe	B_2tbf
Budapest	Beta +	Eastern Europe	C_1cbf
Doha	Beta +	Western Asia	B_1cds
Lima	Beta +	South America	B_1odf
Copenhagen	Beta +	Northern Europe	C_2oaf
Atlanta	Beta +	Northern America	B_2caf
Bucharest	Beta +	Eastern Europe	C_1cbf
Vancouver	Beta +	Northern America	C_1oas
Brisbane	Beta +	Australia and New Zealand	B_1obf
Cairo	Beta +	Northern Africa	B_1ods
Beirut	Beta +	Western Asia	B_1tas
Auckland	Beta +	Australia and New Zealand	B_1oaf
Ho Chi Minh City	Beta	Southeastern Asia	A_1oaw
Athens	Beta	Southern Europe	B_2ccs
Denver	Beta	Northern America	C_2cbf
Tianjin	Beta	Eastern Asia	C_1cbw
Abu Dhabi	Beta	Western Asia	A_2cds

Perth	Beta	Australia and New Zealand	B_1tbs
Casablanca	Beta	Northern Africa	B_1tcs
Kiev	Beta	Eastern Europe	C_2caf
Montevideo	Beta	South America	B_1oaf
Oslo	Beta	Northern Europe	C_2taf
Helsinki	Beta	Northern Europe	C_2oaf
Chennai	Beta	Southern Asia	A_1obf
Hanoi	Beta	Southeastern Asia	B_1taw
Nanjing	Beta	Eastern Asia	B_2caw
Philadelphia	Beta	Northern America	C_1caf
Cape Town	Beta	Southern Africa	B_1obs
Hangzhou	Beta	Eastern Asia	B_2caf
Nairobi	Beta	Eastern Africa	B_1tbf
Seattle	Beta	Northern America	C_1oas
Manama	Beta	Western Asia	B_1tds
Karachi	Beta	Southern Asia	A_2tdw
Rio De Janeiro	Beta	Southern America	A_2oaf
Chongqing	Beta	Eastern Asia	B_2caw
Panama City	Beta	Central America	(missing)
Wuhan	Beta -	Eastern Asia	B_2caw
Manchester	Beta -	Northern Europe	C_1oaf
Geneva	Beta -	Western Europe	C_1taf
Osaka	Beta -	Eastern Asia	B_2caf
Stuttgart	Beta -	Western Europe	C_1taf
Belgrade	Beta -	Southern Europe	C_1cbf
Calgary	Beta -	Northern America	C_2caw
Monterrey	Beta -	Central America	B_1cbf
Kuwait City	Beta -	Western Asia	B_1cds
Caracas	Beta -	South America	A_2oaf
Changsha	Beta -	Eastern Asia	B_2caf
Bratislava	Beta -	Eastern Europe	C_1taf

Sofia	Beta -	Eastern Europe	C_1caf
San Jose (Costa Rica)	Beta -	Central America	A_2oaf
Zagreb	Beta -	Southern Europe	C_1caf
Dhaka	Beta -	Southern Asia	A_2oaw
Xiamen	Beta -	Eastern Asia	B_1taw
Tampa	Beta -	Northern America	B_1tbw
Zhengzhou	Beta -	Eastern Asia	B_2cbw
Tunis	Beta -	Northern Africa	B_1tcs
Almaty	Beta -	Central Asia	C_2caf
Shenyang	Beta -	Eastern Asia	C_1caw
Lyon	Beta -	Western Europe	C_1taf
Minneapolis	Beta -	Northern America	C_2caf
Nicosia	Beta -	Western Asia	B_1ccs
San Diego	Beta -	Northern America	B_1ocs
Amman	Beta -	Western Asia	B_2ccs
Xi'an	Beta -	Eastern Asia	C_1cbw
Guatemala City	Beta -	Central America	B_1obw
Dalian	Beta -	Eastern Asia	C_1cbw
St Petersburg	Beta -	Eastern Europe	C_2taf
Lagos	Beta -	Western Asia	A_1oaw
Quito	Beta -	South America	B_2oaf
Jinan	Beta -	Eastern Asia	C_1cbw
San Salvador	Beta -	Central America	A_1oaw
Kampala	Beta -	Eastern Africa	A_2oaf
George Town	Beta -	Caribbean	A_1obf
Muscat	Beta -	Western Asia	A_2tds
Detroit	Beta -	Northern America	C_1caf
Edinburgh	Beta -	Northern Europe	C_2oaf
Jeddah	Beta -	Western Asia	A_1tds
Hyderabad	Beta -	Southern Asia	A_2tbw
Lahore	Beta -	Southern Asia	B_1ccw

Austin	Beta -	Northern America	B_1cbf

Table S3-Gamma level cities

City	Level	Geographic region	Climate type
San Jose (California)	Gamma +	Northern America	B_2oas
Kolkata	Gamma +	Southern Asia	A_2taw
Charlotte	Gamma +	Northern America	B_2caf
St Louis	Gamma +	Northern America	C_1caf
Pune	Gamma +	Southern Asia	A_2tbw
Antwerp	Gamma +	Western Europe	C_1oaf
Rotterdam	Gamma +	Western Europe	C_1oaf
Adelaide	Gamma +	Australia and New Zealand	B_1obf
Porto	Gamma +	Southern Europe	B_2oaf
Baku	Gamma +	Western Asia	B_2tcs
Guadalajara	Gamma +	Central America	B_1tbw
Ljubljana	Gamma +	Southern Europe	C_1taf
Qingdao	Gamma +	Eastern Asia	B_2cbw
Algiers	Gamma +	Northern Africa	B_1tbs
Suzhou	Gamma +	Eastern Asia	B_2caf
Belfast	Gamma +	Northern Europe	C_1oaf
Glasgow	Gamma +	Northern Europe	C_2oaf
Medellin	Gamma +	South America	B_1oaf
Cologne	Gamma +	Western Europe	C_1oaf
Phnom Penh	Gamma +	Southeastern Asia	A_1oaw
Islamabad	Gamma +	Southern Asia	B_2caf
Phoenix	Gamma +	Northern America	B_1cdf
Riga	Gamma +	Northern Europe	C_2taf
Tbilisi	Gamma +	Western Asia	C_1caf
Kunming	Gamma +	Eastern Asia	B_2taw
Ahmedabad	Gamma +	Southern Asia	A_2ccw

Dar Es Salaam	Gamma +	Eastern Africa	A_1obf
Hefei	Gamma +	Eastern Asia	B_2caw
Orlando	Gamma +	Northern America	B_1tbf
Baltimore	Gamma +	Northern America	C_1caf
Durban	Gamma	Southern Africa	B_1obf
Vilnuis	Gamma	Northern Europe	C_2taf
Gothenburg	Gamma	Northern Europe	C_2oaf
San Juan	Gamma	Caribbean	(missing)
Nantes	Gamma	Western Europe	C_1oaf
Ankara	Gamma	Western Asia	C_1cbf
Santo Domingo	Gamma	Caribbean	A_1obf
Wroclaw	Gamma	Eastern Europe	C_1taf
Ottawa	Gamma	Northern America	C_2caf
Dakar	Gamma	Western Africa	A_2odw
Malmo	Gamma	Northern Europe	C_2oaf
Bristol	Gamma	Northern Europe	C_1oaf
Tirana	Gamma	Southern Europe	B_2caf
Colombo	Gamma	Southern Asia	A_1oaf
Turin	Gamma	Southern Europe	C_1taf
Valencia (Spain)	Gamma	Southern Europe	B_1tcf
Guayaquil	Gamma	South America	A_1oaf
Taichung	Gamma	Eastern Asia	B_1oaw
Managua	Gamma	Central America	A_1obw
La Paz	Gamma	South America	E_1oaw
Nashville	Gamma	Northern America	B_2caf
Tegucigalpa	Gamma	Central America	A_2oaw
Haikou	Gamma	Eastern Asia	A_2oaw
Wellington	Gamma	Australia and New Zealand	B_2oaf
Port Louis	Gamma -	Eastern Africa	A_2obw
Accra	Gamma -	Western Africa	A_1obw
Asuncion	Gamma -	South America	B_1taf

Bilbao	Gamma -	Southern Europe	B_2oaf
Maputo	Gamma -	Eastern Africa	A_2obw
Douala	Gamma -	Middle Africa	A_1oaf
Nassau	Gamma -	Caribbean	A_1obf
Harare	Gamma -	Eastern Africa	B_1tbw
Poznan	Gamma -	Eastern Europe	C_2taf
Luanda	Gamma -	Middle Africa	A_1ocw
Cleveland	Gamma -	Northern America	C_1caf
Fuzhou	Gamma -	Eastern Asia	B_2caw
Nagoya	Gamma -	Eastern Asia	B_2caf
Kansas City	Gamma -	Northern America	C_1caf
Katowice	Gamma -	Eastern Europe	C_2taf
Malaga	Gamma -	Southern Europe	B_1obs
Queretaro	Gamma -	Central America	B_1tbw
Harbin	Gamma -	Eastern Asia	C_2caw
Milwaukee	Gamma -	Northern America	C_1caf
Penang (George Town)	Gamma -	Southeastern Asia	A_1oaf
Salt Lake City	Gamma -	Northern America	C_1cbf
Columbus	Gamma -	Northern America	C_1caf
Kaohsiung	Gamma -	Eastern Asia	A_2oaw
Limassol	Gamma -	Western Asia	B_1tcs
Sacramento	Gamma -	Northern America	B_2cbs
Belo Horizonte	Gamma -	South America	B_1oaw
Lausanne	Gamma -	Western Europe	C_1oaf
Taiyuan	Gamma -	Eastern Asia	C_1cbw
Edmonton	Gamma -	Northern America	C_2caw

Table S4-Highly sufficient cities

City	Geographic region	Climate type
Birmingham (UK)	Northern Europe	C_1oaf

Krakow	Eastern Europe	C_2taf
Abuja	Western Africa	A_1tbw
Tijuana	Central America	B_1ocs
Port of Spain	Caribbean	A_1obf
Abidjan	Western Africa	A_1oaf
Curitiba	South America	B_1oaf
Ningbo	Eastern Asia	B_2caf
Hartford	Northern America	C_1caf
Yangon	Southeastern Asia	A_1oaw
Seville	Southern Europe	B_1cbs
Puebla	Central America	B_1obw
Raleigh	Northern America	B_2caf
Indianapolis	Northern America	C_1caf
Brasilia	South America	A_2oaw
Johor Bahru	Southeastern Asia	A_1oaf
The Hague	Western Europe	C_1oaf
Yerevan	Western Asia	C_1cbf
Strasbourg	Western Europe	C_1taf
Macao	Eastern Asia	B_1oaw
San Antonio	Northern America	B_1cbf
Leeds	Northern Europe	C_1oaf
Lusaka	Eastern Africa	B_1tbw
Ulan Bator	Eastern Asia	Dcbw
Dammam	Western Asia	B_1cds
Cincinnati	Northern America	C_1caf
Porto Alegre	South America	B_1oaf

Table S5-Sufficient cities

City	Geographic region	Climate type
Tallinn	Northern Europe	C_2taf
Aberdeen	Northern Europe	C_2oaf

Astana	Central Asia	C_2cbf
Bologna	Southern Europe	C_1caf
Marseille	Western Europe	B_2obf
Cebu	Southeastern Asia	A_1oaf
Leipzig	Western Europe	C_1taf
Utrecht	Western Europe	C_1oaf
Merida	Central America	A_1obw
Newcastle (UK)	Northern Europe	C_1oaf
Ciudad Juarez	Central America	B_2cdf
Surabaya	Southeastern Asia	A_1oaw
Nurnberg	Western Europe	C_1taf
Cali	South America	A_2oaf
Florence	Southern Europe	C_1taf
Naples	Southern Europe	B_2oas
Canberra	Australia and New Zealand	C_1tbf
Pittsburgh	Northern America	C_1caf
Izmir	Western Asia	B_2cas
Sarajevo	Southern Europe	C_2caf
Portland (Oregon)	Northern America	C_1tas
Las Vegas	Northern America	B_2cds
Liverpool	Northern Europe	C_1oaf
Hannover	Western Europe	C_1oaf
Urumqi	Eastern Asia	C_2cbf
Aguascalientes	Central America	B_1ccw
Minsk	Eastern Europe	C_2taf
Christchurch	Australia and New Zealand	C_1obf
Jacksonville	Northern America	B_1taf
Richmond	Northern America	C_1caf
Skopje	Southern Europe	C_1cbf
Campinas	South America	B_1oaw
Tashkent	Central Asia	C_1cbf
Toulouse	Western Europe	C_1taf

Alexandria	Northern Africa	B_1tds
Zhuhai	Eastern Asia	B_1taw
San Luis Potosi	Central America	B_1tcw
Chisinau	Eastern Europe	C_1cbf
Guiyang	Eastern Asia	B_2caf
Cordoba	South America	B_2tbw
Leon	Central America	B_1tbw
Kochi	Southern Asia	A_1oaw
Valparaiso	South America	B_1obs
Oklahoma City	Northern America	B_2cbf
Des Moines	Northern America	C_1caf
Nanning	Eastern Asia	B_1taw
Changchun	Eastern Asia	C_2caw
Nanchang	Eastern Asia	B_2caf
Bishkek	Central Asia	C_1caf
San Pedro Sula	Central America	A_2oaf
Southampton	Northern Europe	C_1oaf
Montpellier	Western Europe	B_2taf
Tulsa	Northern America	B_2caf
Podgorica	Southern Europe	B_2caf
Valencia (Venezuela)	South America	A_1oaf
Lodz	Eastern Europe	C_2taf
Buffalo	Northern America	C_1caf
Graz	Western Europe	C_2caf
Genoa	Southern Europe	C_1taf
Louisville	Northern America	C_1caf
Winnipeg	Northern America	C_2caw
Rochester	Northern America	C_1caf
Windhoek	Southern Africa	B_1ccw
Vientiane	Southeastern Asia	A_2oaw
Fukuoka	Eastern Asia	B_2caf
Halifax	Northern America	C_2taf

Linz	Western Europe	C_1taf
Shijiazhuang	Eastern Asia	C_1cbw
Hamilton	Northern America	B_1oaf
Gaborone	Southern Africa	B_1ccw
Port Elizabeth	Southern Africa	B_1obf
Birmingham (Alabama)	Northern America	B_2caf
Nottingham	Northern Europe	C_1oaf
Pretoria	Southern Africa	B_1tbw
Recife	South America	A_1obf
Wuxi	Eastern Asia	B_2caf
Kigali	Eastern Africa	A_2tbf
Santa Cruz (Bolivia)	South America	A_2oaf
Mexicali	Central America	B_1cdf
Lille	Western Europe	C_1oaf
Bordeaux	Western Europe	B_2oaf
Bursa	Western Asia	C_1caf
Dresden	Western Europe	C_2taf
Libreville	Middle Africa	A_1oaf
Port Harcourt	Western Africa	A_1oaf
Nice	Western Europe	C_1oaf
Hsinchu City	Eastern Asia	B_1oaw
New Orleans	Northern America	B_1taf
Arhus	Northern Europe	C_1oaf
Quebec	Northern America	C_2caf
Liege	Western Europe	C_1oaf
Bergen	Northern Europe	C_2oaf
Basel	Western Europe	C_1taf
Labuan	Southeastern Asia	A_1oaf
Jerusalem	Western Asia	B_2ccs
Hohhot	Eastern Asia	C_2cbw
Bandar Seri Begawan	Southeastern Asia	A_1oaf
Lanzhou	Eastern Asia	C_1cbw

Bremen	Western Europe	C_1oaf
Saskatoon	Northern America	C_2cbw
Kingston (Jamaica)	Caribbean	A_2obf
Rosario	South America	B_1taf
Grenoble	Western Europe	C_1taf
Haifa	Western Asia	B_1obs
Baghdad	Western Asia	B_1cds
Barranquilla	South America	A_1oaf
Cardiff	Northern Europe	C_1oaf
Mannheim	Western Europe	C_1taf
Chihuahua	Central America	B_1ccw
Memphis	Northern America	B_2caf
Palo Alto	Northern America	B_2oas
Omaha	Northern America	C_1caf
Bern	Western Europe	C_2taf
Tainan	Eastern Asia	A_2oaw
Honolulu	Northern America	A_2ocs
Dushanbe	Central Asia	C_1caf
Kabul	Southern Asia	C_1cbf
Sheffield	Northern Europe	C_1oaf
Kinshasa	Middle Africa	A_1obw
Harrisburg	Northern America	C_1caf
Salvador	South America	A_1oaf
Kazan	Eastern Europe	C_2caf
Reykjavik	Northern Europe	Doaf
Dortmund	Western Europe	C_1oaf
Goiania	South America	A_2oaw
Port Moresby	Melanesia	A_1oaw
Hobart	Australia and New Zealand	C_1oaf
Sapporo	Eastern Asia	C_2caf
Kyoto	Eastern Asia	B_2caf
Brazzaville	Middle Africa	A_1obw

Novosibirsk	Eastern Europe	C_2caf
Blantyre	Eastern Africa	B_1taw
Essen	Western Europe	C_1oaf
Kobe	Eastern Asia	B_2caf
Malacca	Southeastern Asia	A_1oaf
Lome	Western Africa	A_1obf
Palermo	Southern Europe	B_2obf
Busan	Eastern Asia	B_2caw
Yokohama	Eastern Asia	B_2taf
Sendai	Eastern Asia	C_1caf
Trieste	Southern Europe	C_1taf
Sanaa	Western Asia	B_1tcw
Suva	Melanesia	A_1oaf