Assessment of macroclimate and microclimate effects on outdoor thermal comfort via artificial neural network models

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Abstract

Outdoor thermal comfort is significantly affected by climate, including macroclimate, local climate, and microclimate. However, the combined impacts of macroclimate and microclimate factors are less understood in previous thermal comfort studies. This paper employed 43 previously published studies to comprehensively explore the impacts of macro- and micro- climatic factors on the outdoor thermal comfort. The relative importance of these influencing factors was assessed via five verified artificial neural network (ANN) models. For studies employing subjective thermal indices which collected participants' thermal perceptions, the neutral temperature expressed by physiologically equivalent temperature (PET) was found to be significantly correlated with macroclimate factors, especially the latitude and season. In studies employing only objective thermal indices, it was found that macroclimate factors, such as the latitude, distance from the sea, and altitude, have similar contribution to the outdoor thermal comfort as microclimate factors, such as height to width ratio (H/W) and sky view factor. Results resonated with previous findings that outdoor comfort can be improved by changing urban geometry, vegetation, surfaces, and waterbodies. Future design and planning works should consider both macroclimate and microclimate factors and carefully design urban geometry and morphology to improve outdoor thermal comfort for regions with disadvantageous macroclimates.

Keywords: Outdoor thermal comfort; physiologically equivalent temperature (PET); macroclimate and microclimate factors; artificial neural network (ANN); relative importance analysis

1. Introduction

Climate can be defined as ‘the mean and variability of meteorological variables over a time spanning from months to millions of years (Guo 2021). Depending on the horizontal scale and time period, climate can be categorized into the macroclimate, local climate (mesoclimate), and microclimate (Mislan and Helmuth 2008), which have horizontal scales of above 100 km, 1 km to 100 km, and within 1 km, respectively (Castelli et al. 2019). The climate is commonly evaluated using meteorological parameters of climate regions, such as the annual air temperature, wind, and humidity. For example, the most widely used Koppen–Geiger climate classification system (Arnfield et al. 2016) divides climates into five main groups, with a total of 25 sub-groups (Fig 1).

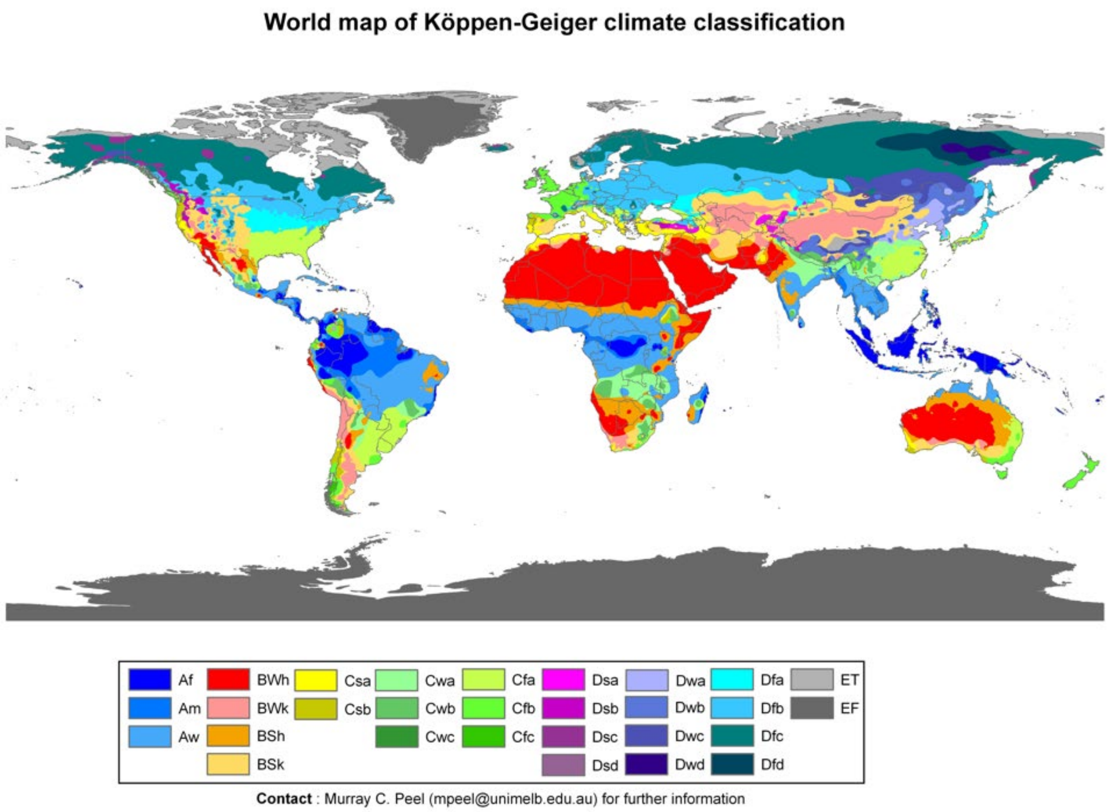

Fig. 1. Global map using the Koppen Climate Classification (Means 2019a).

The climate is closely related to thermal comfort metrics. Most areas suffer from climatic issues (Arnfield et al. 2016), leading to poor outdoor thermal comfort (OTC), such as cold discomfort (Du et al. 2020) or hot discomfort (Lam and Lau 2018). In outdoor open spaces, pedestrians are directly exposed to solar radiation, wind, and precipitation; few facilities are available to mitigate this heat/cold stress (Höppe 2002). There is no doubt that macroclimate directly affects OTC.

Apart from that, mesoclimate and microclimate may also be influential, since they ameliorate or exacerbate the influences of the macroclimate on OTC. For example, an urban climate (mesoclimate) suffering from urban heat island (UHI) may be warmer than rural climates in the same geographical region. Microclimates are affected by many factors, including the local vegetation (Chapman 2018), geometry (Blankenstein and Kuttler 2004), and water surfaces (Amani-Beni et al. 2018). Urban planners often utilise these factors to adjust the microclimates and improve OTC.

2. Literature review

2.1 Types of outdoor thermal comfort studies

Depending on the thermal indices adopted, research on outdoor thermal comfort (OTC) can be divided into two types – studies employing objective indices only (SEO) (Ahmadi Venhari et al. 2019) and studies employing both objective and subjective thermal indices (SEOS) (Cheng et al. 2019; Manavvi and Rajasekar 2020). Objective indices are parameters of the outdoor thermal environment (Morakinyo et al. 2017), while subjective indices are those that express people's perceptions of the thermal environment (Johansson et al. 2018). Commonly adopted objective indices in OTC studies include the air temperature, land surface temperature (LST), mean radiant temperature (MRT, Tan et al. 2013), standard effective temperature (SET, Pickup and de Dear 2000), universal thermal climate index (UTCI, Jendritzky et al. 2012), and physiologically equivalent temperature (PET, Höppe 1999). Because their calculation processes differ, each index has specific applicability—for example, MRT can distinguish sites better owing to varying solar radiation intensities. Among these indices, PET involves the most weather parameters (air temperature, radiation, humidity, etc.), and is the most frequently used OTC index (Binarti et al. 2020).

2.2 Thermal perception in different seasons (indicated by neutral temperature in SEOS)

SEOS usually collect both objective data (outdoor environmental parameters) and subjective data (thermal sensation, thermal comfort, thermal preferences, etc.), and then statistically associate subjective thermal responses with objective parameters (Xi et al. 2012). Commonly used subjective indices include the neutral temperature (NTs) (Hadianpour et al. 2018), preferred temperature (Johansson et al. 2018), and thermal comfort range (acceptable temperature) (Chen et al. 2020). Every region had its own neutral temperature. For example, Changsha and Singapore had a neutral temperature of 27.9 °C and 28.1 °C, respectively (Yang et al. 2013). The neutral temperatures indicated by PET (NPET) during summer for Harbin, Tianjin, and Singapore were 20 °C, 24 °C, and 28.1 °C, respectively (Liu et al. 2021). Comfort temperatures in different seasons can be very different. NPET also varied for seasons. The neutral temperature expressed by PET in Guangzhou is 15.6 °C in winter and 25.3 °C in summer (Li et al. 2016).

2.3 Microclimate factors affecting thermal environment (SEO)

2.3.1 Urban geometry: sky view factor and height to width ratio

Urban geometry is a complex concept that is difficult to define accurately. Urban geometry is usually evaluated by the degree of space openness in OTC studies. On the one hand, compact urban spaces create more shades, which might be more conducive to achieve a comfortable outdoor environment in warmer climates; on the other hand, dense urban morphology blocks solar radiation and reduces wind speed. The two processes have opposing effects. Therefore, studies on geometry need to consider certain additional factors, such as daily periods and land use (Zhang et al. 2019b). Sky view Factor (SVF) and height to width ratio (H/W) are the most frequently used indicators to evaluate space openness. The SVF is a dimensionless number ranging from zero to unity, representing the amount of unobstructed sky seen from a given point (Oke 1988). The higher the SVF, the less obstruction from buildings and/or trees, which means higher degree of space openness. The H/W refers to the ratio between the height of buildings and the width of the street (Lai et al. 2019) which indicates the openness of an urban canyon. Lower H/W values indicates higher level of space openness. There are also other parameters to evaluate space openness. In built-up areas, building density (BD) (Yin et al. 2018), building coverage ratios

(Bimkom 2018), and floor area ratios (FARs) (Seattles Land Use Code 2011) have been used; in natural areas, the height and density of plants (Wong et al. 2011), green spaces (Bowler et al. 2010), the canopy covering of parks (Feyisa et al. 2014), and the tree cover ratio (Lin et al. 2017) have been investigated.

Effects of urban geometry on outdoor thermal environment are mediated by many factors, including but not limited to season, weather, and time of the day. Previous studies reveal that compact urban spaces are thermally comfortable in summertime but are disadvantageous during winter (Lai et al. 2019). Considerable temperature differences were simulated and measured for SVF variations. Temperature variations of 5.8 °C in Beijing (Yan and Dong 2015), 1 °C in Toronto (Chen and Ng 2012), 3.9 °C in Hong Kong (Cheung and Jim 2018b), and 3 °C in Chennai (Horrison and Amirtham 2016) were found for locations with different SVF values. These studies found that temperatures were positively correlated with SVF.

Studies on H/W usually measure the outdoor thermal comfort index (e.g., PET) fluctuations in locations with various H/W values and different orientations (Andreou 2013). It is well known that PET value fluctuates with time (Ali-Toudert and Mayer 2006; Andreou 2013; Johansson 2006). Specifically, PET can change sharply in a short period of time for locations with different H/W values. For instance, the PET increased from 25°C to 37°C at 14:00 for a site with an H/W of 3.5, and from 22°C to 34°C at 13:00 for an H/W of 1.5 (Lobaccaro and Acero 2015). Significant increases and decreases in the daytime PET are results of the emergence and disappearance of the sun. Owing to the irregularity in the magnitude and time taken for changes, the outdoor thermal environment and H/W rarely exhibited any linear correlation. Therefore, most studies present their results using visuals instead of statistical data analysis (Andreou 2013; Chatzidimitriou and Yannas 2017; Johansson 2006).

2.3.2 Vegetation

Vegetation is known to have a cooling effect on the surrounding environment. There are three types of vegetation in the urban environment: roof vegetation, façade vegetation, and ground vegetation. Ground vegetation is most common in urban environment, and there are three sub types—trees, shrubs, and grass. Trees have been frequently studied in OTC research owing to their significant microclimatic adjustment effects (Fig 2). It has been proven that trees have more thermal influence than other types of vegetation (Morakinyo et al. 2020), i.e., grass and shrubs (Zheng et al. 2016). Previous studies have confirmed the cooling effect of trees. The cooling intensities vary from tree characteristics, including the crown diameter (Zhang et al. 2020), shape (Rahman et al. 2020), leaf area index (LAI) (Moser et al. 2015), and species (Moser-Reischl et al. 2019). These parameters are all related to the thermal environment under tree canopies. For example, MRT has a negative linear relationship with LAI (Guo et al. 2020).

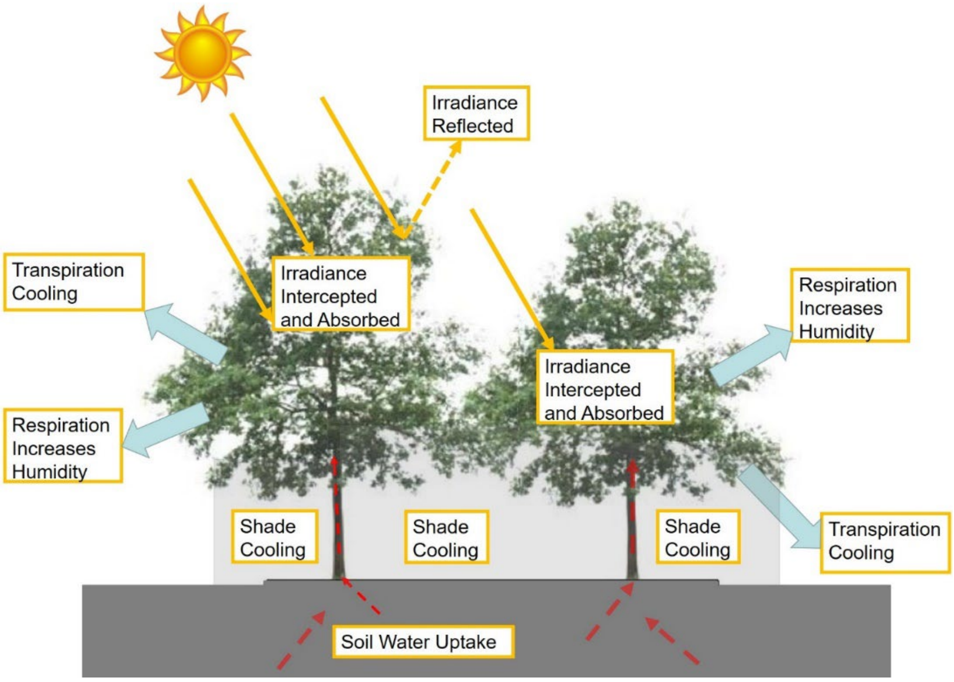

Fig. 2. Principles of tree cooling (Zhang et al. 2019b).

2.3.3 Reflective surface: Albedo

Light colours and reflective surfaces were found to be effective for cooling owing to their low efficiency of heat absorption (Nasa 2005). They are mostly used in roofs and pavement (Taleghani 2018b). White roofs have thermal advantages for both indoor and outdoor spaces, which has been demonstrated in Almeria (Campra et al. 2008), Los Angles (Rosenfeld et al. 1995), and Athens (Doulos et al. 2004). Further, a 0.1 increase in ground albedo could contribute to an air temperature reduction of nearly 0.6 °C in Los Angles (Rosenfeld et al. 1995) and 0.3 °C in Portland (Taleghani et al. 2014), respectively. In addition, the proper design of land cover can significantly mitigate thermal stresses. Its climatic influence is also reflected in the thermal responses. For instance, Tempe's (33.7°N) NPET approached 28.6 °C, which is higher than most other cities at a similar latitude (e.g., Chengdu, 30.6°N, has a NPET of 24.4 °C). This phenomenon may probably result from the land albedo—Tempe's climatic classification is desert. Nevertheless, reflective surfaces did not show consistent effects on OTC; they were not conducive to outdoor cooling in some studies (Erell et al. 2014; Lai et al. 2019).

2.4 Macroclimate factors affecting thermal environment (SEO)

2.4.1 Distance from the sea

Water is a natural coolant owing to its high specific heat capacity (Chatzidimitriou and Yannas 2015). Regions closer to water bodies are cooler because the breeze (Johansson and Emmanuel 2006) and the evaporation of water absorbs heat (Oke 2002). However, adjacency to water may increase the relative humidity in the air, which is disadvantageous to thermal comfort in hot weather (Lai et al. 2019). Despite this, adjacency to waterbodies has more benefit in thermal comfort. The sea is a large natural waterbody that significantly changes the regional macroclimate. It absorbs a large amount of heat radiation, cooling down its surroundings. Previous studies have found that PET is negatively linearly correlated with DFS, and increasing the DFS from 0 to 10 km could lead to a nearly 1 °C increase in air temperature (Zhang et al. 2019a). Nevertheless, this linear correlation existed only in coastal areas (less than 100 km to the sea) (Park and Chae 2018). Further, the effect of DFS on thermal environment was more significant during hot periods rather than cool or neutral periods (Zhang et al. 2019b).

Admittedly, cooling effects of waterbodies were still controversial. Their effects varied for seasons (Ampatzidis and Kershaw 2020; Manteghi et al. 2015), surrounding environments (Gunawardena et al. 2017), time of the day (Jacobs et al. 2020), and so on.

2.4.2 Seasons

Owing to the revolution of the earth, most regions on the earth experience considerable temperature fluctuations in a year, causing seasonal climate variations. OTC studies often focus on hot summers (Sharmin et al. 2019; Smith and Henríquez 2019; Taleghani 2018a) and cold winters (Chen et al. 2020;

Du et al. 2020; Xu et al. 2018), as they often induce the highest level of thermal discomfort. Comfort temperature difference for seasons were expressed in Section 2.2.

2.5 Factors less examined by previous studies

2.5.1 Latitude

The latitude is one of the most important macroclimate factors. Its effect is manifested through differences in the sunlight angles (Policansky 2019). In general, latitudes divide the whole world into tropical (low latitudes), temperate (middle latitudes), and extreme cold zones (high latitudes). People inhabiting in high-latitude and low-latitude zones may suffer from cold and heat stresses respectively.

The latitude affects individuals' thermal perceptions in outdoor spaces. Summer NPET for Hong Kong (22.0 °N) (Ng and Cheng 2012), Dhaka (23.4 °N) (Sharmin et al. 2019), and Urmia (37.9 °N) (Gachkar et al. 2021) were 28.1 °C, 27.7 °C, and 23.0 °C, respectively. PET indicating objective environment also varied from different latitudes. For example, at sites with a LAI value of around 3, PET values were found to be 31.4 °C in Campinas (22. 7 °N) (de Abreu-Harbich et al. 2015), 33.3 °C in Federal (7.25 °N) (Morakinyo et al. 2016), 36.8 °C in Hong Kong (22.5 °N) (Morakinyo et al. 2017), and 34.5 °C in Sao Paulo (23.5 °S) Duarte et al. (2015) at 12 p.m. during summer in different cities.

The effect of latitude may not be easily tested, since it is often confounded with local climate zones, geographical and meteorological factors (Cheung and Jim 2017; Potchter et al. 2018).

2.5.2 Altitude

The altitude is another macroclimate factor. Regions with higher altitudes are usually cooler owing to the lower air density. For instance, despite having similar latitude, Tibet (4000 m altitude; annual temperature range: 3℃–17℃) is much cooler than Sichuan (500 m altitude; annual temperature range: 14℃–22℃) (Net 2021). Altitude has seldom been studied in thermal comfort research probably due to relatively small population size in high-altitude regions and fewer urgent thermal comfort issues (He et al. 2015).

2.6 Research gap and questions

Sections 2.3 and 2.4 have reviewed previous studies regarding impacts of macroclimate and microclimate factors on outdoor thermal comfort/environment. Main findings are reported in Table 1.

Table 1. Effects of macroclimate and microclimate factors on outdoor thermal comfort/environment.

Type	Factors	Effects on thermal comfort /environment	Example reference
Macroclimate	Latitude	Locations with lower absolute latitudes are generally warmer	Cheung and Jim (2018a)
	DFS	Locations closer to the sea is generally cooler but still with debates	Johansson and Emmanuel (2006)
	Season	Most regions are hot in summer and cold in winter	Yang et al. (2013)
	Altitude	High altitude areas are generally colder	Zheng et al. (2021)
Microclimate	H/W	High H/W sites generally have lower temperatures	Andreou (2013)
	SVF	Low SVF sites generally have lower temperatures	Morakinyo et al. (2017)
	Vegetation	Sites with vegetation are generally cooler	Morakinyo and Lam (2016)
	Albedo	Light colour might be cooling effective	Campra et al. (2008)

Previous studies have primarily focused on the impact of the microclimate on the outdoor thermal comfort by examining the effects of one or more microclimate factors in one specific city or region. The effects of macroclimate factors, however, have rarely been studied in that researchers must include geographically dispersed locations in their database to test the effects of latitude, altitude, distance from the sea and alike on outdoor thermal environment. Often case, this was not possible due to limitations of individual research scope, time constraints and labour costs. Without enough studies on macroclimate impacts, it was also impossible to compare the contributions of microclimate factors with those of macroclimate factors. In fact, there is a large volume of outdoor comfort studies that are carried out in distinct cities, countries, climate regions, and topographic conditions. Extracting measurement data from these published studies provides a viable and economic way of investigating macroclimate impacts on thermal comfort, as most of these variable values, such as latitude, altitude, and distance from the sea of the study sites can be determined post hoc.

This study aims to comprehensively explore the impacts of macroclimate and microclimate factors on the outdoor thermal comfort, and also assess their relative importance through artificial neural network (ANN) models. Specifically, it aims to answer the following research questions:

- Examining how macroclimate factors (latitude, season, distance from the sea, and altitude) and microclimate factors (LAI, H/W, SVF, and albedo) affect the outdoor thermal comfort;
- Testing the relative importance of these factors.

3. Methodology

To establish systematic effects of macroclimate and microclimate factors on outdoor thermal /comfort, we conducted a thorough search of the related scientific literature based on the following methods and criteria.

3.1 Literature search

The Google scholar online database provided literature resources from various publishers (e.g., Elsevier, Springer, Tylor, and Sage) in the recent three decades. Studies on outdoor thermal comfort in various climate zones were searched using the following keywords: outdoor thermal environment; outdoor thermal comfort improvement; neutral temperature; thermal preference; urban geometry; heat stress mitigation; vegetation; trees; H/W; SVF; and urban heat island. Each search contained two or three keywords; 'thermal comfort' was included in every search. Apart from the article search via above key words, we also conducted a follow-up round of searching for relevant studies by examining the reference lists of the studies collected via keyword search. The initial search resulted in 60 papers.

3.2 Inclusion and exclusion criteria

OTC studies that utilized either objective or subjective indices were included in this study. Among the 60 papers with objective indices, 43 employed PET to describe the outdoor thermal environment or comfort. All papers could be divided into two types, SEO and SEOS. Each type took up nearly half of all. For the convenience of analysis and modelling, it was determined that studies with the PET index were to be retained in the dataset, whereas studies with other indices (MRT, SET, and UTCI) were excluded. The whole process is illustrated in Fig. 3.

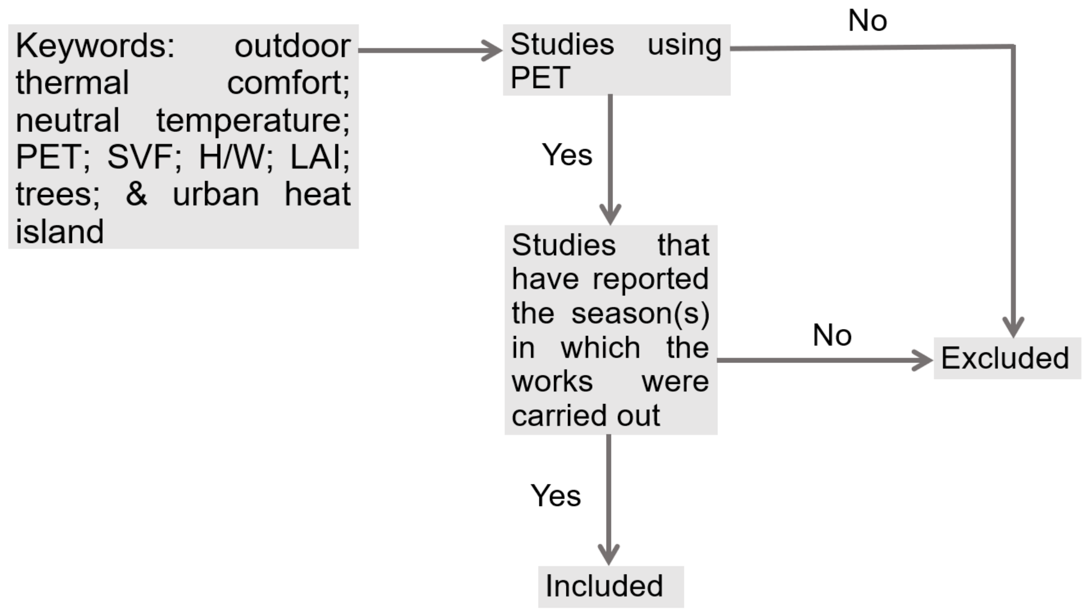

Fig. 3. The process of data inclusion and exclusion.

Studies using line charts clearly express the original data in certain contexts, which is conducive to accurate data readings. Studies using other visualization formats, such as Boxplots, are difficult to read and somewhat obscure the original data. Therefore, such studies were excluded from this research.

Studies on vegetation could include trees, ground vegetation cover, and green roofs. To facilitate simple modelling, only studies with trees were included in this research.

After accounting for these exclusion criteria, the final dataset included 43 studies—22 studies that employed objective thermal indices only (Table 2) and 21 studies that employed both objective and subjective thermal indices (Table 3).

Table 2. Data for studies employing only objective thermal indices in the current analysis.

Study type	Primary variable	Other variables				City (Country, climate)	Resource
		Method	Orientation	Season	Timespan in a day		
1	H/W	Simulation	N-S; E-W;	Summer	9:00-20:00	Tinos (Greece, Csa)	Andreou (2013)

1	H/W	Simulation	E-W; NE-SW; NW-SE	Summer		Thessaloniki (Greece, Cfa)	Chatzidimitriou and Yannas (2017)
1	H/W	Field measurement		Summer	Full day	Fez (Morocco, Csa)	Johansson (2006)
1	H/W	Simulation	NE-SW; S-N; NW-SE	Summer	6:00-21:00 (3 hrs interval)	Ghardaïa (Algeria, BWh)	Ali-Toudert and Mayer (2006)
1	H/W	SimulAtion	S-N;		Full day	Colombo (Sri Lanka, Af)	Emmanuel et al. (2007)
1	H/W	Simulation	S-N;			Singapore (Af)	Yang et al. (2015)
1	H/W	Simulation	S-N;	Summer	6:00-23:00	Bilbao (Spain, Cfb)	Lobaccaro and Acero (2015)
3	Tree species (coded into LAI)	Field measurement		Summer and winter	6:00-18:00	Campinas (Brazil, Cfa)	de Abreu-Harbich et al. (2015)
3	Tree shading towards building (coded into LAI)	Simulation		Summer	0:00-22:00	Akure (Nigeria, Aw)	Morakinyo et al. (2016)
2 & 3	Tree species/LAI/SVF	Simulation		Summer	Full day	Hong Kong (China, Cwa)	Morakinyo et al. (2017)

3	LAI	Simulation	Summer	7:00-21:00	Hong Kong (China, Cwa)	Morakinyo and Lam (2016)
3	Tree/Shelter/Control (H/W)	Field measurement	Summer	Full day	Hong Kong (China, Cwa)	Cheung and Jim (2018b)
2 & 3	Street, park and open	Simulation	Summer	0:00-20:00	Sao Paulo (Brazil, Cfa)	Duarte et al. (2015)
2 & 3	Canopy and open space	Simulation		9:00-18:00	Melbourne (Australia, Cfb)	Jamei and Rajagopalan (2017)
2 & 3	Canopy and open	Simulation	Summer	Full day	Oberhausen (Germany, Cfb)	Müller et al. (2013)
2 & 3	Vegetation cover/SVF	Field measurement	Summer	Full day	Athens (Greece, Cfa)	Charalampopoulos et al. (2012)
2 & 3	Roads with various trees	Field measurement	Early summer	10:00-19:00	Shanghai (China, Cfa)	Elsadek et al. (2019)
2 & 3	SVF etc.	Field measurement	Summer		Beijing (China, Dwa)	He et al. (2015)
2 & 3	Tree cover/SVF	Field measurement	Summer and Winter		Tel Aviv (Israel, Csa)	Cohen et al. (2012)

1 & 2	SVF	Simulation				Melaka (Malaysia, Af)	Manteghi et al. (2019)
1 & 2	SVF	Simulation		Summer	Full day	Delft (Netherland, Cfb)	Taleghani et al. (2015)

Study Type 1: H/W as the key variable; 2: SVF as the key variable; 3: LAI as the key variable.

Table 3. Data for studies employing both subjective and objective thermal indices in the current analysis.

City (area, climate)	Studied seasons	Method	Sample size (Questionnaire)	Resources
Changsha (China, Cfa) & Singapore (Af)	Winter & summer	Random field questionnaire	4,072	Yang et al. (2013)
Dar es Salaam (Tanzania, Aw)	Winter & summer	Random field questionnaire	606	Ndetto and Matzarakis (2017)
Belo Horizonte (Brazil, Aw)	Winter & summer	Random field questionnaire	1,693	Hirashima et al. (2016)
Campo Grande (Aw)	Winter & summer	Random field questionnaire	529	Lucchese and Andreasi (2017)
Hong Kong (China, Cwa)	Summer	Random field questionnaire	2,702	Ng and Cheng (2012)
Shenzhen (China, Cfa)	Summer	Random field questionnaire	1,870	Liu et al. (2018)
Dhaka (Bangladesh, Aw)	Summer	Random field questionnaire	1,286	Sharmin et al. (2019)
Sun Moon Lake (Taiwan, Cwb)	Summer	Random field questionnaire	1,644	Lin and Matzarakis (2008)

Guangzhou (China, Cfa)	Three seasons	Random field questionnaire	1,005	Li et al. (2016)
Taichaung (Taiwan, Cfa)	Winter & summer	Random field questionnaire	505	Lin (2009)
Shanghai (China, Cfa)	Winter	Random field questionnaire	596	Chen et al. (2015)
Chengdu (China, Cfa)	Summer	Random field questionnaire	255	Zeng and Dong (2015)
Ahvaz (Iran, Bsh)	Summer	Random field questionnaire	257	Nasrollahi et al. (2021)
Tempe (the US, Bwh)	Summer	Random field questionnaire	1,284	Middel et al. (2016)
Xi'an (China, BSk & Cwa)	Winter	Repeated field questionnaire	37	Xu et al. (2018)
Tehran (Bsk)	Winter & summer	Random field questionnaire	1,200	Hadianpour et al. (2018)
Urmia (Bsk)	Winter & summer	Random field questionnaire	1,332	Gachkar et al. (2021)
Melbourne (Australia, Cfb)	Winter & summer	Random field questionnaire	2,123	Kenawy and Elkadi (2018)
Harbin (China, Dwa)	All seasons	Long-term repeated questionnaire via smart phone	31	Chen et al. (2018)
Harbin (China, Dwa)	Winter & summer	Random field questionnaire	1,632	Yin et al. (2021)
Umeå (Sweden, Dfc)	Summer	Random field questionnaire	525	Yang et al. (2017)

3.3 Data analysis

3.3.1 Dependent and independent variables in this study

In statistical modelling, the dependent variables were selected to be thermal indices that represent either objective outdoor thermal environment or the subjective perception of the outdoor environment, depending on the purpose of the individual studies and availability of the data.

In studies with only objective thermal indices, PET was selected as the dependent variable. The independent variables include both macroclimate factors (latitude, distance from the sea, altitude, seasons, and albedo) and microclimate factors (SVF, H/W, and LAI). Most studies provided exact LAI values of the investigated sites. The absolute values of the latitude were used in the model; the hemisphere was not distinguished. For tree studies that did not report the LAI, it can be evaluated according to the species, crown size, leaf density, etc. For example, data from de Abreu-Harbich et al. (2015) involved various tree species; LAI values ranged from 0.1 to 3.5 depending on physical characteristics (mainly crown sizes and leaf quantities) of sample trees. LAI of the large crown size (Syzygium cumini) was defined as 3.5, while that of the small size (Pinus polustris) was defined as 1.5 (Charalampopoulos et al. 2012). In addition, in studies on the geometry, all indicators (SVF, H/W, etc.) were expressed as their original values, which can be directly fed to the ANN models. In addition to macroclimate factors, OTC also varied according to the time of the day; it was included as a covariate in the model.

In studies with both objective and subjective indices, the neutral temperature indicated by PET (NPET) was selected as the dependent variable. This type of studies was usually carried out in one city, although there can be multiple study locations with various microclimate features (e.g., Li and Liu 2020; Liu et al. 2016; Lai et al. 2020; Xu et al. 2019). However, these studies usually develop a neutral temperature for the whole city rather than each location with a specific microclimate feature. Therefore, in these studies, only macroclimate factors were extracted as independent variables.

All categorical independent variables were coded based on the following rules.

Trees. LAI generally ranged from 0 to 6, defining open to dense-tree canopy spaces. Some studies used the tree species instead of LAI. However, the tree species had varying cooling effects owing to their canopying degree, which could be coded into LAI values in terms of the crown characteristics. Species with small crowns (Pinus polustris) had low LAI values (0.3), while those with big ones (Mangifera indica) had high LAI values (3.1).

Orientations. In H/W studies, the orientation was a crucial parameter. H/W performances varied for different orientations. Four different orientations were coded in terms of their natural lighting levels. The S-N orientation had the best lighting, which is defined as the highest value (4). The coding is listed in Table 4.

Seasons. Most studies were conducted during the summer. Hence, seasons were coded as 1, 2, 3, and 4, with the warmest season (summer) taking the highest value (4).

Table 4. Coding for categorical independent variables in the artificial neural network models

Categorical independent variables	Coding	Comments
Species	LAI 0 to 6	Depending on tree crown
Orientation	1	East-west (E-W)
	2	Southeast-northwest (SE-NW)
	3	Southwest-northeast (SW-NE)
	4	South-north (S-N)
Time	0-23	Local time (h) of the day
Season	4	Summer
	3	Spring
	2	Autumn
	1	Winter

3.3.2 Artificial neural network

In this study, ANN was utilized to test the impact of various macro- and micro-climate factors on outdoor thermal environment (indicated by PET) and outdoor thermal comfort (represented by neutral

PET). In ANN models, the relative importance of each variable was reported. Statistical contribution of each variable was expressed by importance and normalised importance. The total importance value of the addition of all variables equalled 1. The normalised importance of each variable referred to the ratio between its importance and the highest variable importance. The whole models were processed in three layers—input, the hidden layer, and output. Most studies selected one parameter—either the geometry (e.g., H/W and SVF) or vegetation (e.g., LAI)—for detailed analysis. Therefore, this study analysed the effects of H/W, SVF, and LAI in three different ANN models. Each model included other confounding factors, such as the latitude and local time. In total, five models were established for each target variable. There were different quantities of neurons in the hidden layers (Deng and Chen 2018). For instance, the model of summer NPET had three variables in the input layer (latitude, DFS, and altitude, as shown in Fig. 4); on the contrary, the PET model for SVF had six variables as input (SVF, time, latitude, albedo, distance from the sea, altitude), hence it had more neurons in the hidden layer than summer NPET model (Fig. 5). The categorical factors were quantitatively coded (Table 4). The model's prediction accuracy was tested by correlating the predicted and observed values. This verification method was frequently used in previous studies (Chan and Chau 2019; Hu et al. 2021; Shah et al. 2021). To further explore the variables' detailed contribution statistically, values of dependent variables were correlated with the most important independent variable. All statistical analyses were conducted in SPSS (version 26).

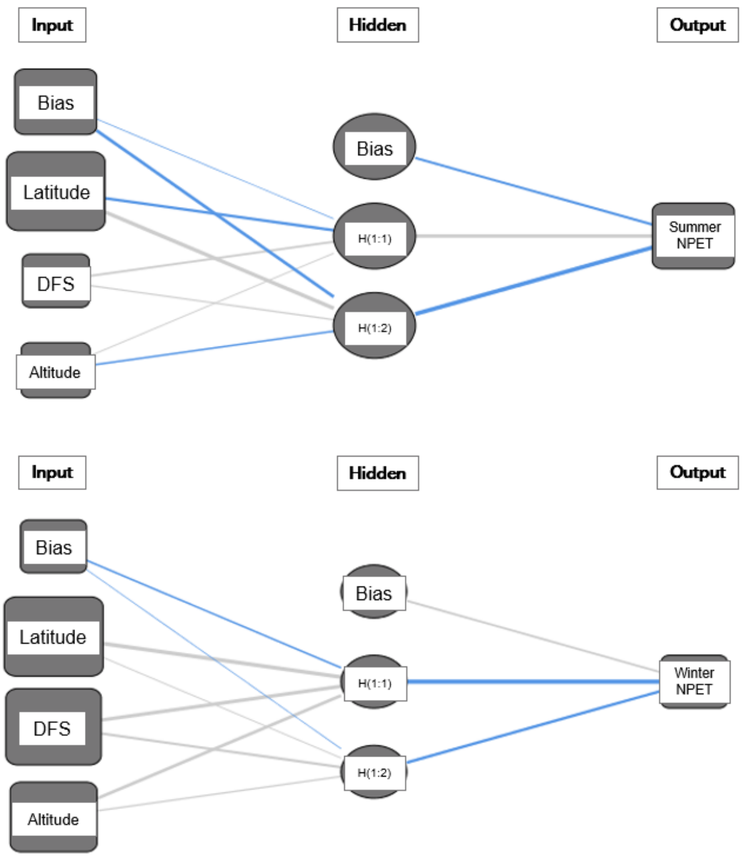

Fig. 4. ANN frameworks for models of SEOS data.

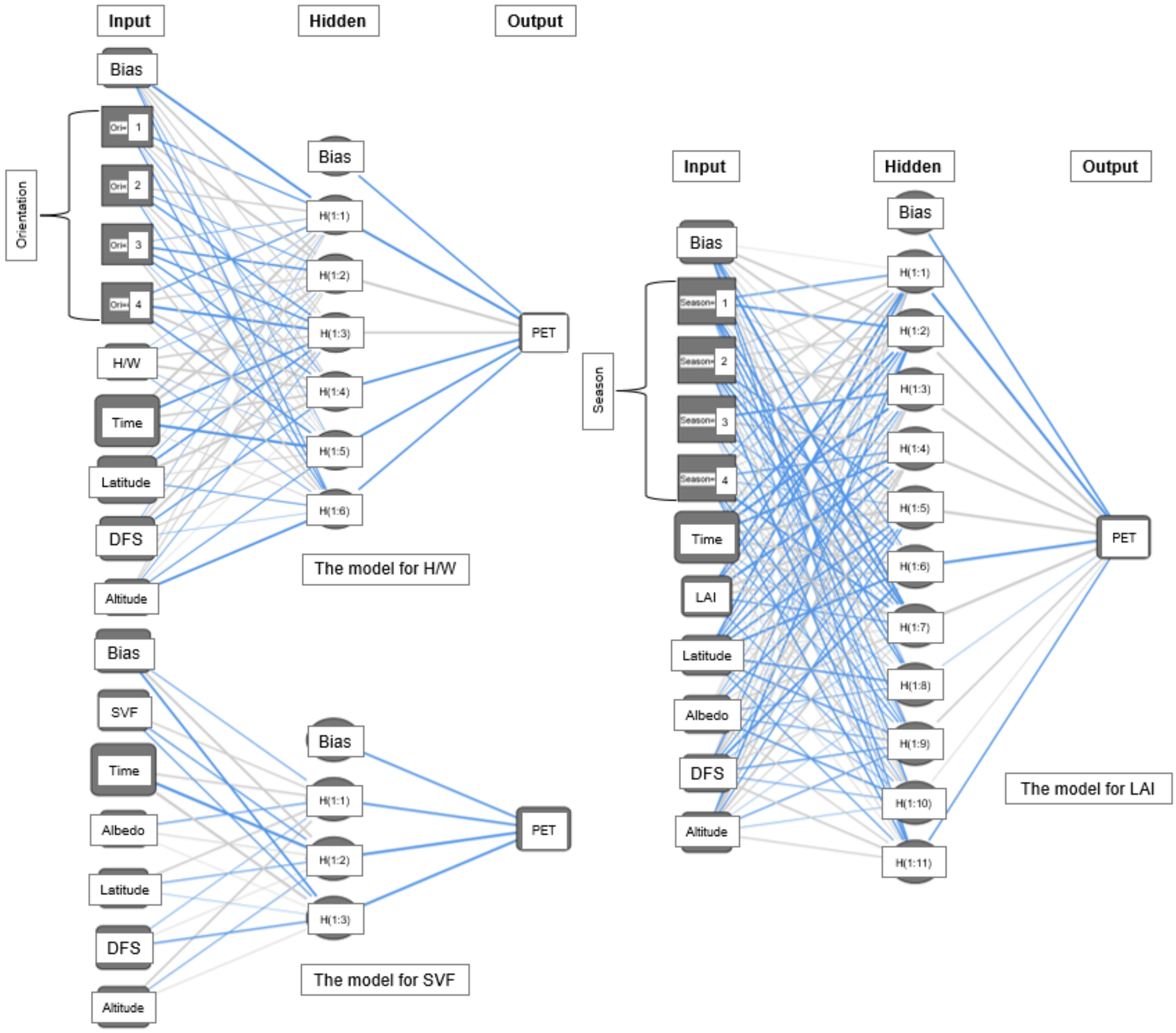

Fig. 5. ANN frameworks for models of SEO data (where Orientations = 1 (E-W), 2 (SE-NW), 3 (SW–NE), 4 (S-N); Seasons = 1 (Winter), 2 (Autumn), 3 (Spring), 4 (Summer)).

4. Results

4.1 Data description

Fig. 6 illustrates the PET ranges clustered by latitude. Data from different local environmental factors (vegetation, H/W, and SVF) were illustrated separately. Included studies for each figure can be found in the "Study Type" column in Table 2. For a full-day span, the PET had a wide range. Generally, the PET spanned from approximately 10 °C to 60 °C, with differences emerging among different studies.

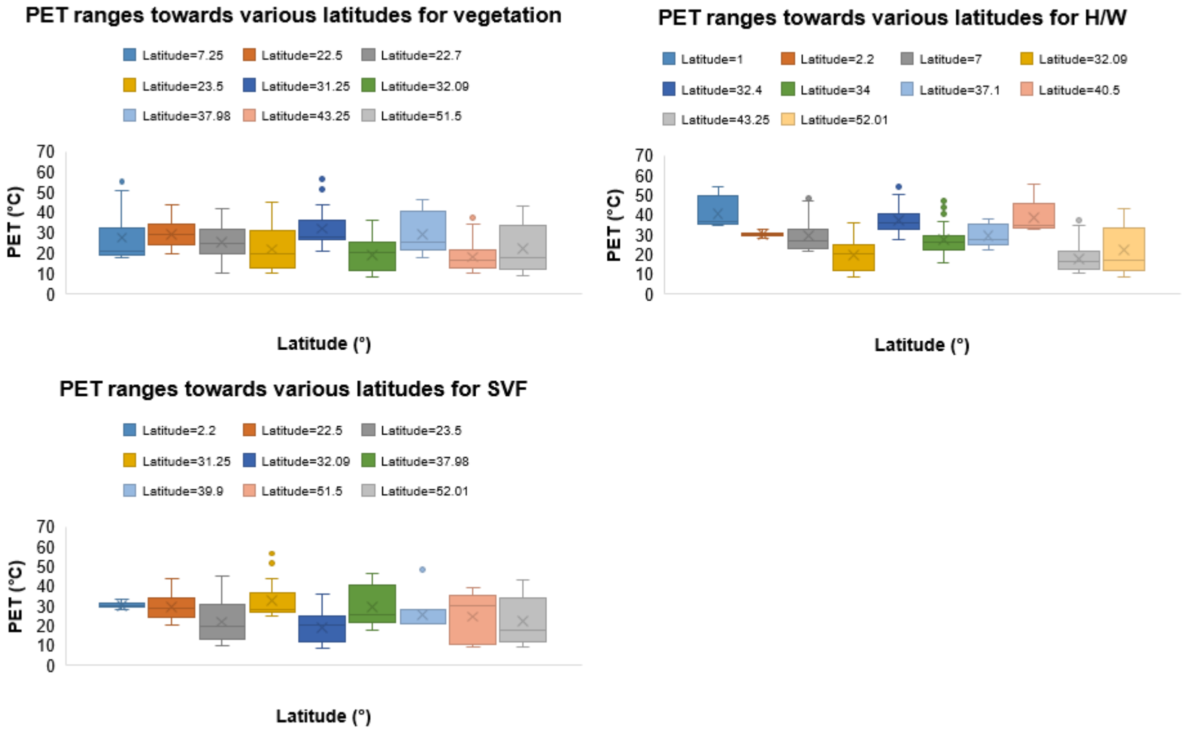

Fig. 6. PET ranges for various latitude zones clustered by the three variables.

4.2 Impacts of macroclimate factors on the regional neutral temperature (indicated by PET)

This section discusses about the modelling results from studies that have employed both objective and subjective thermal indices (Table 5). Their neutral temperatures varied considerably.

Table 5. Seasonal neutral PETs of some sample cities along with their geographical information.

City	Latitude (°)	Winter PET (°C)	Summer PET (°C)	DFS (km)	Altitude (m)	Resource
Singapore	1.3		28.1	5	45	Yang et al. (2013)
Dar es Salaam	6.9	22.9	30.7	5	50	Ndetto and Matzarakis (2017)
Dar es Salaam	6.9	26.9	26.9	0	50	Ndetto and Matzarakis (2017)
Belo Horizonte	20.0	15.9	27.7	346	886	Hirashima et al. (2016)
Campo Grande	20.5	23.1	24.4	0.50	529	Lucchese and Andreasi (2017)
Hong Kong	22.0		28.1	3	5	Ng and Cheng (2012)
Shenzhen	23.0		28.3	5	6	Liu et al. (2018)
Dhaka	23.4		25.0	0.45	176	Sharmin et al. (2019)
Sun Moon Lake	23.9		27.2	60	831	Lin and Matzarakis (2008)
Guangzhou	24.0	15.6	25.3	5	5	Li et al. (2016)
Taichaung	24.1	23.7	25.6	30	86	Lin (2009)
Changsha	28.2	14.9	23.3	500	66	Yang et al. (2013)
Shanghai	30.5	22.4		10	9	Chen et al. (2015)
Chengdu	30.6		24.4	1,000	508	Zeng and Dong (2015)
Ahvaz	31.0		25.3	150	16	Nasrollahi et al. (2021)
Tempe	33.7		28.6	500	350	Middel et al. (2016)
Xi’an	34.3	17.0		950	384	Xu et al. (2018)
Tehran	35.4	17.2	25.1	613	1,200	Hadianpour et al. (2018)
Urmia	37.9	7.2	23.0	844	1,332	Gachkar et al. (2021)
Melbourne	37.9	20.4	24.4	5	33	Kenawy and Elkadi (2018)
Harbin	45.6	18.0	20.0	500	118	Chen et al. (2018)

Harbin	45.6	13.8	21.5	500	118	Yin et al. (2021)
Umeå	63.8		16.0	18.5	11	Yang et al. (2017)

Tables 6 presents the correlation between summer neutral PET and macroclimatic factors (Fig. 6). The latitude exhibited the highest importance (100%), a value far higher than distance from the sea (3.5%) and altitude (9.5%). A similar phenomenon for latitude was observed in the winter data (Table 7); yet DFS (94.5%) and the altitude (81.8%) showed strong effects on PET.

Table 6. Important independent variables for summer neutral PETs.

	Importance	Normalized Importance
Latitude	0.885	100.0%
DFS	0.031	3.5%
Altitude	0.084	9.5%

Table 7. Important independent variables for winter neutral PETs.

	Importance	Normalized Importance
Latitude	0.362	100.0%
DFS	0.343	94.5%
Altitude	0.295	81.8%

To test the models' prediction accuracy, the models' predicted PETs were associated with observed ones, as shown in Fig. 7. They exhibited significant correlation, especially in the summer ($R^2 = 0.72$, $p < 0.001$) but much lower R^2 during the winter ($R^2 = 0.59$, $p = 0.001$), indicating higher prediction accuracy of ANN models during summer than winter.

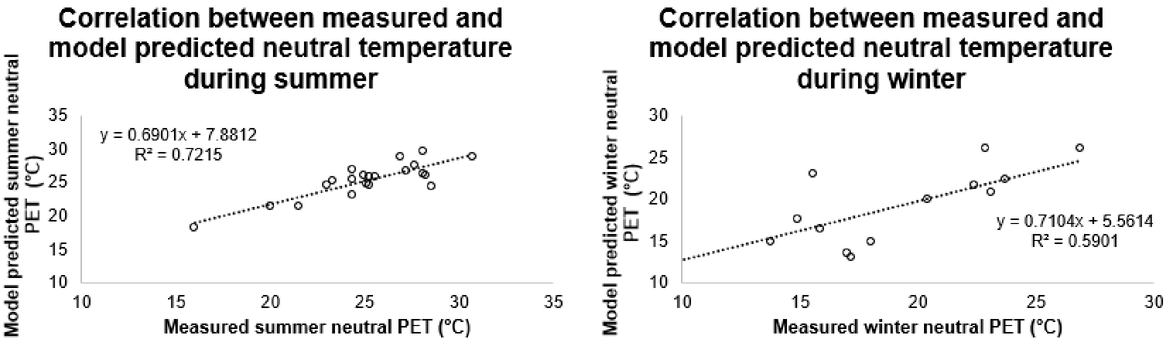

Fig. 7. Correlation between seasonally predicted model and measured neutral PETs.

Since the latitude was found to be the most important factor influencing NPET in the two seasons, a single linear regression model was set up to test how latitude affects neutral temperature. Fig. 8 illustrates the regression between NPET and the latitude. Increasing the latitude from 0° to 65° could cause NPET reduction by more than 10 °C during the summer ($R^2 = 0.70$, $p < 0.001$). The winter witnessed a higher reduction trend. However, only about one third of variance in winter neutral PET can be explained by the latitude ($R^2 = 0.36$, $p = 0.024$).

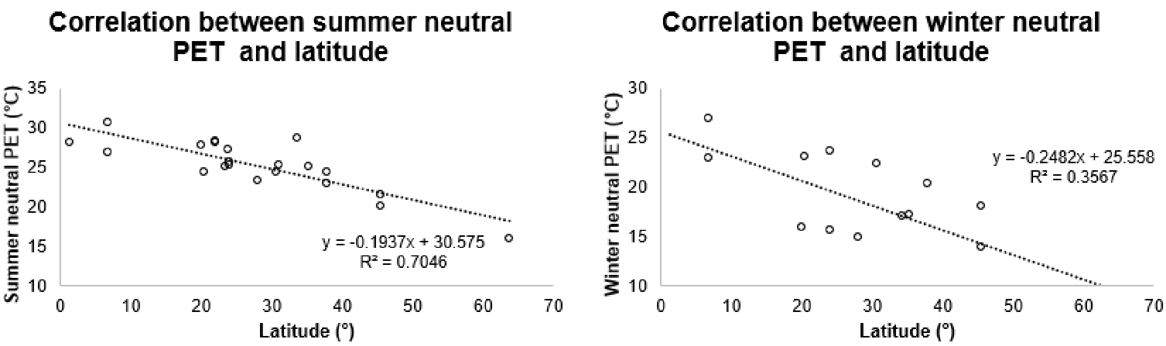

Fig. 8. Correlation between seasonal neutral PET and latitude.

4.3 Impacts of both macroclimate and microclimate factors on the thermal environment (indicated by PET)

This section discusses about the studies that have utilised objective thermal indices only, i.e., PET. This type of studies usually included both macro- and micro-climate factors that can be tested in the model.

4.3.1 H/W

Table 8 lists the relative importance of independent variables for H/W studies, including macro (latitude, etc.) and micro factors (orientation, etc.). In addition to the time of day causing obvious temperature fluctuations, the rest of the physical factors were also important (just above 55%). Among them, the macro factor (latitude, 61.3%) was more important than the others, followed by H/W (60.1%). DFS was the least significant (55.1%); however, all site physical factors were thermally significant, and they commonly influenced site thermal comfort.

Table 8. Importance of all independent variables for studies that focused on H/W utilizing PET index.

	Importance	Normalized Importance
Orientation	0.142	55.0%
H/W	0.155	60.1%
Time of the day	0.258	100.0%
Latitude	0.158	61.2%
DFS	0.142	55.0%
Altitude	0.145	56.0%

4.3.2 SVF

Using the PET as the dependent variable and the time, SVF, albedo, and latitude as covariates, an ANN model was established, and the results shown in Table 9. PET significantly fluctuated with time of the day (100.0%), which is the most important independent variable. The importance of other macro- and micro- climate factors (latitude, DFS, altitude, and SVF) were about 30%. However, albedo had little thermal effect (10.1%).

Table 9. Importance of all independent variables for studies that focused on SVF utilizing PET index.

	Importance	Normalized Importance
SVF	0.148	36.5%
Time of the day	0.405	100.0%
Albedo	0.041	10.1%
Latitude	0.132	32.6%
DFS	0.121	29.9%
Altitude	0.153	37.8%

4.3.3 Trees

Another ANN model was established with the PET as the dependent variable, the season as a factor, and the time, LAI, albedo, and latitude as the covariates. The results were shown in Table 10. The most important macroclimate factor was season (96.1%), followed by altitude (49.9%), latitude (37.0%) and DFS (20.9%). Microclimate factors such as albedo and LAI were also important determinants of the outdoor thermal environment, with the importance of 60.4% and 41.4% respectively.

Table 10. Importance of all independent variables for studies that focused on vegetation utilizing PET index.

	Importance	Normalized Importance
Season	0.237	95.9%
Time of the day	0.247	100.0%
LAI	0.102	41.3%

Latitude	0.091	36.8%
Albedo	0.149	60.3%
DFS	0.051	20.6%
Altitude	0.123	49.8%

4.3.4 Evaluation of model performance

ANN models only expressed the relative importance of variables. Other coefficients, such as the model's or independent variable's significance, remain unknown. To evaluate the prediction accuracy of the model, the predicted PET was associated with the observed PET through linear regression, as shown in Fig. 9. It can be seen that they were significantly correlated (R^2 = approximately 0.8). In other words, the model can reliably predict at least 80% of the PET values correctly. Models for geometry and vegetation exhibited similar results.

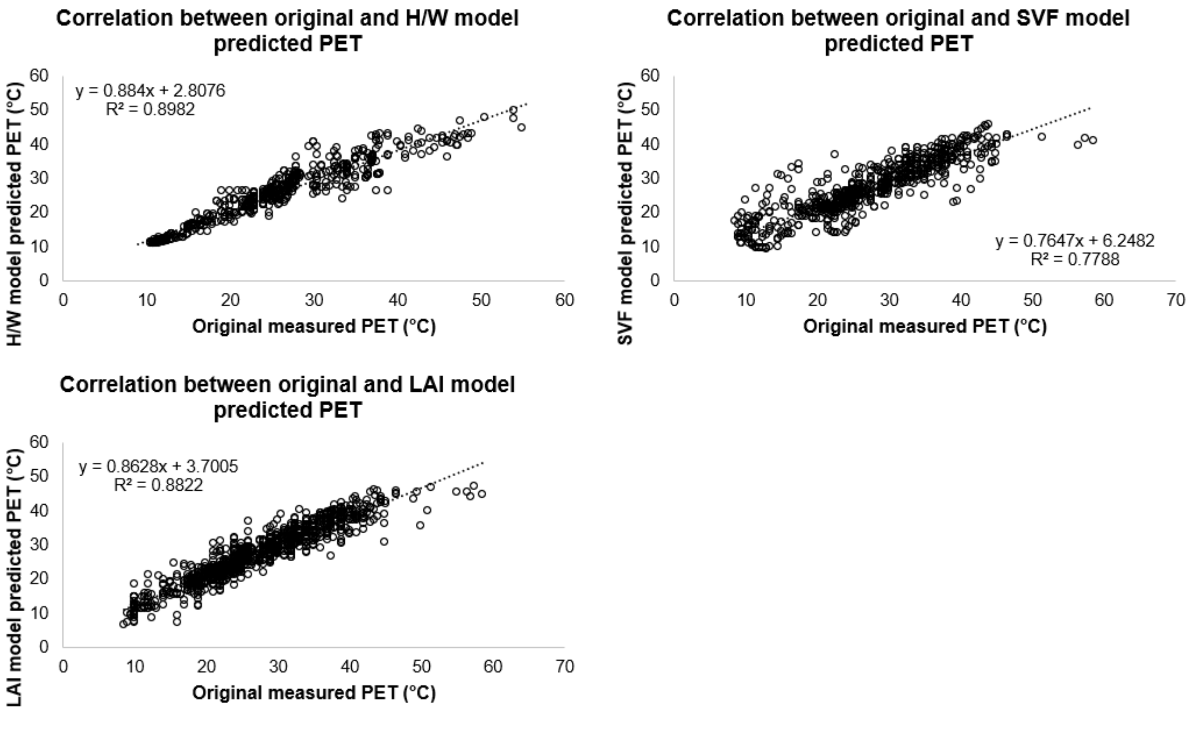

Fig. 9. Correlations between original and model-predicted PETs.

5. Discussion

This study found that macroclimate factors like latitude and season had significant effects on the outdoor thermal comfort. The thermal comfort was confirmed to be significantly correlated with microclimate factors, such as vegetation (Skelhorn et al. 2016), geometry (Blankenstein and Kuttler 2004), water surfaces (Du et al. 2016), the orientation (Pathirana et al. 2019), and time of day (Means 2019b).

Additionally, the macroclimate has a significant correlation with subjective thermal perception, especially latitude and thermal perception (Andersen et al. 1990) during the summer. The latitude showed the most significant contribution to the regional neutral temperatures (importance = 100%, R^2 = 0.7215 and 0.5901, for summer and winter, respectively). The importance of DFS was consistently low in summer (3.5%) but high in winter (94.5%). Altitude showed similar effect with DFS, 9.5% in the summer model but 81.8% in the winter model.

Various effects of DSF expressed the complexity of thermal effects of waterbodies, which has been reported by earlier studies (Jameia et al. 2016). People's thermal perceptions significantly varied for latitudes. This finding also agreed with previous studies investigating effects of contextual factors on thermal perception (Jowkar et al. 2020; Lam et al. 2021a; Lam et al. 2021b; Zhang and Dear 2019). Summer NPET was more significantly affected by the latitude than winter NPET, as evidenced by higher R^2 value for the summer model. This might result from different adaptive opportunities to cope with different types of thermal stress. Naturally, people have more avenues to achieve comfort in an outdoor winter environment, such as adding clothes, seeking sunny spaces, and so on. In contrast, there were fewer adaptative opportunities to achieve comfort in summer outdoor spaces suppose the clo values are already low, and/or there is no shelter for shading. This may be one of the main reasons why latitude explained higher proportion of variances in summer NPET than in winter NPET.

Findings from studies that utilized objective thermal indices only demonstrated that macroclimate and microclimate factors had comparable thermal effects on objective thermal environments. For studies involving H/W, the importance of macroclimate factors, i.e., latitude (61.3%), DFS (55.0%) and altitude (56.7%) was similar to that of microclimate factors, such as H/W (60.1%) and orientation (55.1%). In respect to studies in SVF, the macroclimate factors (latitude, DFS, altitude) and microclimate factors (SVF) also had similar contributions (about 30%-40%) to the outdoor thermal environment, except for albedo (10.1%). For studies with trees, the contribution of macroclimate factors (altitude, latitude and DFS) and microclimate factors (albedo and LAI) were also comparable in general. The importance of microclimate factors echoed the findings of some previous studies, such as Ali-Toudert and Mayer (2006), Manteghi et al. (2019), and Guo et al. (2020) for H/W, SVF, and LAI. More importantly, they have confirmed previous findings that the local thermal environment and comfort can be improved by changing the urban geometry, planting vegetation, using cool surface, and incorporating waterbodies (Lai et al. 2019). The urban geometry, represented by the openness of the urban space, is equally important in determining the local thermal environment and comfort as the macroclimate factors of latitude, altitude, and distance from the sea. The ground albedo and leaf area index of the urban trees also have similar effect on outdoor thermal environment and comfort as the above-mentioned macroclimate factors. These findings are significant in highlighting the crucial role of heat/cold mitigation strategies in urban planning and landscape design practice, particularly for geographical areas that are naturally disadvantaged in providing amiable outdoor thermal environments.

This study is not without limitations. Firstly, only studies that employed PET index were examined, while studies that utilized other indices, such as UTCI were excluded. For studies that involved subjective thermal indices, this study only used neutral PET in the analysis. Preferred PET, acceptable PET range (Cheung and Jim 2018a) and other thermal benchmarks can also be assessed in the future. Secondly, studies containing objective indices analysed in this paper included both field monitoring studies and computer simulation studies, which may have affected the results. Thirdly, the macroclimate and microclimate factors examined in the models were not exhaustive. Therefore, it was likely that the reported effect of a certain climate factor was in fact confounded by other factors. For example, the claimed effect of latitude may also be an impact of certain geographic features. Lastly, there were methodological differences in the examined studies, i.e., meteorological instruments, survey questions and scales to assess thermal comfort (Johansson et al. 2014), sample sizes, and index calculation methods (Kántor and Unger 2011) that may have biased the results. These limitations should be addressed in future studies.

6. Conclusion

This study has explored impacts of macro- and micro-climate factors on the outdoor thermal environment and thermal comfort by extracting data from published research studies. Some key findings of this work are as follows:

(a) Human thermal perception is significantly affected by macroclimate factors, such as latitudes and seasons. The neutral temperature expressed by PET in areas with the latitude of 0° is nearly 13 °C higher than that in regions with a latitude of 65° in summer according to linear regression models; winter showed slightly higher NPET differences across various latitudes. Yet the correlation between NPET and latitude is lower in winter than in summer.

(b) In studies employing only objective thermal indices, it was found that macroclimate factors, such as the latitude, distance from the sea, and altitude, have similar contribution to the outdoor thermal environment as microclimate factors, such as height to width ratio and sky view factor. For studies involving H/W, the importance of macroclimate factors, i.e., latitude (61.3%), DFS (55.0%) and altitude (56.7%) was similar to that of microclimate factors, such as H/W (60.1%) and orientation (55.1%). In respect to studies in SVF, the macroclimate factors (latitude, DFS, altitude) and microclimate factors (SVF) also had similar contributions to the outdoor thermal environment, except for albedo. For studies with trees, the contribution of macroclimate factors (altitude, latitude and DFS) and microclimate factors (albedo and LAI) were also comparable in general.

(c) The findings from this study have confirmed the significance of microclimate factors (such as urban geometry and morphology) in creating pleasant outdoor thermal environment in areas that have unfavourable macroclimates. Urban planners and landscape architects should integrate heat/cold mitigation strategies in their design practice to help build a liveable and amiable urban thermal environment.

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