Renewable and Sustainable Energy Reviews 138 (2021) 110551

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

A systematic review of urban climate research in cold and polar climate regions

J. Brozovsky *, N. Gaitani, A. Gustavsen

Department of Architecture and Technology, Faculty for Architecture and Design, NTNU – Norwegian University of Science and Technology, Høgskoleringen 1, 7491, Trondheim, Norway

ARTICLE INFO

Keywords:
Urban climate
Cold and polar climate
Microclimate
Urban heat island
Climate adaptation
Mitigation

ABSTRACT

Cities are at the forefront of the climate change issue and are responsible for about 39% of global carbon dioxide emissions. They can form their own climate which is often characterized by higher temperatures and pollution levels, less wind, and solar access compared to their surroundings. This paper presents a systematic review of publications on cities in cold and polar climate regions as defined by the Köppen-Geiger climate classification to determine the most-researched topics, identify sparsely incorporated research areas, synthesize research evidence and summarize the most important results. In total, 101 papers have been included, categorized, and analyzed according to their publication year, country, climate, topic, method, keywords, citations, and publication channels. The articles were classified into nine main topics: urban heat island (UHI) magnitude, UHI mitigation, other UHI related, biometeorology, air pollution, urban boundary layer and atmospheric boundary layer, time series analysis, other urban meteorological phenomena, and research not falling under the previous eight categories. The most-covered topic was the UHI effect. The outweighing part of studies used on-site measurements for obtaining data, while some studies were dedicated to understanding the structure, or the temporal and spatial variability of the UHI, often by using numerical tools. The review reveals significant gaps in the research of microclimatic characteristics and physical properties of the materials in urban design. Ongoing climate change and the particular vulnerability of cold and polar climate regions makes it especially important to review, develop, and adopt climate adaption and mitigation strategies for sustainable urban development.

1. Introduction

1.1. Global situation

The buildings and construction sector amounts to about 36% of global final energy consumption and 39% of energy-related carbon dioxide emissions globally [1]. Reducing the adverse environmental impact of it is hence undoubtedly one of the key aspects to keep global temperature rise within 1.5 °C above pre-industrial levels. Of particular concern are cities which currently account for around 67–76% of global energy use and between 71 and 76% of CO_2 emissions from global final energy use [2].

Since 1950, the number of people living in cities has rapidly grown from 751 million (30% of the world's population) to 4.2 billion (55%) in 2018 [3]. By 2050, 68% of the projected global population of 9.7 billion is expected to live in urban settlements [3,4]. With the ongoing growth of the global economy and population, which are the most important drivers in CO_2 emissions from fossil fuel consumption, the situation aggravates [2]. These numbers, in particular, express the need for sustainable concepts and solutions to address the risks and problems connected to health, the environment and the consumption ofvd energy and resources in urban environments.

1.2. Urban climate characteristics

Urban spaces differ from rural areas primarily by the materials of the built environment and the high density of people. As a consequence, the consumption of resources, the use of energy, and the production of waste concentrate in densely populated areas. Differences in the physical properties of the surface covers, topography and anthropogenic impacts (such as increased anthropogenic heat, lack of green spaces, increased air pollution etc.) can influence the weather variables at the meteorological microscale, as for instance temperature, rainfall, wind or humidity [5]. Commonly, *microscale* is used as a term for horizontal extents smaller than 1 km. In the definition by the American Meteorological

* Corresponding author.
E-mail addresses: johannes.brozovsky@ntnu.no (J. Brozovsky), niki.gaitani@ntnu.no (N. Gaitani).

https://doi.org/10.1016/j.rser.2020.110551
Received 22 August 2019; Received in revised form 4 October 2020; Accepted 2 November 2020
Available online 12 November 2020

Abbreviations

ABL	Atmospheric boundary layer
AP	Air pollution
BM	Biometeorology
BVOC	Biogenic volatile organic compounds
CFD	Computational Fluid Dynamics
CLHI	Canopy layer heat island
CW	Comfort and wellbeing
GEM	Gaseous elementary mercury
GIS	Geographical Information System
GOM	Gaseous oxidized mercury
HVAC	Heating, ventilation and air-conditioning
LST	Land surface temperature (°C)
LULC	Land use/land cover
MODIS	Moderate-Resolution Imaging Spectroradiometer
M-OS	On-site measurements
M-RS	Remote sensing measurements
NMV	Numerical models with validation
OUMP	Other urban meteorological phenomena
PBM	Particle-bound mercury
PET	Physiological equivalent temperature (°C)
PM	Particulate matter
Rev	Review
RMUHI	Relief-modified urban heat island
S	Survey
SLHI	Surface layer heat island
SVF	Sky view factor (-)
TEB	Town Energy Balance
TSA	Time series analysis
UBL	Urban boundary layer
UCL	Urban canopy layer
UHI	Urban heat island
UHI-Mag	Urban heat island magnitude
UHI-Mit	Urban heat island mitigation strategy
UHI-Other	Other research on the urban heat island
UTCI	Universal Thermal Climate Index (°C)

Society, the upper limit is taken as 2 km [6,7]. The distinctive climate of such a small-scale area that differs from the surrounding area is then called microclimate. The climate for a city is, therefore, to be regarded as a mixture of many slightly different microclimates [5].

Numerous publications – the first pioneering work was published in three volumes in 1833 by Luke Howard on *The Climate of London* [8] – have shown that urbanization changes the characteristics of surface and atmospheric properties of a region significantly, e.g. Ref. [9–11]. These changes include thermal, moisture and aerodynamic properties. Those then again affect natural solar and hydrological balances, as well as air flow patterns, heat fluxes etc. [9] (see also Table 1).

One of the most-investigated phenomena is the so-called urban heat island (UHI). The term came up in the 1940s, for example in Balchin and Pye's study on Bath, UK [13], and describes the warmth of a settlement compared with its rural surroundings [14]. It is reported to occur in almost all urban areas, of every size and disregarding warm or cold climate conditions [15]. According to a study from Oke in 1973, almost half a century ago, it was "*one of the most widely documented climatological effects of man's modification of the atmospheric environment*" [16]. As early as in 1970, Chandler [17] prepared a selected bibliography on urban climate, a first draft of which already contained more than 2000 references.

Table 1
Causes for the urban heat island (not rank-ordered) [12].

Altered energy balance terms	Underlying features of urbanization
Canopy layer	
1. Increased absorption of short-wave radiation	Street canyon geometry – increased surface area and multiple reflection
2. Increased long-wave radiation from the sky	Air pollution – greater absorption and re-emission
3. Decreased long-wave radiation loss	Street canyon geometry – reduction of sky view factor
4. Anthropogenic heat source	Building, traffic and people heat loss
5. Increased sensible heat storage	Construction materials – increased thermal admittance
6. Decreased evapotranspiration	Construction materials – increased 'water proofing'
7. Decreased total turbulent heat transport	Street canyon geometry – reduction of wind speed
Boundary layer	
1. Increased absorption of short-wave radiation	Air pollution – increased aerosol absorption
2. Anthropogenic heat source	Chimney and stack heat losses
3. Increased sensible heat input-entrainment from below	Canopy heat island – increased heat flux from canopy layer and roofs
4. Increased sensible heat input-entrainment from above	Heat island, roughness – increased turbulent entrainment

In 1976, Oke [18] concluded that there is not one but at least two heat islands produced by urbanization, and he proposed to divide the urban atmosphere into two layers. The urban canopy layer (UCL) is made up of the air spaces between a city's "roughness elements" (mainly between buildings up to their rooftops) and is governed by the processes at the microscale. The urban boundary layer (UBL) is directly adjoining the UCL above. The UBL is governed by the processes at mesoscale and defined as *"that part of the planetary boundary layer whose characteristics are affected by the presence of an urban area at its lower boundary"* [18]. It extends from roof level to a few kilometers above it. Both layers interact strongly. While the UCL affects the UBL through heating, cooling and evaporation, the UBL contributes greater mesoscale weather conditions to the UCL [12]. Most studies refer to atmospheric heat islands that can be determined by higher air temperatures, like the urban canopy layer heat island (CLHI). With the increasing availability of remote sensing techniques and resources, surface layer heat islands (SLHI) get evermore attention. Unlike the atmospheric heat islands before, it is determined by a higher surface temperature of an area [9,10].

Warmer temperatures in the inner city can furthermore cause the so-called urban heat island circulation or urban breeze – a weak flow close to the ground directed towards the city's center [19]. Even though the daytime UHI is usually weaker, the instability of the air during the day makes the vertical movement easier and thus induces more developed horizontal airflows, than at night [20–24]. This weak surface flow amounts to around 0.3 m/s [10] and creates a plume over the city center [9]. It was reported to develop even at relatively small heat island intensities of 1–2 °C [22]. However, the term *urban climatology* incorporates a lot more aspects than the UHI, even though it is the most prominent one. It is furthermore not limited to meteorology or climatology only but includes many other disciplines like air pollution science, architecture, building engineering, urban design, biometeorology etc. [25].

Traditionally, data was obtained experimentally, before increasing computing power led to several arithmetic codes, calculation methodologies and publications in urban physics, especially during the last two decades [26]. Most commonly, computational fluid dynamics (CFD) tools or large-scale energy balance models like the Town Energy Balance (TEB) scheme [27,28] are used. Namely, the tool ENVI-met [29] has gained particular popularity since it had been available freely for a long time [26] and has, therefore, been used extensively over the years, e.g. Refs. [30–38]. Due to the high complexity of these models, a careful validation process is imperative when using them. Moonen et al. [39] discussed five major problems connected with urbanization in their review and provided examples, how numerical approaches can help to address them: pedestrian wind comfort, pedestrian thermal comfort, building energy demand, pollutant dispersion and wind-driven rain.

1.3. Cold and polar climate classification

According to the widely used Köppen-Geiger climate classification, updated by Peel et al. [40], *cold climate* encompasses 12 subtypes, beginning with a *D* in Table 2. Those beginning with an *E* are subtypes of *polar climate*. Fig. 1 shows the location of climate zones based on a 0.1° × 0.1° grid resolution and the cities where the research of the reviewed articles was carried out.

Due to the distribution of landmass, the cold and polar climate zones are mostly situated on the northern hemisphere (with exception of Antarctica, where no permanent settlements with significant population are present). Subclimate “Dfc” extends over large parts of the Russian Federation, Canada and Northern Europe, as well as several smaller mountainous areas e.g. in the US and Europe and represents the most common type of cold climate (again with exception of climate type “ET” in Antarctica).

In this paper, studies on the urban microclimate in cold and polar climate (14 climate types) according to the Köppen-Geiger climate classification are reviewed. Numerical studies were only considered when sufficient validation, for instance with experimental data, was provided. The aim is to determine the most researched topics, identify sparsely incorporated research areas and summarize the most important results. The outcomes of this review and meta-analysis will help researchers to grasp the structure of published research and identify future research possibilities. They will also facilitate comparing obtained results with previously published studies with the same (sub)climate, location, research topic, or method, as the reviewed literature will be listed in comprehensive tables, providing all necessary information. To the best of our knowledge, no systematic review focusing on urban climate research in the cold and polar climate regions has been published yet. This systematic review will therefore fill this gap and provide a statistical analysis of included articles and summarize their main results.

Section 2 of this study will describe the applied methodology for obtaining the reviewed articles. Section 3 gives a statistical evaluation of different characteristics of the included articles and lists them according to their categories. It furthermore summarizes the main outcomes of the reviewed articles. Sections 4 and 5 discuss and conclude the findings from this paper, respectively.

Table 2
Description of Köppen climate symbols and defining criteria for cold and polar climate from Peel et al. [40].

1st	2nd	3rd	Description	Criteria
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without Dry Season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

T_{hot} = temperature of the hottest month [°C], T_{cold} = temperature of the coldest month [°C], T_{mon10} = number of months where the temperature is above 10 °C, P_{dry} = precipitation of the driest month [mm], P_{sdry} = precipitation of the driest month in summer [mm], P_{wdry} = precipitation of the driest month in winter [mm], P_{swet} = precipitation of the wettest month in summer [mm], P_{wwet} = precipitation of the wettest month in winter [mm]. Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

2. Method

To identify relevant literature, a systematic review approach was pursued. A systematic literature review is mainly characterized by a structured question formulation, the use of methodological filters for retrieving a subset of literature and the specification of a reproducible search procedure [41]. With employing the term “subset”, this definition already implies that retrieving every relevant article with this approach is rather unlikely. The extent of search results is strongly dependent on the search terms and databases used. However, using too many terms and key phrases may result in an unnecessarily high number of database hits, more irrelevant literature and thus disproportionally high demand for screening.

This study applies the four-phase approach described by Moher et al. [42] as part of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement for structuring literature retrieval and reporting in systematic reviews. In each of the four phases, articles that do not fit into the scope of this review or have been identified twice were removed as illustrated in the flow chart in Fig. 2. This methodological approach has been widely applied, mainly in health care and medicine. Using this approach benefits this systematic review as it presents a repeatable and well-defined in-depth procedure for including literature which not only facilitates the reader to follow but also other researchers to conduct a similar review.

Following the practice in other studies, e.g. Ref. [43,44], the indexed electronic databases Scopus and Web of Science were used. In Scopus, the search was conducted within the search fields *Article Title, Abstract and Keywords*. Analogously, in Web of Science, the search field was chosen to be *Topic*, which means *Title, Abstract, Author keywords* and *Keywords Plus*®. The search was conducted in March 2019. Due to different requirements for the search syntax in the two databases, the entered query was slightly different from one another. For Scopus it was: *((microclimate W/5 urban) OR “anthropogenic heat” OR “heat island” OR “UHI”) AND (cold OR arctic)*. In Web of Science, the corresponding query was: *((microclimate NEAR/5 urban) OR “anthropogenic heat” OR “heat island” OR “UHI”) AND (cold OR arctic)*. *W/5* and *NEAR/5* indicate that the search should only identify articles where the words *microclimate* and *urban* appear within a range of 5 words in the selected search fields.

Numerical studies which do not include validation were removed since validation usually comprises three parts: (1) a thorough model description, (2) model verification, and (3) model validation. While model description and model verification is usually done by the developer when using a commercial tool (comprehensive description of the model content, assumptions, parametrizations, quality control etc.), model validation is an imperative step that has to be done by the user [45]. This is because in practice the quality of model outputs depend not only on the accuracy of the model itself or its input but also on the qualification of the person running a model as a numerical simulation is a knowledge-based activity [46]. Therefore, it is considered vital for reliable research results to present sufficient validation documentation in numerical studies.

2.1. Classification

The included articles were then grouped according to their main topic (category) and the methods used for evaluation. Sometimes, articles were devoted to more than one topic. They were then placed into a category according to their focus of research. The categories were:

1. *UHI magnitude:* Articles that mainly address the urban-rural temperature difference, either in air temperatures or land surface temperatures. Furthermore, studies on the spatial and temporal variability of those temperature differences are included.

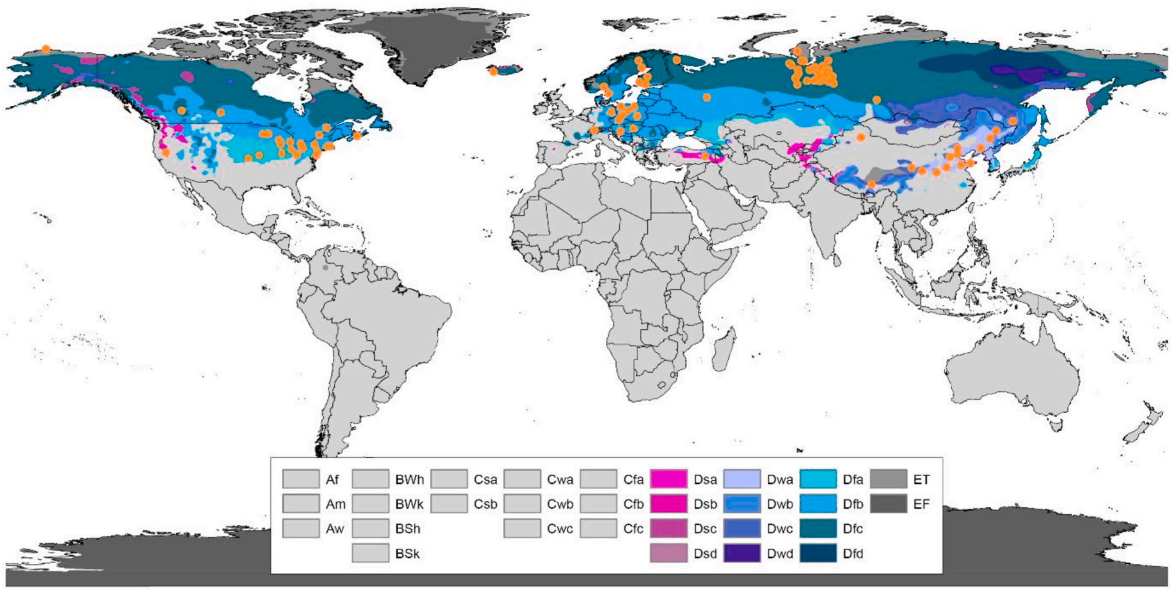

Fig. 1. Cold and polar climate regions according to the data from Peel et al. [40] and locations of studies included in the review, if specifically indicated. Each of the orange dots represents one city. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

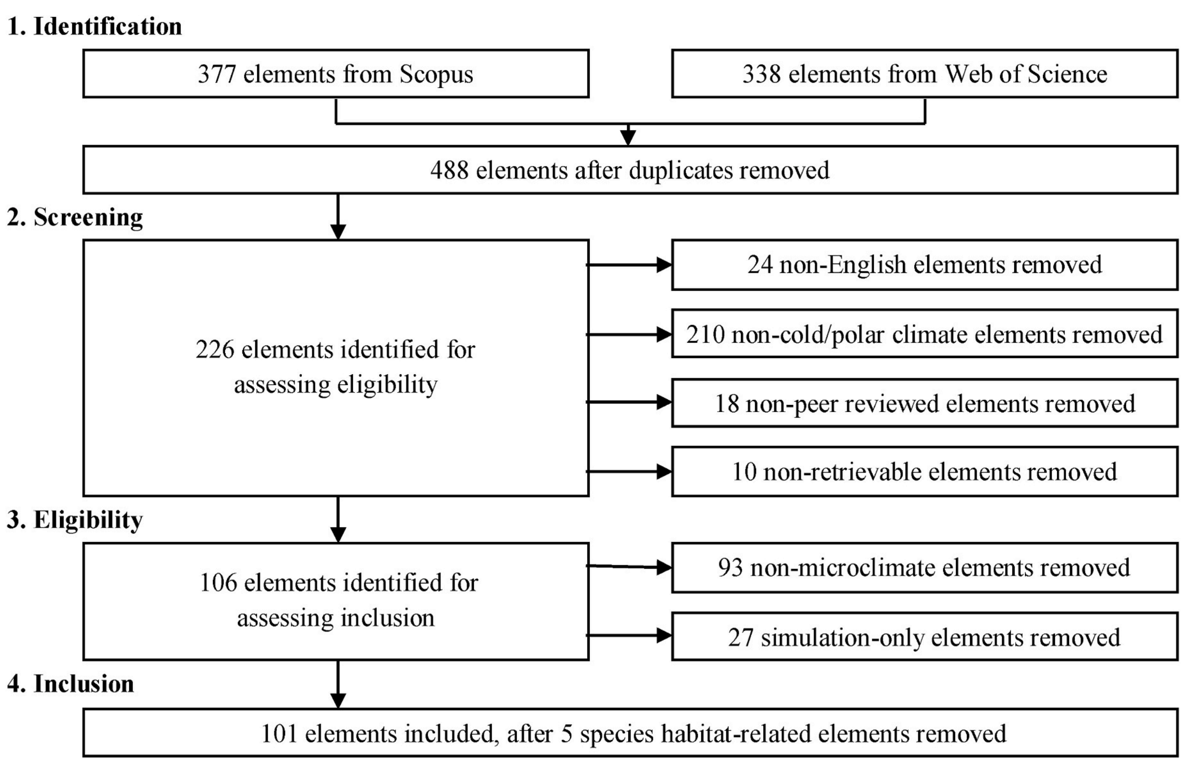

Fig. 2. Flow chart of the applied model for article inclusion (modified from Moher et al. [42]).

2. *UHI mitigation:* Research mainly investigating techniques to mitigate the UHI. This category includes the influence of vegetation, the urban fabric, urban geometry etc.
3. *Other UHI related:* Remaining studies addressing other aspects of the UHI effect.
4. *Biometeorology:* Investigating the impact of meteorological aspects on humans. This can be thermal comfort, health and social studies like behavioral investigations.
5. *Air pollution:* Research focusing on pollutant and aerosol concentrations etc.
6. *UBL and ABL:* Studies on the properties and characteristics of the urban and atmospheric boundary layer.
7. *Time series analyses:* Statistical investigations of long-term temperature measurements without focusing specifically on the UHI etc.
8. *Other urban meteorological phenomena:* All remaining studies satisfying the above-mentioned criteria for inclusion.
9. *Other:* Research not falling under the previous eight categories.

In addition, the articles were classified according to the methods used. The included articles often used more than one method. Following methods were assigned: *On-site measurements*, *remote-sensed measurements*, *numerical studies with validation*, *survey/interview/questionnaire*, and *review*. Table 3 gives an overview of categories and methods with their abbreviations.

3. Results

In total, 715 studies were identified from the two databases. However, not all of the studies were eligible for inclusion in this study. Only 101 fulfilled the criteria and were thus included in this systematic review. Note that the articles presented in this section are the result of applying the above-described methodology. Characteristics like the global distribution of city locations, research topics etc. are purely influenced by the search terms and the content of the databases. The authors did neither include additional sources nor remove any of the identified articles from the literature search in the following analysis.

3.1. Publication analysis

3.1.1. Publication history

Fig. 3 shows a timeline and the number of articles in each year together with the main topic covered in the studies. The red dashed line indicates the percentage of papers in each year dedicated to one of the three UHI-related categories. In total, more than half of the included studies (58 out of 101) address the UHI effect (see also Fig. 4). There is a clear tendency towards more recent publication years. While of the included studies, the first was published in 1975 on the pollution concentration and stratification in the Calgary UHI [47], only 8 of the included studies have been published before the year 2000. However, searching for studies in scientific databases often misses reports issued by public or other research institutions that were not published in the form of a peer-reviewed article but still are of high quality. Especially those public institutions started researching the urban microclimate quite early, e.g. a report on the UHI in Fairbanks, Alaska by the United States Environmental Protection Agency in 1978 [48]. Furthermore, many relevant publications and reports were missed as they did not explicitly mention any of the search terms in their title or abstract. Regarding Norway for instance, missed but very relevant studies covered (among others) the vertical temperature profile [49,50], a statistical analysis of air quality observations [51] in Bergen, or snow mapping in Longyearbyen, Svalbard to improve forecasting of avalanches [52]. Moreover, it needs to be pointed out that many relevant publications have not been published in English and are thus not as accessible to international researchers. It can hence be reasonably assumed that the literature included in this article is only a part of all relevant studies.

Table 3
Abbreviations and descriptions of categories and methods.

Category		Method	
Abbreviation	Description	Abbreviation	Description
UHI-Mag	Focusing on quantifying the UHI	M-OS	On-site measurements
UHI-Mit	UHI-mitigation strategies	M-RS	Remote sensing measurements
UHI-Other	Other research on the UHI	NMV	Numerical models with validation
BM	Biometeorology (health, comfort)	S	Survey (interviews, questionnaires)
AP	Air pollution	Rev	Review
UBL/ABL	Urban and atmospheric boundary layer		
TSA	Time series analysis		
OUMP	Other urban meteorological phenomena		
Other	Research not related to previous categories		

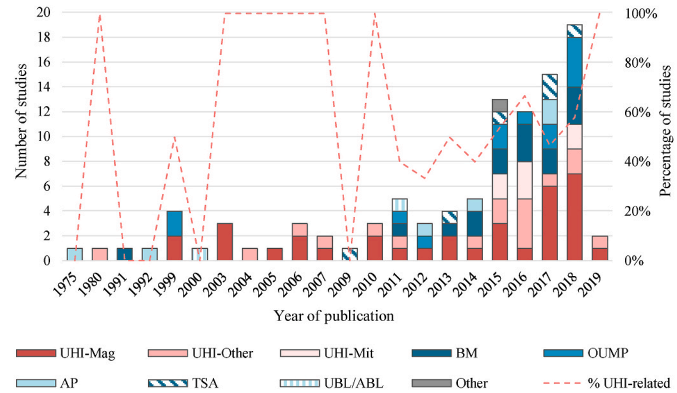

Fig. 3. Number and distribution of categories of studies by year. The dashed line indicates the percentage of studies dedicated to one of the three UHI-related categories.

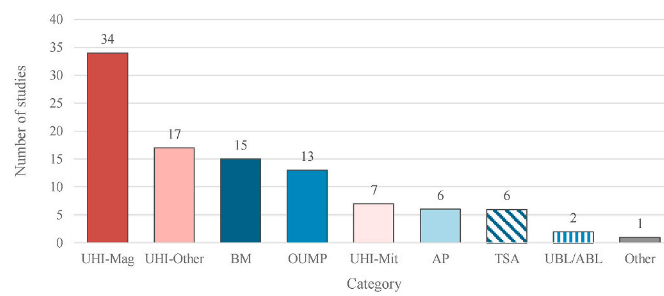

Fig. 4. Number of publications within each category.

3.1.2. Keywords

The dominance of UHI-related research was confirmed by the analysis of used keywords. Table 4 shows the 10 most utilized keywords, where *urban heat island* clearly takes the first rank with 23 times used. *Urban climate* is ranked second (9 times) and *urban microclimate, urbanization/urbanisation, land surface temperature,* and *climate change* share the third place (6 times). However, about one-third of the included articles (34 out of 101) had no keywords indicated.

3.1.3. Journals published and citations

In total, the included articles were published in 53 different peer-reviewed journals. Three studies were conference articles, published in indexed conference proceedings. The journals' thematic background covered atmospheric sciences and climatology, engineering, biometeorology, geography, and health and medicine among others. Fig. 5 illustrates the five most popular journals among the included studies, together with the number of published articles.

Most frequently, they were published in *Theoretical and Applied Climatology* with a count of 13. Following behind, 6 were published in the *Journal of Applied Meteorology and Climatology*, 5 in *Atmospheric*

Table 4
10 most used keywords in the included studies.

Rank	Keyword	No. of times used
1	Urban heat island	23
2	Urban climate	9
3	Urban microclimate	6
3	Urbanization/Urbanisation	6
3	Land surface temperature	6
3	Climate change	6
7	Air temperature	5
8	Finland	3
8	MODIS (imagery)	3
8	Surface Energy balance	3

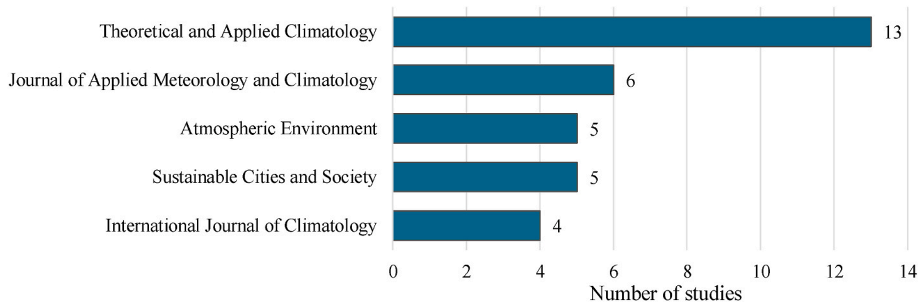

Fig. 5. Most popular journals among the included studies for publication on urban microclimate in cold and polar climate.

environment and *Sustainable Cities and Society*, and 4 in the *International Journal of Climatology.* The overwhelming part of journals was used for one article only.

According to the Scopus database as of March 2019, the study on the *Temporal and spatial characteristics of the urban heat island of Łódź, Poland* by Kłysik and Fortuniak [53] is the most cited article that was included in this study (see Table 5). All but one of the 10 most cited studies covered a UHI-related topic.

3.1.4. Location and climate

Research on urban microclimate in cold and polar climate regions (according to the Köppen-Geiger classification) was carried out in 16 different countries (see Fig. 6). In 6 of those, only one study was conducted. Three of the included studies were review papers that did not focus on specific locations. Most frequently, research was carried out on locations in the USA (21), China (16) and Russia (15). Only a few articles took Scandinavian cities as case studies (11 in total), most of them in Finland (6).

In a similar way, Fig. 7 shows the number of studies according to the climate type of their locations.

A climate type received a count only if an article used at least one location from the respective climate type. Several locations from one climate type in the same study only result in one count. Most frequently, Dfb-locations (Warm summer humid continental climate) were object of investigation (51), mainly in North America and Europe, followed by Dwa (20) (Monsoon-influenced hot-summer humid continental climate) mainly from studies in China and South Korea, and Dfc (15) (Subarctic climate) which is by far the most common subarctic type primarily from studies in Russia. Only few studies covered Dfa (Hot summer humid continental), ET (Tundra climate), Dwd (Monsoon-influenced extremely cold subarctic climate), Dsb (Mediterranean-influenced warm-summer humid continental climate) and Dwc (Moonsoon-influenced subarctic climate) regions.

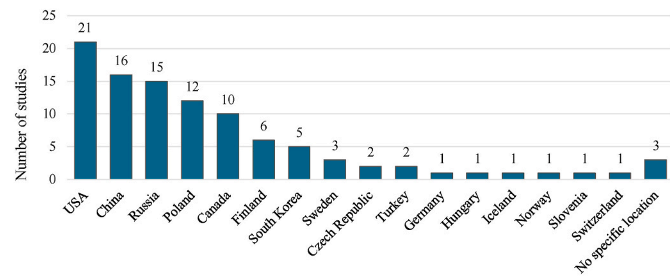

Fig. 6. Number of studies covering research on a location in the respective countries.

Several climate types were not represented by any of the included studies, such as Dsa (Mediterranean-influenced hot summer humid continental climate), Dsc (Mediterranean influenced subarctic climate), Dsd (Mediterranean-influenced extremely cold subarctic climate), Dwd (Monsoon-influenced subarctic climate), Dfd (extremely cold subarctic climate), and EF (Ice cap climate).

3.1.5. Research methods

The following Fig. 8 illustrates the number of studies applying each

Table 5
Top 10 most cited articles of included studies according to Scopus.

Rank	Times cited	Title	Authors	Year	Journal	Category
1	195	Temporal and spatial characteristics of the urban heat island of Łódź, Poland	Kłysik and Fortuniak [53]	1999	Atmospheric Environment	UHI-Mag
2	148	Spatial and Temporal Structure of the Urban Heat Island in Seoul	Kim and Baik [54]	2005	Journal of Applied Meteorology	UHI-Mag
3	144	Mesoscale aspects of the Urban Heat Island around New York City	Gedzelman et al. [55]	2003	Theoretical and Applied Climatology	UHI-Mag
4	81	Urban Canopy Modeling of the New York City Metropolitan Area: A Comparison and Validation of Single- and Multilayer Parameterizations	Holt and Pullen [56]	2007	Monthly Weather Review	UHI-Other
5	80	The Urban Heat Island in Winter at Barrow, Alaska	Hinkel et al. [57]	2003	International Journal of Climatology	UHI-Mag
6	78	Comparing the effects of urban heat island mitigation strategies for Toronto, Canada	Wang et al. [58]	2016	Energy & Buildings	UHI-Mit
7	48	Influence of geographical factors and meteorological variables on nocturnal urban-park temperature differences - a case study of summer 1995 in Göteborg, Sweden	Upmanis and Chen [59]	1999	Climate Research	OUMP
8	47	Urban climatological studies in the Reykjavik subarctic environment, Iceland	Steinecke [60]	1999	Atmospheric Environment	UHI-Mag
9	42	Analysis of observations on the urban surface energy balance in Beijing	Miao et al. [61]	2012	Science China Earth Sciences	UHI-Other
10	41	Statistical and dynamical characteristics of the urban heat island intensity in Seoul	Lee and Baik [62]	2010	Theoretical and Applied Climatology	UHI-Mag

Abbreviations: Magnitude of the UHI (UHI-Mag); Other research on the UHI effect (UHI-Other); Mitigation strategies of the UHI (UHI-Mit); Other urban meteorological phenomena (OUMP).

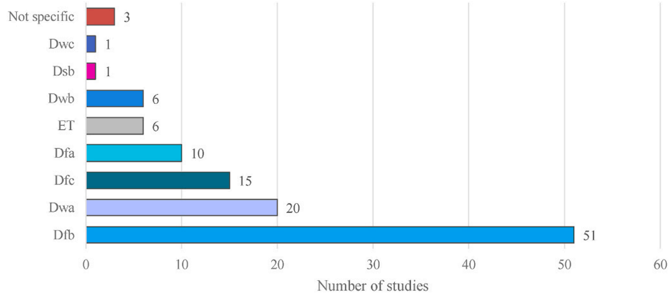

Fig. 7. Number of studies covering a specific climate type according to the Köppen-Geiger classification. The colors of the bars represent the same colors as used in Fig. 1 and thus the study by Peel et al. [40]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

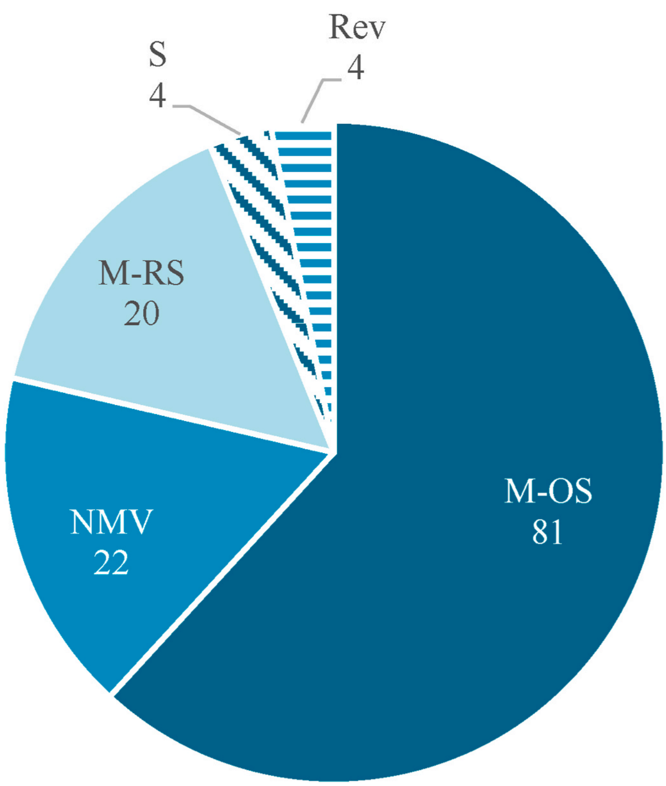

Fig. 8. Number of studies using each research method. M-OS: On-site measurement; NMV: Numerical model with validation; M-RS: Remote sensing measurement; S: Survey; Rev: Review.

of the research methods.

Many of the included studies based on more than one method, combining a numerical model for example with on-site or remote sensing measurements etc. However, direct measurements on site were the predominantly used method with 81 out the 101 included studies, followed by validated numerical models (22) and remote sensing measurements (20). Since one of the eligibility criteria was to not include numerical studies without validation, NMV has exclusively been applied in combination with M − OS and M-RS for validation purposes. Only 4 of the included articles conducted a survey (interview/questionnaire) and a review, respectively.

3.2. Research evaluation

The following sections discuss the main findings of research carried

Table 6
Overview of studies in the category “UHI-magnitude”.

No.	Authors	Year	Location, Country	Climate	Method
1	Kłysik and Fortuniak [53]	1999	Łódź, Poland	Dfb	M-OS
2	Steinecke [60]	1999	Reykjavik, Iceland	Dfc	M-OS
3	Gedzelman et al. [55]	2003	New York, USA	Dfa	M-OS
4	Hinkel et al. [57]	2003	Barrow, USA	ET	M-OS
5	Klene et al. [63]	2003	Barrow, USA	ET	M-OS
6	Kim and Baik [54]	2005	Seoul, South Korea	Dwa	M-OS
7	Khaikine et al. [64]	2006	Moscow, Russia	Dfb	M-RS
8	Lu and Weng [65]	2006	Indianapolis, USA	Dfa	M-RS
9	Hinkel and Nelson [66]	2007	Barrow, USA	ET	M-OS
10	Lee and Baik [62]	2010	Seoul, South Korea	Dwa	M-OS
11	Stopa-Boryczka et al. [67]	2010	Warsaw, Poland	Dfb	M-OS
12	Malevich and Klink [68]	2011	Minneapolis, USA	Dfb	M − OS, NMV
13	Suomi and Käyhkö [69]	2012	Turku, Finland	Dfb	M-OS
14	Klene et al. [70]	2013	Barrow, USA	ET	M-OS
15	Walawender et al. [71]	2013	Kraków, Poland	Dfb	M-RS
16	Schatz and Kucharik [72]	2014	Madison, USA	Dfb	M-OS
17	Konstantinov et al. [73]	2015	Apatity, Russia	Dfc	M − OS, M-RS
18	Schatz and Kucharik [74]	2015	Madison, USA	Dfb	M-OS
19	Sun et al. [75]	2015	Beijing, China	Dwa	M-RS
20	Ramamurthy and Sangobanwo [76]	2016	several in Northern USA	Dfa/Dfb	M-OS
21	Huang et al. [77]	2017	several in China	Dwa/ Dwb/ Dwc	M − OS, M-RS
22	Kuznetsova et al. [78]	2017	Moscow, Russia	Dfb	M-OS
23	Miles and Esau [79]	2017	Northern West Siberia	Dfc	M-RS
24	Półrolniczak et al. [80]	2017	Poznań, Poland	Dfb	M-OS
25	Przybylak et al. [81]	2017	Toruń, Poland	Dfb	M-OS
26	Shumilov et al. [82]	2017	Kirovsk and Apatity, Russia	Dfc	M-OS
27	Konstantinov et al. [83]	2018	Russian Arctic	Dfc	M-OS
28	Marzban et al. [84]	2018	Berlin, Germany	Dfb	M − OS, M-RS
29	Matuzko and Yakubailik [85]	2018	Krasnoyarsk, Russia	Dfc	M − OS, M-RS
30	Suomi [86]	2018	Lahti, Finland	Dfc	M-OS
31	Varentsov et al. [87]	2018	Apatity, Russia	Dfc	M − OS, NMV, M-RS
32	Yang and Bou-Zeid [88]	2018	12 cities in the US	Dfa/Dfb	M − OS, NMV
33	Yao et al. [89]	2018	Northern China	Dwa/ Dwb	M-RS
34	Esau et al. [90]	2019	Nefteyugansk, Russia	Dfc	M-RS

Abbreviations: On-site measurements (M − OS); Remote-sensed measurements (M-RS); Numerical models with validation (NMV).

out in each of the categories and summarizes some of the main publications shortly.

3.2.1. UHI-magnitude

With almost one-third of all studies dealing with the UHI-magnitude, which are summarized in Table 6, it was the most-covered research topic of all included articles.

Typically, direct M − OS was used to identify the magnitude, spatial and temporal structure of the UHI. A smaller number of studies used M-RS or satellite images, like Moderate-Resolution Imaging Spectroradiometer (MODIS) [75,79], Landsat-8 [71,90], or both [89] for obtaining data, sometimes also in addition to M − OS [73,77,84,85,87]. One study on the UHI in Moscow, Russia used microwave temperature profilers (MTP-5) to obtain a temperature profile of the lower 600-m layer of the atmosphere [64].

Generally, magnitude and temporal appearance of the UHI differed significantly between the reviewed studies. Almost all of them observed a seasonal variation of the UHI, although quite varied and with highest intensities in different seasons: summer [53,67,69,72,81,86], summer and autumn [55], autumn [62], and winter [54,57,66,76,79]. In the majority of cases, highest UHI-intensities were reported during nights [62,64,67,76,80,81] or nights with clear skies [53–55,72,78]. The studies largely agreed that higher wind speeds weakened the intensity of the UHI [53–55,57,60,66,67,72,76,78,81,83,86,87]. Highest UHI-intensities frequently occurred during anticyclonic weather conditions as they often come along with clear and dry weather [80,83,87].

Several studies reported the distinct cooling influence of large water bodies on the spring and summer UHI in coastal cities [55,60,69,76]. Equally, they contribute to the UHI in autumn [62,86], which frequently evoked a cool island during the day [60,69]. Even without the influence of large water bodies, a cool island during daytime was observed in two studies [53,62]. Arguably, even though not specifically mentioned in the study by Lee and Baik [62], the daytime cool island in spring in Seoul, South Korea may be evoked by the close-by and cooler sea in a similar way, as it is supposed to contribute to the UHI in autumn because of higher water temperatures and frequent westerly winds [91].

The studies in this category largely agree upon the significant influence of anthropogenic heat release [62,66,76,78,83,87,88,90]. One article, on the contrary, suspected meteorological and topographical factors to be more important than anthropogenic in Apatity and Kirovsk in the Russian Arctic [82].

Studies focusing on the land surface temperature (LST) agreed that highest temperature anomalies generally occur within industrial and commercial areas like shopping centers where vegetation is scarce. Forests, larger urban parks, and water bodies were always coolest [65,71,74,85]. Not surprisingly, due to increased heat storage capacity and shadowing, urban areas were often reported to have slower warming and cooling pace [60,67,69]. In Minneapolis, USA, a snow cover of 5 cm or more was reported to increase the UHI by about 1 °C due to a higher albedo during the day and 0.5 °C at night because of enhanced insulation properties, compared to same weather conditions, just without snow [68,72]. Moderate snowfall decreased the magnitude of the UHI by up to 2 °C [68].

A considerable amount of research has been conducted in Barrow in Northern Alaska, USA (now Utqiaġvik), one of the few locations in climate type ET. Despite the small size of the settlement (around 4.500 inhabitants), a distinct winter-UHI has been measured, amounting to 2.2 °C on average and reaching up to 6 °C [57]. A strong correlation between the UHI-intensity and anthropogenic heat release (consumption of natural gas) was reported [66]. Both studies mention a reduction in freezing degree days [57,66]. Furthermore, summer soil-surface temperatures were reported to be between 0.3 and 2.3 °C higher in the city. This caused the active layer (the near-surface layer of the soil that freezes and thaws annually) to be 15–40 cm thicker in urban than in rural locations [70]. Similar results were obtained in an earlier study, where the active layer was indicated even 25–55 cm thicker [63].

Some of the largest settlements by population above the Arctic Circle are situated in Russia. In Apatity, Konstantinov et al. [73] made use of MODIS satellite images and field measurements to quantify the urban-rural temperature differences. The mean UHI magnitude of a three-day period in January 2014 was 2.7 °C from the satellite images and 1.6 °C from the field measurements. Differences got as high as 4–5 °C. Other studies in Apatity [87], and Apatity and Kirovsk [82] reported similar results.

In a comprehensive study, the UHI characteristics of 28 cities in northern West Siberia were analyzed from MODIS imagery [79]. All cities are located above 60° N with populations from just a few in Bovanenkovskiy in the very North of the region, up to around 330 000 in Surgut in the South. Despite the very low mean annual surface air temperatures of between −2 and −9 °C and permafrost soil [92], the mean summer UHI was 0.5–2.5 °C. Only in the three northernmost (and quite small) towns Yar-Sale, Bovanenkovskiy, and Tazovskiy, a cool island of −0.5 to −1.7 °C was detected. In winter, the UHI ranges from around 0.2 to 3.1 °C. Only in the city of Surgut, where a huge gas-fired power plant changes LST significantly, the UHI reaches 8 °C on average in winter. A study using on-site measurements in a smaller subset of cities in the same region reports a UHI intensity in a similar magnitude [83]. In this category's most recent study, a similar UHI intensity was reported in the city of Nefteyugansk, near Surgut (2.4 °C in summer and 2.1 °C in winter) [90].

Sun et al. [75] compared the CLHI and the remotely measured SLHI in Beijing, China. They report greater differences during the daytime than during the nighttime. The daytime difference had a noticeable seasonal variation that was small and negative in cold seasons but large and positive in warm seasons. The night-time difference was not subjected to significant seasonal variation. A similar study in Berlin, focusing on the differences between remotely measured LST and air temperature in 2 m height, found a quite opposing relationship. The correlation was reported higher during cold seasons than in warm seasons, and higher during daytime than during night-time [84].

3.2.2. UHI-other

In this category, articles of several different research areas around the UHI that are not primarily focusing on its intensity or mitigation strategies are collected (see Table 7). However, there are partly overlaps to other categories, especially when it comes to the categories *UHI-Mag* and *UHI-Mit*.

Some of the studies used NMV to investigate how new construction will affect the UHI or the microclimate in urban areas [34,100]. Using single- and multilayer parametrizations, two studies conducted simulations with the coupled *Ocean-Atmosphere Mesoscale Prediction System* and different urban canopy parametrizations to assess their impact in a mesoscale model of New York in the USA [56,95].

Another two studies were dedicated to predicting urban-rural temperature differences. While one study in Turku, Finland used variables from Geographical Information System (GIS) databases [97], a study in Ljutomer, Slovenia, used a geospatially weighted regression model to predict the urban-rural temperature differences in different weather patterns [107]. Similar to other studies mentioned before, e.g. Ref. [80,83,87], they found the UHI intensity was highest during anticyclonic weather patterns. However, predictions were most accurate during cyclonic weather patterns [107]. Lemonsu et al. [96] used the TEB and the *Interactions between Soil, Biosphere, and Atmosphere parametrization* to simulate surface radiation and energy exchanges in Montreal, Canada. Simulations showed good performance when the roads were snow-covered. Snowmelt and anthropogenic heat fluxes were reasonably well represented, whereas storage heat flux was underestimated.

Bokwa et al. [99] proposed a relief-modified UHI (RMUHI) approach since in cities that are located in concave landforms, the impact of land use and relief on air temperature cannot be separated from one another. Their RMUHI approach consists of two steps: (1) recognition of the areal thermal structure taking into consideration the city center as a reference

Table 7
Overview of studies in the category "UHI-Other"

No.	Authors	Year	Location, Country	Climate	Method
1	Nkemdirim [93]	1980	Calgary, Canada	Dfb	M-OS
2	Hinkel et al. [94]	2004	Barrow, USA	ET	M-OS
3	Pullen et al. [95]	2006	New York/New Jersey, USA	Dfa	M − OS, NMV
4	Holt and Pullen [56]	2007	New York, USA	Dfa	M − OS, NMV
5	Lemonsu et al. [96]	2010	Montreal, Canada	Dfb	M − OS, NMV
6	Hjort et al. [97]	2011	Turku, Finland	Dfb	M-OS
7	Arola and Korkka-Niemi [98]	2014	Turku, Lohja, and Lahti, Finland	Dfb/Dfc	M-OS
8	Bokwa et al. [99]	2015	Kraków, Poland	Dfb	M-OS
9	Fang et al. [100]	2015	Beijing, China	Dwa	M − OS, NMV, M-RS
10	Berardi et Wang [101]	2016	Toronto, Canada	Dfb	M − OS, NMV
11	Hatchett et al. [102]	2016	Reno, USA	Dsb	M-OS
12	Klimenko et al. [103]	2016	Large cities in Russia, Poland and Germany	Dfb	M-OS
13	Lokoshchenko et al. [104]	2016	Moscow, Russia	Dfb	M-OS
14	Wicki and Parlow [105]	2017	Basel, Switzerland	Dfb	M-RS
15	Fu and Weng [106]	2018	Numerous cities in the US	Dwb/Dfa/Dfb/Dfc	M-RS
16	Ivajnšič and Žiberna [107]	2018	Ljutomer, Slovenia	Dfb	M − OS, NMV
17	He et al. [108]	2019	Shenyang, China	Dwa	M-RS

Abbreviations: On-site measurements (M − OS); Remote-sensed measurements (M-RS); Numerical models with validation (NMV).

point and (2) calculation of RMUHI intensity separately for each vertical zone. Using helicopter transacts in Calgary, Canada, it was found that the influence of relief, or more precisely of cold air drainage from the surrounding hills reduced the magnitude of the UHI by about 40% of its potential value [93].

Arola and Korkka-Niemi [98] investigated groundwater temperature differences in southern Finland. They found that the average temperature below the zone of seasonal temperature fluctuations (from around 8 m depth) was 1.3–2.0 °C higher in the urban area and 3–4 °C higher in the city centers than in the rural areas. They estimate that 50–60% more peak heating power could be utilized from a groundwater-based heat pump in populated areas. Simultaneously 40–50% peak cooling power is lost through the higher temperatures.

Two studies were dedicated to the relationships between LST and land use/land cover (LULC). He et al. [108] investigated the impact of background temperature on the performances of cool/hot sources in either enhancing or mitigating the LST. Wicki and Parlow [105] analyzed the dependence of LST on LULC and found a stronger correlation during warmer summer months and the increasing influence of the topography and albedo during colder seasons. Both studies confirmed the frequently reported positive relationship between higher LST in industrially and commercially dominated surface patches and the negative relationship between forests or highly vegetated surface patches [65,71,74,85].

3.2.3. UHI-mitigation

Despite the cold or polar climate classification, several cities face pronounced heat waves and thus overheating during summer. In this category, those dedicated to mitigating the adverse effects of the UHI are collected (see Table 8).

Two Canadian studies used the numerical micro-scale climate model

Table 8
Overview of studies in the category "UHI-Mit"

No.	Authors	Year	Location, Country	Climate	Method
1	Jianying et al. [109]	2015	Cleveland, USA	Dfb	M-OS
2	Touchaei and Akbari [110]	2015	Montreal, Canada	Dfb	M − OS, NMV
3	Kim et al. [111]	2016	Seoul, South Korea	Dwa	M − OS, NMV
4	Wang and Akbari [112]	2016	Montreal, Canada	Dfb	M − OS, NMV
5	Wang et al. [58]	2016	Toronto, Canada	Dfb	M − OS, NMV
6	Chun and Guldmann [113]	2018	Columbus, USA	Dfa	M-RS
7	Jiang et al. [114]	2018	Xi'an, China	Dwa	M-OS

Abbreviations: On-site measurements (M − OS); Remote-sensed measurements (M-RS); Numerical models with validation (NMV).

ENVI-met to analyze different UHI mitigation strategies in Montreal and Toronto. In Montreal, vegetation planting and an increased urban albedo can reduce the UHI effect during the day, while urban sky view factor (SVF) control can reduce the UHI effect at nighttime [112]. Urban typology and urban vegetation shading affected solar radiation storage during the summer day in Toronto and contributed to the UHI mitigation. By adding 10% of urban vegetation, the outdoor air temperature could be reduced by 0.5–0.8 °C in the day time [58]. The positive effects of urban greenery were furthermore emphasized in a study in Seoul, South Korea [111] and Columbus, Ohio, USA [113]. However, in an article investigating the cooling potential of an increased albedo in Montreal and the impact on annual energy demands of heating, ventilation and air-conditioning (HVAC) systems found only a minor financial saving potential of around 1 $/100 m^2 urban area [110].

Two studies dealt with experimental investigations on asphalt composition since their impervious and dark surfaces contribute strongly to the UHI. It was found that thermoelectric asphalt pavements can reduce the surface temperature by 8–9 °C in hot seasons by simultaneously generating electricity. The output of a 1 km long and 10 m wide surface was quantified with 33 kWh on a single day in summer [114]. The other article studied the asphalt's optical properties when thermochromic powder is added to a conventional asphalt binder. They report that a thermochromic asphalt binder can reduce the surface temperature during summer and increase it during winter. This way, it contributes to the asphalt's durability and mitigates the adverse effects of the UHI in summer [109].

3.2.4. Other urban meteorological phenomena

This section collects articles on different other urban meteorological phenomena (see Table 9).

Some articles were dedicated for example to the urban-rural humidity difference [115], the statistical properties of low-level jets [116], or low-level temperature inversions [117]. Other addressed the magnitude of nighttime air temperature differences between an urban park and a built-up area [59], the simulation of nighttime cold airflow from near-by mountains [123], or the occurrence of cold days and cold waves [124].

The urban energy balance was the object of investigation in three articles. In particular, one study focused on the area-averaged sensible heat flux [125], another used measurements on a 325-m tower in downtown Beijing to quantify the energy balance of the urban surface [61]. The third study investigated the performance of three urban land-surface models for two distinctly different sites in Helsinki. They suggested that improvements are needed in the parametrization of anthropogenic heat flux, thermal parameters in winter, snow cover in spring, and evapotranspiration [119]. Generally, all models had the most difficulties in simulating the latent heat flux.

Multiple studies confirmed the significant influence of cities on

Table 9
Overview of studies in the category "OUMP"

No.	Authors	Year	Location, Country	Climate	Method
1	Unger [115]	1999	Szeged, Hungary	Dfb	M-OS
2	Upmanis and Chen [59]	1999	Gothenburg, Sweden	Dfb	M-OS
3	Kallistratova and Kouznetsov [116]	2011	Moscow, Russia	Dfb	M-OS
4	Miao et al. [61]	2012	Beijing, China	Dwa	M-OS
5	Stryhal et al. [117]	2015	Prague, Czech Republic	Dfb	M-RS
6	Zhong and Yang [118]	2015	Beijing, China	Dwa	M – OS, NMV
7	Karsisto et al. [119]	2016	Helsinki, Finland	Dfb	M – OS, NMV
8	Li et al. [120]	2017	Beijing, China	Dwa	M – OS, NMV
9	Li et al. [121]	2017	Beijing, China	Dwa	M – OS, NMV
10	Johnson and Shepherd [122]	2018	Northeastern US	Dfa/Dfb	M-OS
11	Son et al. [123]	2018	Gwangju, South Korea	Dfb	M – OS, NMV, M-RS
12	Tomczyk et al. [124]	2018	Poznań, Poland	Dfb	M-OS
13	Zieliński et al. [125]	2018	Łódź, Poland	Dfb	M-OS

Abbreviations: On-site measurements (M – OS); Remote-sensed measurements (M-RS); Numerical models with validation (NMV).

precipitation events [118,120–122]. Johnson and Shepherd [122] concluded that in the northeastern USA, the boundary layer UHI may play an important role in increasing the melting of hydrometeors. Proximity to urban centers plays a role in the surface observation of mixed precipitation events.

3.2.5. Biometeorology

The term biometeorology comprises the interactions between atmospheric processes and living organisms, i.e. plants, animals and humans [126]. Due to the focus of this systematic review on climate-human interactions, studies addressing plants and animal species have been excluded. Most of the studies that used a survey (S) as research method (3 out of 4) are embodied in this category. Comfort and wellbeing were the most frequently covered topics in this category. The studies in this category are summarized in Table 10.

A survey in the subarctic Finnish town of Kuopio reported that green spaces and time spent in nature were associated with high levels of comfort and wellbeing (CW) while cold housing and poor indoor air quality were related with low levels of CW [137]. An experiment in an urban park in Xi'an, China indicated that CW and thermal sensation closely correlated. In winter, most important factors affecting CW were global radiation, followed by air temperature and relative humidity. Wind speed was found to be least important [141].

Three articles studied the meteorological factors influencing comfort in the Polish cities Szczecin, Warsaw and Gdańsk. Generally, the studies agree that close to the city center "hot" conditions appear more and "cold" less often than in the outskirts. Therefore, the outskirts provide a more favorable microclimate during summer but the city during winter [128,130,132]. Dursun and Yavaş [140] used simulations with ENVI-Met and measurements in Erzurum, Turkey, to investigate the relationship between microclimate and urban planning, specifically in terms of CW. Results indicated that irregular building plots and heights led to more favorable microclimatic conditions than regular ones. Targhi and van Dessel [133] studied the summer conditions in Worcester, Massachusetts USA. They found considerable differences in heat stress for pedestrians between street canyons of different orientations in July. Especially at around noon, the East-West configuration led to extreme values of the Physiological Equivalent Temperature (PET) [142] of

Table 10
Overview of studies in the category "BM"

No.	Authors	Year	Location, Country	Climate	Method
1	Taesler [127]	1991	–	–	Rev
2	Czarnecka et al. [128]	2011	Szczecin, Poland	Dfb	M-OS
3	Bauche et al. [129]	2013	Birobidzhan, Russia	Dwb	M-OS
4	Majewski et al. [130]	2014	Warsaw, Poland	Dfb	M-OS
5	Urban et al. [131]	2014	Prague and Bohemia, Czech Republic	Dfb	M-OS
6	Nidzgorska-Lencewicz [132]	2015	Gdańsk, Poland	Dfb	M-OS
7	Targhi and van Dessel [133]	2015	Worcester, USA	Dfb	M – OS, NMV
8	Coccolo et al. [134]	2016	–	D/E	Rev
9	Lowe [135]	2016	Several in Northern USA	Dfa/Dfb	M-RS
10	Chapman et al. [136]	2017	Luleå, Sweden	Dfc	S
11	Hiscock et al. [137]	2017	Kuopio, Finland	Dfc	S
12	Petrov et al. [138]	2017	Samburg, Russia	Dfc	M-OS
13	Chi et al. [139]	2018	Several Cities in China	Dwa/Dwb	M-OS
14	Dursun and Yavaş [140]	2018	Erzurum, Turkey	Dsa	M – OS, NMV
15	Xu et al. [141]	2018	Xi'an, China	Dwa	M – OS, S

Abbreviations: On-site measurements (M – OS); Remote-sensed measurements (M-RS); Numerical models with validation (NMV); Review (Rev); Survey (S).

around 50 °C, while maximum values of a North-South oriented canyon in the afternoon hours led to a PET of only around 30–40 °C [133].

Another component of biometeorology is the impact of meteorological factors on people's health. Bauche et al. [129] investigated the effect of urban structures on human thermal comfort indices in the extreme climate of Birobidzhan in the Russian Far East, where the annual temperature can range from around −30 °C to +30 °C. The winter conditions lead to extreme cold stress with a PET below −20 °C in about 70% of the time in January. Urban et al. [131] examined the heat- and cold-stress related cardiovascular morbidity and possible regional differences in the Czech Republic, namely the city of Prague and the rural region of southern Bohemia from 1994 to 2009. They reported a generally higher relative cardiovascular excess mortality on warm compared to cold days. The results furthermore indicated slight differences in population vulnerability between the two regions, due to environmental and socioeconomic factors. Petrov et al. [138] considered the impact of urbanization and climatic conditions on the health status of the indigenous Nenets people in Samburg, Russia, by taking blood samples and correlating immunological parameters with climatic indicators. Lowe [135] analyzed the impact of the UHI on energy and mortality. He found that in the north of the US, energy use decreased from the UHI as heating energy reductions were larger than cooling energy increase. At the same time, cold-related deaths were estimated with a decrease of 4 deaths per million people. Hypothermia-related death rates were three times higher in rural areas than in urban areas. A surprising result, considering that homeless people that predominantly live in urban areas are usually considered the most at risk.

Teasler [127] collected research and elaborated on the processes of the urban atmosphere in temperate and high-latitude locations. He stressed the need for relevant bioclimatic design tools. Certainly, regarding the almost three-decade spanning period of time in between his study and today, a great amount of computational progress has been made and a variety of tools and models have been developed to assess and quantify thermal comfort in outdoor spaces. The Universal Thermal

Climate Index (UTCI) [143] or the PET, for instance, can be obtained spatially resolved from several numerical tools. Another review of tools for modelling outdoor human comfort and thermal stress was conducted by Coccolo et al. [134].

3.2.6. Air pollution

Anthropogenic pollution is considered to be one of the main threats to physiological systems and the environment [144]. Especially urban air is frequently linked to medical risks. Several studies were thus dedicated to air pollution, e.g. the variation of toxicants and the coefficient of haze [47], the air pollution concentration of particulate matter (PM) [145] or air pollution levels an ancient city U-type street canyon in China [146] (see Table 11).

Leahey and Hansen [147] presented a method for estimating the CO_2 flux from Calgary, Canada, during nocturnal periods characterized by stable air. Cheng et al. [148] studied the seasonal and diurnal patterns of gaseous elementary mercury (GEM), gaseous oxidized mercury (GOM) and particle-bound mercury (PBM) in Dartmouth, Canada.

Because trees can contribute actively to air pollution through the emission of Biogenic Volatile Organic Compounds (BVOC) in particular conditions, Fierravanti et al. [149] gave an overview of reference cities for expanding research on this issue. However, several publications that were not identified by the search methodology indicated that urban trees are able to reduce the concentration of pollutants like traffic emissions in the air [150–155]. On the other hand, some studies point to the diminished ventilation ability in urban tree canopies and thus locally higher pollutant concentrations, e.g. Ref. [156].

3.2.7. Time series analysis

A time series is defined as a collection of observations taken sequentially in time [157]. In the case of meteorological observations, those are often long-time records over several years, decades or even centuries. They are usually analyzed to extract statistically relevant information or correlations to other covariates or trends. Table 12 summarizes the studies in this category.

The articles in this category frequently reported increasing temperatures during the times of observation. In the 175-year temperature records of Oslo, Norway, Nordli et al. [160] found a significant increase of annual mean temperature (1.5 °C), which mainly occurred during the last 50 years and in the early 20th century. Especially cold seasons were affected the most by the changes, as temperatures in winter and spring increased more than twice as much as in summer.

Anderson and Gough [161] contextualized the pronounced cold-anomaly winters of 2013/14 and 2014/15 in Toronto, Canada within historical weather observations. Toronto winter temperatures have warmed significantly during the history of the weather records since 1840, especially the December temperatures. Urbanization and the UHI are supposed to contribute considerably to the local conditions since Toronto's weather station is situated in the very center of the city.

Lokoshchenko et al. [162] used long-term radiosonde measurements and sensors installed on a television tower in Moscow, Russia from 1991 to 2013 to investigate the lower 4-km layer of the atmosphere. During this period, the mean annual temperature at all heights from 2 to 4000 m increased by an average of 0.1 °C per year, with the warming slowing down in the more recent years.

In the Huang-Huai-Hai river basin in China, the daily maximum temperature increased with a magnitude of 0.15 °C per decade on the regional scale from 1961 to 2014. The increase of daily minimum temperatures was even more pronounced with 0.49 °C per decade. Due to rapid urbanization, the UHI is assumed to have an impact on the amplitude of variations in extreme temperatures [163].

In Erzurum in Turkey, population growth, the number of vehicles, buildings and green area amount in the city had no significant effect on mean air temperatures from 1950 to 2005. However, the relationships partly between population growth and maximum temperature and partly between the number of vehicles and minimum temperature were found to be statistically significant [158].

Wang et al. [159] quantified the impact of urbanization on changes in observed surface air temperatures and temperature extremes in Beijing, China, between 1978 and 2008. They found that at urbanized sites an added warming trend in annual mean temperature occurred. Urbanization has furthermore increased the amount of extremely warm nights and decreased the amount of extremely cold nights at the urbanized sites.

3.2.8. Urban and atmospheric boundary layer

Only two articles specifically focused on the structure of the urban boundary layer (UBL) or the atmospheric boundary layer (ABL) (see Table 13).

Sang et al. [164] studied the characteristics of the winter UBL in Shenyang, China. Observations showed that with light winds the ground inversion at nighttime was around 200 m deep and that anthropogenic heating caused a heat island circulation that induced reverse flow at the downwind part of the city. Lee and Baik [165] compared simulation results from coupling the Vegetated Urban Canopy Model with the Regional Atmospheric Modeling System with meteorological observations in Seoul, South Korea. The results indicate a similar size of the nighttime UBL of about 100–200 m, as in Shenyang [164].

3.2.9. Other

One included paper could not be categorized by one of the previously presented categories, as it addresses a quite different perspective of

Table 11
Overview of studies in the category "AP"

No.	Authors	Year	Location, Country	Climate	Method
1	Nkemdirim et al. [47]	1975	Calgary, Canada	Dfb	M-OS
2	Leahey and Hansen [147]	1992	Calgary, Canada	Dfb	M-OS
3	Górka-Kostrubiec et al. [145]	2012	Warsaw, Poland	Dfb	M-OS
4	Cheng et al. [148]	2014	Dartmouth, Canada	Dfb	M-OS
5	Cui et al. [146]	2017	Xi'an, China	Dwa	M-OS
6	Fierravanti [149]	2017	–	various	Rev

Abbreviations: On-site measurements (M – OS); Review (Rev).

Table 12
Overview of studies in the category "TSA"

No.	Authors	Year	Location, Country	Climate	Method
1	Yilmaz et al. [158]	2009	Erzurum, Turkey	Dsa	M-OS
2	Wang et al. [159]	2013	Beijing, China	Dwa	M-OS
3	Nordli et al. [160]	2015	Oslo, Norway	Dfb	M-OS
4	Anderson and Gough [161]	2017	Toronto, Canada	Dfb	M-OS
5	Lokoshchenko et al. [162]	2017	Moscow, Russia	Dfb	M-OS
6	Wang et al. [163]	2018	Huang-Huai-Hai River Basin, China	Dwa/ Dwb	M-OS

Abbreviations: On-site measurements (M – OS).

Table 13
Overview of studies in the category "UBL/ABL"

No.	Authors	Year	Location, Country	Climate	Method
1	Sang et al. [164]	2000	Shenyang, China	Dwa	M – OS, NMV
2	Lee and Baik [165]	2011	Seoul, South Korea	Dwa	M – OS, NMV

Abbreviations: On-site measurements (M – OS); Numerical models with validation (NMV).

microclimate. This article by Ebrahimabadi et al. [166] focused specifically on the problems of incorporating microclimatic factors into urban planning practices in subarctic northern Sweden (climate type Dfc). They conducted a literature study and interviewed planning practitioners. Some of the major problems identified are the lack of design knowledge relevant to cold climate, lack of user-friendly tools to analyze microclimate, overlooking the potential uses of local climate, and lack of support from politicians.

4. Discussion

Most of the studies in this systematic review addressed the UHI effect as a primary topic (58 out of 101). The reviewed studies indicate that the UHI is a common phenomenon in cold polar climate locations with UHI intensities of up to 10–12 °C being reported (e.g. Refs. [53,87]). While commonly, the UHI is most pronounced during summer nights, winter heat islands are usually weaker and occur less often. Despite the cold or polar climate conditions, the UHI can lead to excessive heat during summer. Some of the articles, therefore, focused on mitigation strategies (e.g. Refs. [58,110,112]). However, the UHI was reported to lead to greater heating energy savings than cooling energy increases on an annual basis in two studies [103,135]. Many studies were furthermore dedicated to understanding the structure and the temporal and spatial variability of the UHI, often by using numerical tools [95,97].

However, it needs to be pointed out that the results and especially the UHI-magnitudes of the reviewed studies are not directly comparable with one another. This is because methodologies, season, time of the day, measurement periods and equipment, elevations of (and differences in elevation between) the city weather station and its "non-urban" counterpart in the studies varied significantly. Those "non-urban" stations were sometimes parks, airports, suburbs, intraurban (within urban areas) locations of different typology or rural areas located outside the city.

Even more importantly, every city is different from each other. They differ with respect to population, extension and density, amount of green spaces, building density and typologies, height profile, centrality (what can be actually characterized as a city center) and furthermore building standards. Due to the typically longer absence of the sun in cold and polar climate during winter, the heat islands are often substantially supported by urban self-heating, mainly as a result of anthropogenic heat release and the urban fabric's increased heat storage capacity [66,87]. The anthropogenic heat flux is mainly caused by building energy use and heat from vehicle transport. With a higher energy standard in buildings, it is a reasonable assumption that the anthropogenic impact is smaller in areas like Zero or Plus Energy Neighborhoods and will generally decrease in the future. Changes in urban mobility like increased use of electric vehicles is expected to further reduce anthropogenic heat emissions.

Urban microclimate also affects precipitation and vice versa [118,120–122]. These increasingly observable changes in precipitation behavior (less snow, more rain [122,136]) might furthermore influence people's mobility habits and outdoor free time activities in cold and polar climate cities more than low temperatures do. Especially in high-latitude cities, where daylight in winter is scarce, snow cover is substantially increasing outdoor lighting levels in winter [136]. And as long-time meteorological records have shown in many cities, especially winter temperatures have been rising distinctly [160,161]. Considering higher air pollution and heat stress from elevated temperatures, even cold and polar climate cities increasingly pose a risk to human health. Given that city planners might often lack relevant design knowledge for cold and polar climate conditions and even are not aware of the problems [166], the situation could aggravate.

Vegetation is a commonly used intervention in warmer climate regions to mitigate the adverse effects of the UHI. However, greenery spaces were also reported to increase the temperature in winter [113]. Considering the many other reported advantages of vegetation like pollution dispersion and removal [153–155,167], decreasing wind speeds in winter [168], and the positive effects of urban greenspaces on human health [169–174] and relaxation [175,176], it might be a key element to achieve climate-adapted cold and polar climate cities with high environmental quality and livability.

5. Conclusion

The trend towards population growth, urbanization and increasing awareness of the health issues that are connected to life in cities are expected to further increase popularity and attention on urban microclimate in the future. While there has been a considerable amount of publications in the field of urban microclimate, to the best of our knowledge, there has been no review article focusing on cold and/or polar climate locations yet.

This paper presented a systematic literature review of urban microclimate relevant publications, identified from the scientific databases Scopus and Web of Science by using a reproducible search query and eligibility criteria. In total, 101 papers have been identified for inclusion, categorized, and analyzed according to their publication year, country, climate, topic, method, keywords, citations, and publication channels. The oldest study identified was published in 1975, the most recent one in early 2019. For every category, the studies were listed in tables according to their publication year, location, climate, and method. The main findings of this review can be summarized as follows:

- The most-covered topic of the included studies in this review is the UHI. 58 of 101 studies were categorized in one of the three UHI-related categories *UHI-Mag* (34), *UHI-Mit* (7), and *UHI-Other* (17). This was also visible from the keyword analysis, where *Urban heat island* was by far the most used keyword (23) before *Urban climate* (9) and *Urban microclimate* (6). Behind *UHI-Mag* and *UHI-Other, BM* (15) is the third most researched topic.
- Considering the global population distribution in cold and polar climate areas, some climate types have been subject of research more often than others. Most articles covered locations in Dfb-climate (51), mainly from studies in North America and Europe, followed by Dwa (20), predominately from studies in China and South Korea. Dfc (15) was the third most often used climate type, mainly in studies from Russia.
- The outweighing part of studies used on-site measurements as a method for obtaining data (81), 20 used remote sensed data. In 22 studies, numerical models have been validated with measurements and used to predict the outcomes of urban redevelopments. Only 4 studies used a survey to collect data, another 4 conducted a review.

With the ongoing climate change and urbanization, UHI-related research is expected to stay dominant among publications about the urban microclimate in cold and polar climate regions. However, there is a lack of studies investigating the microclimatic characteristics and physical properties of the materials in urban design. Moreover, future research should focus more on the interactions between humans and urban climate, for instance in order to promote outdoor activities, soft mobility and comfort in cold and polar climate regions. This is seen as an aspect of major importance in sustainable urban development.

Many of the included studies used numerical tools to evaluate different design interventions or to model meteorological processes. However, during the eligibility phase of article-inclusion methodology, many simulation-only studies that did not provide sufficient validation with experimental data had to be removed. Further validation studies should be made in order to improve the reliability and user-friendliness of numerical models and tools to make them also useable for planning professionals and not limit them to research applications only.

Several climate types were not represented by any study included in the review, such as Dsa, Dsc, Dsd, Dwd, Dfd, and EF and should, therefore, be subject to future research. Even though most of these climate regions are sparsely populated, research on those remote locations can enhance the understanding of the urban microclimate.

The outcomes of this systematic review and meta-analysis will help researchers to grasp the structure of published research and facilitate comparing obtained results with previously published studies. The statistical analysis and overview of studies provided in this article revealed core areas and side issues of current urban climate research in cold and polar climate regions. Researchers can use this information to quickly find published articles covering their topic of interest and identify gaps for future research possibilities.

Ongoing climate change and the particular vulnerability of cold and polar climate regions make it especially important to disseminate knowledge among planning professionals to adopt climate adaption strategies for sustainable urban development. Therefore, studies focusing specifically on measures for improving urban microclimatic conditions in cold and polar climate regions are needed to advise planners and municipalities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the ZEN partners and the Research Council of Norway.

References

[1] UN Environment, International Energy Agency. Towards a zero-emission, efficient, and resilient buildings and construction sector: global Status Report 2017. 2017.
[2] Edenhofer O, editor. Climate change 2014: contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change: mitigation of climate change. New York (USA): Cambridge Univ. Pr; 2014.
[3] United Nations, Department of Economic, Affairs Social, Division Population. World population prospects: key findings and advance tables. 2017.
[4] United Nations, Department of Economic, Affairs Social, Division Population. World urbanization prospects: the 2018 revision. New York, USA: Online Edition; 2018.
[5] UK: Met Office. Microclimates. Devon; 2011.
[6] American Meteorological Society. Glossary of Meteorology. [September 21, 2020]; Available from: http://glossary.ametsoc.org/wiki/Microscale.
[7] Orlanski I. A rational subdivision of scales for atmospheric processes. Bull Am Meteorol Soc 1975;56(5):527–30.
[8] Howard L. The climate of London deduced from meteorological observations made in the metropolis and at various places around it. second ed. London: Harvey and Darton; J. Rickerby; 1833.
[9] Oke TR, Mills G, Christen A, Voogt JA. Urban climates. Cambridge: Cambridge University Press; 2017.
[10] Erell E, Pearlmutter D, Williamson T. Urban microclimate: designing the spaces between buildings. London: Earthscan; 2011.
[11] Kratzer A. The climate of cities (Das Stadtklima). In: Bedford mass. second ed. Air Force Cambridge Research Laboratories; 1956.
[12] Oke TR. The energetic basis of the urban heat island. Q J Roy Meteorol Soc 1982; 108(455):1–24. https://doi.org/10.1002/qj.49710845502.
[13] Balchin WGV, Pye N. A micro-climatological investigation of Bath and the surrounding district. Q J Roy Meteorol Soc 1947;73(317–318):297–323.
[14] Oke TR. Urban heat islands. In: Douglas I, Goode D, Houck M, Maddox D, editors. The routledge handbook of urban ecology. first ed. London: Routledge; 2011. p. 120–31.
[15] Stewart ID, Oke TR. Local climate zones for urban temperature studies. Bull Am Meteorol Soc 2012;93(12):1879–900. https://doi.org/10.1175/BAMS-D-11-00019.1.
[16] Oke TR. City size and the urban heat island. Atmos Environ 1973;7(8):769–79. https://doi.org/10.1016/0004-6981(73)90140-6.
[17] Chandler TJ. Selected bibliography on urban climate. 1970. Geneva, Switzerland.
[18] Oke TR. The distinction between canopy and boundary-layer urban heat islands. Atmosphere 1976;14(4):268–77.
[19] Eliasson I, Holmer B. Urban heat island circulation in Göteborg, Sweden. Theor Appl Climatol 1990;42(3):187–96. https://doi.org/10.1007/BF00866874.
[20] Shreffler JH. Detection of centripetal heat-island circulations from tower data in St. Louis. Bound-Layer Meteorol 1978;15(2):229–42.
[21] Wong KK, Dirks RA. Mesoscale perturbations on airflow in the urban mixing layer. J Appl Meteorol 1978;17:677–88.
[22] Vukovich FM, King WJ, Dunn JW, JJB Worth. Observations and simulations of the diurnal variation of the urban heat island circulation and associated variations of the ozone distribution: a case study. J Appl Meteorol 1979;18(7): 836–54. https://doi.org/10.1175/1520-0450(1979)018<0836:OASOTD>2.0.CO;2.
[23] Hidalgo J, Masson V, Gimeno L. Scaling the daytime urban heat island and urban-breeze circulation. J Appl Meteorol Climatol 2010;49(5):889–901. https://doi.org/10.1175/2009JAMC2195.1.
[24] Ryu Y-H, Baik J-J, Han J-Y. Daytime urban breeze circulation and its interaction with convective cells. Q J Roy Meteorol Soc 2013;139(671):401–13. https://doi.org/10.1002/qj.1973.
[25] Mills G. Urban climatology: history, status and prospects. Urban Clim 2014;10: 479–89. https://doi.org/10.1016/j.uclim.2014.06.004.
[26] Toparlar Y, Blocken B, Vos PEJ, van Heijst GJF, Janssen WD, van Hooff T, et al. CFD simulation and validation of urban microclimate: a case study for Bergpolder Zuid, Rotterdam. Build Environ 2015;83:79–90. https://doi.org/10.1016/j.buildenv.2014.08.004.
[27] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. Bound-Layer Meteorol 2000;94(3):357–97.
[28] Masson V, Grimmond CSB, Oke TR. Evaluation of the town energy balance (TEB) scheme with direct measurements from dry districts in two cities. J Appl Meteorol 2002;41(10):1011–26.
[29] Bruse M, Fleer H. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ Model Software 1998;13(3–4):373–84. https://doi.org/10.1016/S1364-8152(98)00042-5.
[30] Shahidan MF, Jones PJ, Gwilliam J, Salleh E. An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials. Build Environ 2012;58:245–57. https://doi.org/10.1016/j.buildenv.2012.07.012.
[31] Simon H, Lindén J, Hoffmann D, Braun P, Bruse M, Esper J. Modeling transpiration and leaf temperature of urban trees – a case study evaluating the microclimate model ENVI-met against measurement data. Landsc Urban Plann 2018;174:33–40. https://doi.org/10.1016/j.landurbplan.2018.03.003.
[32] Zhang H, Gao Z, Ding W, Zhang W. Numerical study of the impact of green space layout on microclimate. Process Eng 2017;205:1762–8. https://doi.org/10.1016/j.proeng.2017.10.027.
[33] Chokhachian A, Santucci D, Auer T. A human-centered approach to enhance urban resilience, implications and application to improve outdoor comfort in dense urban spaces. Buildings 2017;7(4):113. https://doi.org/10.3390/buildings7040113.
[34] Berardi U. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. Energy Build 2016;121:217–29. https://doi.org/10.1016/j.enbuild.2016.03.021.
[35] Castaldo VL, Pisello AL, Piselli C, Fabiani C, Cotana F, Santamouris M. How outdoor microclimate mitigation affects building thermal-energy performance: a new design-stage method for energy saving in residential near-zero energy settlements in Italy. Renew Energy 2018;127:920–35. https://doi.org/10.1016/j.renene.2018.04.090.
[36] Deng J-Y, Wong NH, Zheng X. The study of the effects of building arrangement on microclimate and energy demand of CBD in Nanjing, China. Process Eng 2016; 169:44–54. https://doi.org/10.1016/j.proeng.2016.10.006.
[37] Jin H, Shao T, Zhang R. Effect of water body forms on microclimate of residential district. Energy Proc 2017;134:256–65. https://doi.org/10.1016/j.egypro.2017.09.615.
[38] Wei R, Song D, Wong NH, Martin M. Impact of urban morphology parameters on microclimate. Process Eng 2016;169:142–9. https://doi.org/10.1016/j.proeng.2016.10.017.
[39] Moonen P, Defraeye T, Dorer V, Blocken B, Carmeliet J. Urban Physics: effect of the micro-climate on comfort, health and energy demand. Front Archit Res 2012; 1(3):197–228. https://doi.org/10.1016/j.foar.2012.05.002.
[40] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci Discuss 2007;4(2):439–73. https://doi.org/10.5194/hessd-4-439-2007.
[41] Booth A, Carroll C. Systematic searching for theory to inform systematic reviews: is it feasible? Is it desirable? Health Inf Libr J 2015;32(3):220–35. https://doi.org/10.1111/hir.12108.
[42] Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Int J Surg 2010;8 (5):336–41. https://doi.org/10.1016/j.ijsu.2010.02.007.
[43] Bustami RA, Belusko M, Ward J, Beecham S. Vertical greenery systems: a systematic review of research trends. Build Environ 2018;146:226–37. https://doi.org/10.1016/j.buildenv.2018.09.045.
[44] Mavrigiannaki A, Ampatzi E. Latent heat storage in building elements: a systematic review on properties and contextual performance factors. Renew Sustain Energy Rev 2016;60:852–66. https://doi.org/10.1016/j.rser.2016.01.115.
[45] Schatzmann M, Rafailidis S, Pavageau M. Some remarks on the validation of small-scale dispersion models with field and laboratory data. J Wind Eng Ind Aerod 1997;67–68:885–93. https://doi.org/10.1016/S0167-6105(97)00126-8.

[46] Schatzmann M, Leitl B. Issues with validation of urban flow and dispersion CFD models. J Wind Eng Ind Aerod 2011;99(4):169–86. https://doi.org/10.1016/j.jweia.2011.01.005.
[47] Nkemdirim LC, Lunn GR, Rowe RD. Pollutant concentration and stratification in urban heat island. Water Air Soil Pollut 1975;4(1):99–112.
[48] Bowling SA, Benson CS. Study of the subarctic heat Island at Fairbanks. 1978. Alaska.
[49] Wolf T, Esau I, Reuder J. Analysis of the vertical temperature structure in the Bergen valley, Norway, and its connection to pollution episodes. J Geophys Res Atmos 2014;119(18):10,645–10,662. https://doi.org/10.1002/2014JD022085.
[50] Ezau IN, Wolf T, Miller EA, Repina IA, Troitskaya YI, Zilitinkevich SS. The analysis of results of remote sensing monitoring of the temperature profile in lower atmosphere in Bergen (Norway). Russ Metorol Hydrol 2013;38(10):715–22. https://doi.org/10.3103/S1068373913100099.
[51] Wolf T, Esau I. A proxy for air quality hazards under present and future climate conditions in Bergen, Norway. Urban Clim 2014;10:801–14. https://doi.org/10.1016/j.uclim.2014.10.006.
[52] Hancock H, Prokop A, Eckerstorfer M, Hendrikx J. Combining high spatial resolution snow mapping and meteorological analyses to improve forecasting of destructive avalanches in Longyearbyen, Svalbard. Cold Reg Sci Technol 2018;154:120–32. https://doi.org/10.1016/j.coldregions.2018.05.011.
[53] Kłysik K, Fortuniak K. Temporal and spatial characteristics of the urban heat island of Łódź, Poland. Atmos Environ 1999;33(24–25):3885–95. https://doi.org/10.1016/S1352-2310(99)00131-4.
[54] Kim Y-H, Baik J-J. Spatial and temporal structure of the urban heat island in Seoul. J Appl Meteorol 2005;44:591–605.
[55] Gedzelman SD, Austin S, Cermak R, Stefano N, Partridge S, Quesenberry S, et al. Mesoscale Aspects of the urban heat island around New York city. Theor Appl Climatol 2003;75(1–2):29–42. https://doi.org/10.1007/s00704-002-0724-2.
[56] Holt T, Pullen J. Urban canopy modeling of the New York city metropolitan area: a comparison and validation of single- and multilayer parameterizations. Mon Weather Rev 2007;135(5):1906–30. https://doi.org/10.1175/MWR3372.1.
[57] Hinkel KM, Nelson FE, Klene AE, Bell JH. The urban heat island in winter at Barrow, Alaska. Int J Climatol 2003;23(15):1889–905. https://doi.org/10.1002/joc.971.
[58] Wang Y, Berardi U, Akbari H. Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. Energy Build 2016;114:2–19. https://doi.org/10.1016/j.enbuild.2015.06.046.
[59] Upmanis H, Chen D. Influence of geographical factors and meteorological variables on nocturnal urban-park temperature differences - a case study of summer 1995 in Göteborg, Sweden. Clim Res 1999;13(2):125–39.
[60] Steinecke K. Urban climatological studies in the Reykjavík subarctic environment, Iceland. Atmos Environ 1999;33(24–25):4157–62.
[61] Miao S, Dou J, Chen F, Li J, Li A. Analysis of observations on the urban surface energy balance in Beijing. Sci China Earth Sci 2012;55(11):1881–90. https://doi.org/10.1007/s11430-012-4411-6.
[62] Lee S-H, Baik J-J. Statistical and dynamical characteristics of the urban heat island intensity in Seoul. Theor Appl Climatol 2010;100(1–2):227–37. https://doi.org/10.1007/s00704-009-0247-1.
[63] Klene AE, Hinkel KM, Nelson FE. The Barrow urban heat island study: soil temperatures and active-layer thickness. Int Conf Permafrost Proc 2003:555–60.
[64] Khaikine MN, Kuznetsova IN, Kadygrov EN, Miller EA. Investigation of temporal-spatial parameters of an urban heat island on the basis of passive microwave remote sensing. Theor Appl Climatol 2006;84(1–3):161–9. https://doi.org/10.1007/s00704-005-0154-z.
[65] Lu D, Weng Q. Spectral mixture analysis of ASTER images for examining the relationship between urban thermal features and biophysical descriptors in Indianapolis, Indiana, USA. Remote Sens Environ 2006;104(2):157–67. https://doi.org/10.1016/j.rse.2005.11.015.
[66] Hinkel KM, Nelson FE. Anthropogenic heat island at Barrow, Alaska, during winter: 2001–2005. J Geophys Res 2007;112(D6):1. https://doi.org/10.1029/2006JD007837.
[67] Stopa-Boryczka M, Boryzka J, Wawer J. Impact of build-up areas and housing estate vegetation on diversity of the local climate in Warsaw. Misc Geogr 2010;14(1):121–34. https://doi.org/10.2478/mgrsd-2010-0012.
[68] Malevich SB, Klink K. Relationships between snow and the wintertime Minneapolis urban heat island. J Appl Meteorol Climatol 2011;50(9):1884–94. https://doi.org/10.1175/JAMC-D-11-05.1.
[69] Suomi J, Käyhkö J. The impact of environmental factors on urban temperature variability in the coastal city of Turku, SW Finland. Int J Climatol 2012;32(3):451–63. https://doi.org/10.1002/joc.2277.
[70] Klene AE, Nelson FE, Hinkel KM. Urban–rural contrasts in summer soil-surface temperature and active-layer thickness, Barrow, Alaska, USA. Polar Geogr 2013;36(3):183–201. https://doi.org/10.1080/1088937X.2012.706756.
[71] Walawender JP, Szymanowski M, Hajto MJ, Bokwa A. Land surface temperature patterns in the urban agglomeration of Krakow (Poland) derived from landsat-7/ETM+ data. Pure Appl Geophys 2014;171(6):913–40. https://doi.org/10.1007/s00024-013-0685-7.
[72] Schatz J, Kucharik CJ. Seasonality of the urban heat island effect in Madison, Wisconsin. J Appl Meteorol Climatol 2014;53(10):2371–86. https://doi.org/10.1175/JAMC-D-14-0107.1.
[73] Konstantinov P, Grishchenko MY, Varentsov M. Mapping urban heat islands of arctic cities using combined data on field measurements and satellite images based on the example of the city of Apatity (Murmansk Oblast). Izvestiya Atmos Ocean Phys 2015;51(9):992–8. https://doi.org/10.1134/S000143381509011X.
[74] Schatz J, Kucharik CJ. Urban climate effects on extreme temperatures in Madison, Wisconsin, USA. Environ Res Lett 2015;10(9):94024. https://doi.org/10.1088/1748-9326/10/9/094024.
[75] Sun H, Chen Y, Zhan W. Comparing surface- and canopy-layer urban heat islands over Beijing using MODIS data. Int J Rem Sens 2015;36(21):5448–65. https://doi.org/10.1080/01431161.2015.1101504.
[76] Ramamurthy P, Sangobanwo M. Inter-annual variability in urban heat island intensity over 10 major cities in the United States. Sustain Cities Soc 2016;26:65–75. https://doi.org/10.1016/j.scs.2016.05.012.
[77] Huang F, Zhan W, Wang Z, Wang K, Chen JM, Liu Y, et al. Positive or negative? Urbanization-induced variations in diurnal skin-surface temperature range detected using satellite data. J Geophys Res Atmos 2017;122(24):13,229–13,244. https://doi.org/10.1002/2017JD027021.
[78] Kuznetsova IN, Brusova NE, Nakhaev MI. Moscow urban heat island: detection, boundaries, and variability. Russ Metorol Hydrol 2017;42(5):305–13. https://doi.org/10.3103/S1068373917050053.
[79] Miles V, Esau I. Seasonal and spatial characteristics of urban heat islands (UHIs) in northern West siberian cities. Rem Sens 2017;9(10):989. https://doi.org/10.3390/rs9100989.
[80] Półrolniczak M, Kolendowicz L, Majkowska A, Czernecki B. The influence of atmospheric circulation on the intensity of urban heat island and urban cold island in Poznań, Poland. Theor Appl Climatol 2017;127(3–4):611–25. https://doi.org/10.1007/s00704-015-1654-0.
[81] Przybylak R, Uscka-Kowalkowska J, Araźny A, Kejna M, Kunz M, Maszewski R. Spatial distribution of air temperature in Toruń (Central Poland) and its causes. Theor Appl Climatol 2017;127(1–2):441–63. https://doi.org/10.1007/s00704-015-1644-2.
[82] Shumilov OI, Kasatkina EA, Kanatjev AG. Urban heat island investigations in Arctic cities of northwestern Russia. J Meteorol Res 2017;31(6):1161–6. https://doi.org/10.1007/s13351-017-7048-8.
[83] Konstantinov P, Varentsov M, Esau I. A high density urban temperature network deployed in several cities of Eurasian Arctic. Environ Res Lett 2018;13(7):75007. https://doi.org/10.1088/1748-9326/aacb84.
[84] Marzban F, Sodoudi S, Preusker R. The influence of land-cover type on the relationship between NDVI–LST and LST- Tair. Int J Rem Sens 2018;39(5):1377–98. https://doi.org/10.1080/01431161.2017.1402386.
[85] Matuzko AK, Yakubailik OE. Urban heat island effects over Krasnoyarsk obtained on the basis of Landsat 8 remote sensing data. IOP Conf Ser Earth Environ Sci 2018;211:12010. https://doi.org/10.1088/1755-1315/211/1/012010.
[86] Suomi J. Extreme temperature differences in the city of Lahti, southern Finland: intensity, seasonality and environmental drivers. Weather Clim Extrem 2018;19:20–8. https://doi.org/10.1016/j.wace.2017.12.001.
[87] Varentsov M, Konstantinov P, Baklanov A, Esau I, Miles V, Davy R. Anthropogenic and natural drivers of a strong winter urban heat island in a typical Arctic city. Atmos Chem Phys Discuss 2018;1–28. https://doi.org/10.5194/acp-2018-569.
[88] Yang J, Bou-Zeid E. Should cities embrace their heat islands as shields from extreme cold? J Appl Meteorol Climatol 2018;57(6):1309–20. https://doi.org/10.1175/JAMC-D-17-0265.1.
[89] Yao R, Wang L, Huang X, Chen J, Li J, Niu Z. Less sensitive of urban surface to climate variability than rural in Northern China. Sci Total Environ 2018;628–629:650–60. https://doi.org/10.1016/j.scitotenv.2018.02.087.
[90] Esau I, Miles V, Varentsov M, Konstantinov P, Melnikov V. Spatial structure and temporal variability of a surface urban heat island in cold continental climate. Theor Appl Climatol 2019;31(12):1990. https://doi.org/10.1007/s00704-018-02754-z.
[91] Kim Y, Guldmann J-M. Impact of traffic flows and wind directions on air pollution concentrations in Seoul, Korea. Atmos Environ 2011;45(16):2803–10. https://doi.org/10.1016/j.atmosenv.2011.02.050.
[92] International Permafrost Association. What is Permafrost? [October 18, 2018]; Available from: https://ipa.arcticportal.org/publications/occasional-publications/what-is-permafrost.
[93] Nkemdirim LC. Cold air drainage and temperature fields in an urban environment: a case study of topographical influence on climate. Atmos Environ 1980;14(3):375–81.
[94] Hinkel KM, Klene AE, Nelson FE. The summer climate of an arctic coastal village: preliminary observations from the Barrow urban heat-island study. Polar Geogr 2004;28(3):197–221. https://doi.org/10.1080/789610187.
[95] Pullen J, Holt T, Blumberg AF, Bornstein RD. Atmospheric response to local upwelling in the vicinity of New York–New Jersey harbor. J Appl Meteorol Climatol 2007;46(7):1031–52. https://doi.org/10.1175/JAM2511.1.
[96] Lemonsu A, Bélair S, Mailhot J, Leroyer S. Evaluation of the town energy balance model in cold and snowy conditions during the Montreal urban snow experiment 2005. J Appl Meteorol Climatol 2010;49(3):346–62. https://doi.org/10.1175/2009JAMC2131.1.
[97] Hjort J, Suomi J, Käyhkö J. Spatial prediction of urban–rural temperatures using statistical methods. Theor Appl Climatol 2011;106(1–2):139–52. https://doi.org/10.1007/s00704-011-0425-9.
[98] Arola T, Korkka-Niemi K. The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland. Hydrogeol J 2014;22(8):1953–67. https://doi.org/10.1007/s10040-014-1174-5.
[99] Bokwa A, Hajto MJ, Walawender JP, Szymanowski M. Influence of diversified relief on the urban heat island in the city of Kraków, Poland. Theor Appl Climatol 2015;122(1–2):365–82. https://doi.org/10.1007/s00704-015-1577-9.
[100] Fang X-Y, Cheng C, Liu Y-H, Du W-P, Xiao X-J, Dang B. A climatic environmental performance assessment method for ecological city construction: application to

Beijing Yanqi Lake. Adv Clim Change Res 2015;6(1):23–35. https://doi.org/10.1016/j.accre.2015.08.001.
[101] Berardi U, Wang Y. The effect of a denser city over the urban microclimate: the case of Toronto. Sustainability 2016;8(8):822. https://doi.org/10.3390/su8080822.
[102] Hatchett BJ, Koračin D, Mejía JF, Boyle DP. Assimilating urban heat island effects into climate projections. J Arid Environ 2016;128:59–64. https://doi.org/10.1016/j.jaridenv.2016.01.007.
[103] Klimenko VV, Ginzburg AS, Demchenko PF, Tereshin AG, Belova IN, Kasilova EV. Impact of urbanization and climate warming on energy consumption in large cities. Dokl Phys 2016;61(10):521–5. https://doi.org/10.1134/S1028335816100050.
[104] Lokoshchenko MA, Korneva IA, Kochin AV, Dubovetsky AZ, Novitsky MA, Razin PY. Vertical extension of the urban heat island above Moscow. Dokl Earth Sci 2016;466(1):70–4. https://doi.org/10.1134/S1028334X16010128.
[105] Wicki A, Parlow E. Multiple regression analysis for unmixing of surface temperature data in an urban environment. Rem Sens 2017;9(7):684. https://doi.org/10.3390/rs9070684.
[106] Fu P, Weng Q. Variability in annual temperature cycle in the urban areas of the United States as revealed by MODIS imagery. ISPRS J Photogrammetry Remote Sens 2018;146:65–73. https://doi.org/10.1016/j.isprsjprs.2018.09.003.
[107] Ivajnšič D, Žiberna I. The effect of weather patterns on winter small city urban heat islands. Meteorol Appl 2018;16(3):275. https://doi.org/10.1002/met.1752.
[108] He B-J, Zhao Z-Q, Shen L-D, Wang H-B, Li L-G. An approach to examining performances of cool/hot sources in mitigating/enhancing land surface temperature under different temperature backgrounds based on landsat 8 image. Sustain Cities Soc 2019;44:416–27. https://doi.org/10.1016/j.scs.2018.10.049.
[109] Jianying Hu, S.M.ASCE1, Quan Gao, S.M.ASCE2, and Xiong Yu, M. ASCE31Graduate Research Assistant et al. Characterization of the optical and mechanical properties of innovative multifunctional thermochromic asphalt binders.
[110] Touchaei AG, Akbari H. Evaluation of the seasonal effect of increasing albedo on urban climate and energy consumption of buildings in Montreal. Urban Clim 2015;14:278–89. https://doi.org/10.1016/j.uclim.2015.09.007.
[111] Kim Y, An S, Eum J-H, Woo J-H. Analysis of thermal environment over a small-scale landscape in a densely built-up asian megacity. Sustainability 2016;8(4):358. https://doi.org/10.3390/su8040358.
[112] Wang Y, Akbari H. Analysis of urban heat island phenomenon and mitigation solutions evaluation for Montreal. Sustain Cities Soc 2016;26:438–46. https://doi.org/10.1016/j.scs.2016.04.015.
[113] Chun B, Guldmann J-M. Impact of greening on the urban heat island: seasonal variations and mitigation strategies. Comput Environ Urban 2018;71:165–76. https://doi.org/10.1016/j.compenvurbsys.2018.05.006.
[114] Jiang W, Xiao J, Yuan D, Lu H, Xu S, Huang Y. Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions. Energy Build 2018;169:39–47. https://doi.org/10.1016/j.enbuild.2018.03.049.
[115] Unger J. Urban-rural air humidity differences in Szeged, Hungary. Int J Climatol 1999;19(13):1509–15.
[116] Kallistratova MA, Kouznetsov RD. Low-level jets in the Moscow region in summer and winter observed with a sodar network. Bound-Layer Meteorol 2012;143(1):159–75. https://doi.org/10.1007/s10546-011-9639-8.
[117] Stryhal J, Huth R, Sládek I. Climatology of low-level temperature inversions at the Prague-Libuš aerological station. Theor Appl Climatol 2017;127(1–2):409–20. https://doi.org/10.1007/s00704-015-1639-z.
[118] Zhong S, Yang X-Q. Ensemble simulations of the urban effect on a summer rainfall event in the Great Beijing Metropolitan Area. Atmos Res 2015;153:318–34. https://doi.org/10.1016/j.atmosres.2014.09.005.
[119] Karsisto P, Fortelius C, Demuzere M, Grimmond CSB, Oleson KW, Kouznetsov R, et al. Seasonal surface urban energy balance and wintertime stability simulated using three land-surface models in the high-latitude city Helsinki. Q J Roy Meteorol Soc 2016;142(694):401–17. https://doi.org/10.1002/qj.2659.
[120] Li H, Cui X, Zhang D-L. On the initiation of an isolated heavy-rain-producing storm near the central urban area of beijing metropolitan region. Mon Weather Rev 2017;145(1):181–97. https://doi.org/10.1175/MWR-D-16-0115.1.
[121] Li H, Cui X, Zhang D-L. Sensitivity of the initiation of an isolated thunderstorm over the Beijing metropolitan region to urbanization, terrain morphology and cold outflows. Q J Roy Meteorol Soc 2017;143(709):3153–64. https://doi.org/10.1002/qj.3169.
[122] Johnson B, Shepherd JM. An urban-based climatology of winter precipitation in the northeast United States. Urban Clim 2018;24:205–20. https://doi.org/10.1016/j.uclim.2018.03.003.
[123] Son J-M, Eum J-H, Kim D-P, Kwon J. Management strategies of thermal environment in urban area using the cooling function of the mountains: a case study of the honam Jeongmaek areas in South Korea. Sustainability 2018;10(12):4691. https://doi.org/10.3390/su10124691.
[124] Tomczyk A, Półrolniczak M, Kolendowicz L. Cold waves in poznań (Poland) and thermal conditions in the city during selected cold waves. Atmosphere 2018;9(6):208. https://doi.org/10.3390/atmos9060208.
[125] Zieliński M, Fortuniak K, Pawlak W, Siedlecki M. Long-term turbulent sensible-heat-flux measurements with a large-aperture scintillometer in the Centre of Łódź, Central Poland. Bound-Layer Meteorol 2018;167(3):469–92. https://doi.org/10.1007/s10546-017-0331-5.
[126] International Society of Biometeorology. What is Biometeorology? [May 12, 2019]; Available from: https://uwm.edu/biometeorology/what-is-biometeorology/.
[127] Taesler R. The bioclimate in temperate and northern cities. Int J Biometeorol 1991;35(3):161–8.
[128] Czarnecka M, Mąkosza A, Nidzgorska-Lencewicz J. Variability of meteorological elements shaping biometeorological conditions in Szczecin, Poland. Theor Appl Climatol 2011;104(1–2). https://doi.org/10.1007/s00704-010-0326-3. 101–10.
[129] Bauche JP, Grigorieva EA, Matzarakis A. Human-Biometeorological assessment of urban structures in extreme climate conditions: the example of birobidzhan, Russian Far East. Adv Meteorol 2013;2013(2):1–10. https://doi.org/10.1155/2013/749270.
[130] Majewski G, Przewoźniczuk W, Kleniewska M. The effect of urban conurbation on the modification of human thermal perception, as illustrated by the example of Warsaw (Poland). Theor Appl Climatol 2014;116(1–2):147–54. https://doi.org/10.1007/s00704-013-0939-4.
[131] Urban A, Davídkovová H, Kyselý J. Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. Int J Biometeorol 2014;58(6):1057–68. https://doi.org/10.1007/s00484-013-0693-4.
[132] Nidzgorska-Lencewicz J. Variability of human-biometeorological conditions in Gdańsk. Pol J Environ Stud 2015;24:215–26. https://doi.org/10.15244/pjoes/26116.
[133] Targhi MZ, van Dessel S. Potential contribution of urban developments to outdoor thermal comfort conditions: the influence of urban geometry and form in worcester, Massachusetts, USA. Process Eng 2015;118:1153–61. https://doi.org/10.1016/j.proeng.2015.08.457.
[134] Coccolo S, Kämpf J, Scartezzini J-L, Pearlmutter D. Outdoor human comfort and thermal stress: a comprehensive review on models and standards. Urban Clim 2016;18:33–57. https://doi.org/10.1016/j.uclim.2016.08.004.
[135] Lowe SA. An energy and mortality impact assessment of the urban heat island in the US. Environ Impact Assess Rev 2016;56:139–44. https://doi.org/10.1016/j.eiar.2015.10.004.
[136] Chapman D, Nilsson K, Larsson A, Rizzo A. Climatic barriers to soft-mobility in winter: luleå, Sweden as case study. Sustain Cities Soc 2017;35:574–80. https://doi.org/10.1016/j.scs.2017.09.003.
[137] Hiscock R, Asikainen A, Tuomisto J, Jantunen M, Pärjälä E, Sabel CE. City scale climate change policies: do they matter for wellbeing? Prev Med Rep 2017;6:265–70. https://doi.org/10.1016/j.pmedr.2017.03.019.
[138] Petrov S, Mamaeva N, Narushko M. Urban development of heat island territories and the health of the northern indigenous population. MATEC Web Conf 2017;106(1–3):1035. https://doi.org/10.1051/matecconf/201710601035.
[139] Chi X, Li R, Cubasch U, Cao W. The thermal comfort and its changes in the 31 provincial capital cities of mainland China in the past 30 years. Theor Appl Climatol 2018;132(1–2):599–619. https://doi.org/10.1007/s00704-017-2099-4.
[140] Dursun D, Yavaş M. Microclimate analysis of different urban forms in cold climates and the effect of thermal comfort. Int Arch Photogram Rem Sens Spatial Inf Sci 2018;XLII-4:155–60. https://doi.org/10.5194/isprs-archives-XLII-4-155-2018.
[141] Xu M, Hong B, Mi J, Yan S. Outdoor thermal comfort in an urban park during winter in cold regions of China. Sustain Cities Soc 2018;43:208–20. https://doi.org/10.1016/j.scs.2018.08.034.
[142] Höppe P. The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol 1999;43(2):71–5. https://doi.org/10.1007/s004840050118.
[143] Jendritzky G, Maarouf A, Fiala D, Staiger H. An update on the development of a universal thermal climate index. 15th Conf. on Biometeorology/Aerobiology and 16th International Congress of Biometeorology 2002:129–33.
[144] Rhind SM. Anthropogenic pollutants: a threat to ecosystem sustainability? Philos Trans R Soc Lond B Biol Sci 2009;364(1534):3391–401. https://doi.org/10.1098/rstb.2009.0122.
[145] Górka-Kostrubiec B, Król E, Jeleńska M. Dependence of air pollution on meteorological conditions based on magnetic susceptibility measurements: a case study from Warsaw. Studia Geophys Geod 2012;56(3):861–77. https://doi.org/10.1007/s11200-010-9094-x.
[146] Cui DJ, Mak CM, Ai ZT, Kwok KCS, Meng XZ, Niu JL. On-site evaluation of pedestrian-level air quality at a U-type street canyon in an ancient city. J Wind Eng Ind Aerod 2017;168:322–33. https://doi.org/10.1016/j.jweia.2017.06.014.
[147] Leahey DM, Hansen MC. Estimates of dark ecosystem respiration of CO2 from the city of calgary, alberta. Atmos Environ 1992;26(9):1725–33.
[148] Cheng I, Zhang L, Mao H, Blanchard P, Tordon R, Dalziel J. Seasonal and diurnal patterns of speciated atmospheric mercury at a coastal-rural and a coastal-urban site. Atmos Environ 2014;82:193–205. https://doi.org/10.1016/j.atmosenv.2013.10.016.
[149] Fierravanti A, Fierravanti E, Cocozza C, Tognetti R, Rossi S. Eligible reference cities in relation to BVOC-derived O 3 pollution. Urban For Urban Green 2017;28:73–80. https://doi.org/10.1016/j.ufug.2017.09.012.
[150] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol Energy 2001;70(3):295–310. https://doi.org/10.1016/S0038-092X(00)00089-X.
[151] Janhäll S. Review on urban vegetation and particle air pollution – deposition and dispersion. Atmos Environ 2015;105:130–7. https://doi.org/10.1016/j.atmosenv.2015.01.052.
[152] Litschke T, Kuttler W. On the reduction of urban particle concentration by vegetation a review. Metereol Z 2008;17(3):229–40. https://doi.org/10.1127/0941-2948/2008/0284.
[153] Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. Urban For Urban Green 2006;4(3–4):115–23. https://doi.org/10.1016/j.ufug.2006.01.007.

[154] Selmi W, Weber C, Rivière E, Blond N, Mehdi L, Nowak DJ. Air pollution removal by trees in public green spaces in Strasbourg city, France. Urban For Urban Green 2016;17:192–201. https://doi.org/10.1016/j.ufug.2016.04.010.

[155] Tallis M, Taylor G, Sinnett D, Freer-Smith P. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landsc Urban Plann 2011;103(2):129–38. https://doi.org/10.1016/j.landurbplan.2011.07.003.

[156] Vos PEJ, Maiheu B, Vankerkom J, Janssen S. Improving local air quality in cities: to tree or not to tree? Environ Pollut 2013;183:113–22. https://doi.org/10.1016/j.envpol.2012.10.021.

[157] Palma W. Time series analysis. Hoboken, NY: Wiley; 2016.

[158] Yilmaz S, Toy S, Demircioglu Yildiz N, Yilmaz H. Human population growth and temperature increase along with the increase in urbanisation, motor vehicle numbers and green area amount in the sample of Erzurum city, Turkey. Environ Monit Assess 2009;148(1–4):205–13. https://doi.org/10.1007/s10661-007-0151-z.

[159] Wang J, Yan Z, Li Z, Liu W, Wang Y. Impact of urbanization on changes in temperature extremes in Beijing during 1978–2008. Chin Sci Buill 2013;58(36): 4679–86. https://doi.org/10.1007/s11434-013-5976-y.

[160] Ø Nordli, Hestmark G, Benestad RE, Isaksen K. The Oslo temperature series 1837-2012: homogeneity testing and temperature analysis. Int J Climatol 2015;35(12): 3486–504. https://doi.org/10.1002/joc.4223.

[161] Anderson CI, Gough WA. Evolution of winter temperature in Toronto, ontario, Canada: a case study of winters 2013/14 and 2014/15. J Clim 2017;30(14): 5361–76. https://doi.org/10.1175/JCLI-D-16-0562.1.

[162] Lokoshchenko MA, Korneva IA, Kochin AV, Dubovetsky AZ, Novitsky MA, Razin PY. Current changes of the lower troposphere temperature in the Moscow region. Izvestiya Atmos Ocean Phys 2017;53(4):392–401. https://doi.org/10.1134/S0001433817040089.

[163] Wang G, Yan D, He X, Liu S, Zhang C, Xing Z, et al. Trends in extreme temperature indices in huang-huai-Hai river basin of China during 1961–2014. Theor Appl Climatol 2018;134(1–2):51–65. https://doi.org/10.1007/s00704-017-2252-0.

[164] Sang J, Liu H, Liu H, Zhang Z. Observational and numerical studies of wintertime urban boundary layer. J Wind Eng Ind Aerod 2000;87(2–3):243–58.

[165] Lee S-H, Baik J-J. Evaluation of the vegetated urban canopy model (VUCM) and its impacts on urban boundary layer simulation. Asia-Pacific J Atmos Sci 2011;47 (2):151–65. https://doi.org/10.1007/s13143-011-0005-z.

[166] Ebrahimabadi S, Nilsson KL, Johansson C. The problems of addressing microclimate factors in urban planning of the subarctic regions. Environ Plann B 2015;42(3):415–30. https://doi.org/10.1068/b130117p.

[167] Setälä H, Viippola V, Rantalainen A-L, Pennanen A, Yli-Pelkonen V. Does urban vegetation mitigate air pollution in northern conditions? Environ Pollut 2013; 183:104–12. https://doi.org/10.1016/j.envpol.2012.11.010.

[168] McPherson EG, Herrington LP, Heisler GM. Impacts of vegetation on residential heating and cooling. Energy Build 1988;12(1):41–51. https://doi.org/10.1016/0378-7788(88)90054-0.

[169] Grahn P, Stigsdotter UA. Landscape planning and stress. Urban For Urban Green 2003;2(1):1–18. https://doi.org/10.1078/1618-8667-00019.

[170] Alcock I, White MP, Wheeler BW, Fleming LE, Depledge MH. Longitudinal effects on mental health of moving to greener and less green urban areas. Environ Sci Technol 2014;48(2):1247–55. https://doi.org/10.1021/es403688w.

[171] Mitchell R, Popham F. Greenspace, urbanity and health: relationships in England. J Epidemiol Community Health 2007;61(8):681–3. https://doi.org/10.1136/jech.2006.053553.

[172] Mitchell R, Popham F. Effect of exposure to natural environment on health inequalities: an observational population study. Lancet 2008;372(9650):1655–60.

[173] Maas J, Verheij RA, Vries S de, Spreeuwenberg P, Schellevis FG, Groenewegen PP. Morbidity is related to a green living environment. J Epidemiol Community Health 2009;63(12):967–73. https://doi.org/10.1136/jech.2008.079038.

[174] Maas J, Verheij RA, Groenewegen PP, Vries S de, Spreeuwenberg P. Green space, urbanity, and health: how strong is the relation? J Epidemiol Community Health 2006;60(7):587–92. https://doi.org/10.1136/jech.2005.043125.

[175] Kaplan R. The role of nature in the context of the workplace. Landsc Urban Plann 1993;26(1–4):193–201. https://doi.org/10.1016/0169-2046(93)90016-7.

[176] Park BJ, Tsunetsugu Y, Kasetani T, Kagawa T, Miyazaki Y. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): evidence from field experiments in 24 forests across Japan. Environ Health Prev Med 2010;15(1):18–26. https://doi.org/10.1007/s12199-009-0086-9.