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TITLE	Urban heat island research at high latitudes — utilising Finland as an example
YEAR	2023
VERSION	Publisher's PDF
CITATION	Drebs A., Suomi J. & Mäkelä A. 2023: Urban heat island research at high latitudes — utilising Finland as an example. Boreal Env. Res. 28: 81–96.
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BOREAL ENVIRONMENT RESEARCH 28: 81–96 © 2023
ISSN 1797-2469 (online) Helsinki 15 March 2023

Urban heat island research at high latitudes — utilising Finland as an example

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Received 2 May. 2022, final version received 20 Jan. 2023, accepted 13 Jan. 2023

Drebs A., Suomi J. & Mäkelä A. 2023: Urban heat island research at high latitudes — utilising Finland as an example. *Boreal Env. Res.* 28: 81–96.

The effects of a built environment on its climate, i.e., the urban heat island (UHI), has been under extensive research for more than 200 years. However, most of the research has focused on cities and regions at low and mid-level latitudes, while cities positioned at high latitudes have gained much less interest. In this article, we focus on summarising a total of 22 Finnish UHI research studies from 1961 to 2021 in cities located between the 60° and 65° north latitude. In these research studies, statements are made about UHI intensity and extent, and about the utilised analysis methods and techniques. Nine of the studies refer to the Finnish capital Helsinki, while the others concern the larger cities Turku, Oulu, and Lahti, as well as the medium-sized municipalities Hyvinkää and Joensuu. Our paper presents the previous studies in chronological order, thereby illustrating the methodological development of UHI research in Finland. One of the most important findings is that the past Finnish studies show a high level of scientific understanding and similar scientific practices to those in corresponding international research. However, the study also shows the challenges of comparing UHI characteristics between different cities because the specific local features (such as topography, water proximity, green infrastructure, etc.) typically play a significant role in local climatological conditions. The results of our investigation show that, firstly, there is a significant difference between the intensity of the summer and winter urban heat island. The UHI intensity can reach up to 14 K under the influence of local conditions. Secondly, the urban heat island intensity, where it could be studied over a longer period of time, has not essentially increased. However, there have been initial indications of an increase in recent studies. Thirdly, the research methods and results show a consistency in content over time, so that early research results can serve as the basis of further investigations. This study highlights the challenging nature of observing urban climate in high spatial-temporal detail and the different methods that have been traditionally used for UHI examinations: the conclusions are that all of these methods are also needed at present in order to grasp the full picture of urban climatic characteristics.

Editor in charge of this article: Antti Arola

Introduction

The urban climate is determined by the changes of meteorological parameters, such as air temperature, humidity, wind, and precipitation — caused by urbanization of a defined size (Kratzer 1956; Chandler 1965). In the pre-modern era, when urban clusters were considerably smaller than contemporary cities, urban development was guided inter alia by tradition and gained experiences. If we consider the influences of different (e.g., historical, social, economic, and geographical) conditions on the physical development of cities, we will operate with the understanding that each city has its own pattern of urban development. For this reason, it does not always seem useful to compare cities with each other (Hietala *et al.* 2009). Urban climate research is the realm of multidisciplinary natural sciences research, which describes, analyses, and in its best form, predicts the physical characteristics of an area most people live in today. It can be assumed that centuries ago, there were thermal and hydrological climatological differences between rural and urban areas. However, only technical and scientific developments have made it possible to measure and compare these differences with reliable instruments and observation methods.

It is well known that cities alter the local climate (Alcoforado and Matzarakis 2010). In addition, the overall climate is changing due to ongoing human-induced climate change. The feedback of the urban climate into the local and regional climate, on the other hand, is not well understood; after all, increasing urban heat island (UHI) intensity can be mitigated to some extent through urban planning.

The urban heat island is a phenomenon that describes the differences in the meteorological parameters of an area compared with its surrounding areas (Oke *et al.* 2017). Under certain circumstances, UHI has been characterised as follows: cities are warmer, drier, and calmer than areas in their surrounding vicinity (Landsberg 1981). In addition to the canopy layer UHI, which refers to the air temperature differences below the rooftop level height, UHI has also been determined for the boundary layer that extends vertically well above the rooftop level (Oke 1976). The third UHI type, surface UHI, is mainly used in the context of remote sensing, and denotes the difference in land surface temperature between the urban and rural areas (Voogt and Oke 2003). In this study, we will focus on the canopy layer UHI.

The UHI is a worldwide phenomenon and can be found even in the most remote human settlements such as Barrow, Alaska, USA (Hinkel *et al.* 2003) as well as in the most densely populated New York City, New York, USA (Bornstein 1968).

The formation and development of UHI can be enhanced or suppressed by the geographical location, terrain topography, the proximity of water bodies, soil characteristics and green infrastructure (Wienert and Kuttler 2005; Oke *et al.* 2017).

The UHI phenomenon in its most extreme manifestation has an impact on outdoor thermal conditions in parks, public places, and streets as well as on indoor thermal conditions in residential buildings, kindergartens, schools, and hospitals. Widely recognised measurement and analysis methods make it possible to have the results of investigations processed directly by a broad scientific community. Thus, urban climatological findings are directly available to urban planners and architects.

The UHI phenomenon was first demonstrated in 1818 by the English chemist and amateur meteorologist Luke Howard through his measurements of air temperature at two locations within and on the periphery of London. Through his many years of research, he was able to identify, among other things, a daily urban heat island intensity of ~2.1°C and reasons for each season of urban warming: the anthropogenic energy sources for wintertime, urban geometry as a radiation trap, urban roughness that suppressed general air exchange, and the lack of humidity that reduced the cooling impact of evaporation, in the months from spring to autumn (Howard 1833, Mills 2008). By the 1920s, comparable research was conducted in almost every capital and larger city in Europe (Kratzer 1956). Prior to the 1920s, research focussed on comparing stationary observational sites in urban and rural areas. The introduction of automobiles as a measuring platform allowed for the expansion of the studied area (Schmidt 1927; Peppler 1929). From the 1960s, the use of computer technology became evermore popular, which made it possible to handle a large amount of data and a deeper exploration of theoretical approaches. Additionally, growing concern for the environment led to an increased focus on UHI research. In one regard, understanding the connection between air pollution and urban climate led to the use of UHI research in city planning (Kratzer 1956). Other aspects of the changing urban climate that may have a direct impact on at-risk groups (e.g., the elderly, the sick, or children) in the urban population include an increase in extreme weather events such as heat waves, heavy rain and high winds and other undesirable weather events (Revi, A, *et al.* 2014). For example, an increase in premature longevity due to the more frequent and longer occurrence of heat waves has also been demonstrated in Helsinki (Ruuhela *et al.* 2017, 2021; Votsis *et al.* 2021).

At present, the UHI research results are important for global climate change research due to the impact of urban climate on global climate. The research focuses on two opposing assumptions about the development of UHI intensity, the measure that indicates the largest daily temperature difference between urban built-up and rural undeveloped areas. By the end of this century, Oleson *et al.* (2011) estimated that a slight decrease of the urban-rural air temperature differences is mainly due to a different response of rural and urban areas to increased long-wave radiation from a warmer atmosphere. On the contrary, Wilby (2007) concluded that there will still be an increase of the UHI intensity in the future despite global warming. Due to the varying progress of the earth's climate warming, globally, the UHI phenomenon will develop differently in its expansions and intensities. Cities and communities at higher latitudes will experience greater and faster changes in their UHI phenomenon than cities in other regions of the world (Wienert and Kuttler 2005). In addition to the well-known linear UHI relationships between open spaces, suburbs and city centres, sub-centres with the same characteristics but with lower heat island intensities are emerging in modern, more sprawling urban areas (Fogelberg *et al.* 1973; Drebs 2011). This increasingly extends the urban heat island phenomenon with its effects on whole urban areas.

Finnish UHI research began in the early 1960s. The late start of Finnish UHI research was due to delayed urbanisation and the limited number of major cities. Until the 1950s, more than half of Finns lived in rural areas (United Nations 2018), and there were only three cities in Finland with more than 100 000 inhabitants: Helsinki, Turku, and Tampere (City of Helsinki 2012; City of Turku 2017; Central Statistical Office 1959). By 1990, the urbanisation rate reached 79 % in Finland, and it is predicted that by 2050 about 90% of Finnish people will live in urban surroundings (United Nations 2018). From the point of view of the growing urban population, various researchers have shown the connection between population size and UHI intensity (Oke, 1973). In Finland, the general municipal development has often been influenced by the amalgamation of towns and municipalities, so that an increase in population has usually been explained by an increase in territory. The objectives of this study are to present Finnish UHI research in its historical sequence and to analyse the individual research results in the context of one another primarily by using four large sample cities (Helsinki, Turku, Oulu, and Lahti) with the two medium-sized cities (Joensuu and Hyvinkää) to obtain a condensed overall picture (Table 1). Furthermore, this summary is intended to activate UHI research in high latitudes by encouraging the university students and researchers to replicate UHI studies in cities where UHI studies have already taken place, and finally to also conduct UHI studies in other cities. This study also aims to enhance the utilisation of UHI-related knowledge in urban planning to, e.g., improve climate change adaptation on an inner-city scale.

Our decision to focus on Finnish UHI studies stems from the fact that it is challenging to separate the influence of the general climate from city-specific characteristics when comparing cities in different geographical regions. These city-specific characteristics are often more relevant for urban planning.

Urban heat island research in Finland

Helsinki

The first known UHI survey in Helsinki was conducted by Tommila (1961). He compared the city centre weather station (Kaisaniemi) to three more northerly stations and an island station in the Gulf of Finland about eight kilometres off the coast of Helsinki. Here, the air temperature was measured three times a day with mercury-in-glass-thermometers according to the World Meteorological Organisation (WMO) standards in a hut two metres above ground level. The monthly air temperature means were calculated by adapting a different monthly correction value to the means. Tommila compared the monthly air temperature averages from the years 1947 to 1949, creating graphs to illustrate his findings. He concluded that, under certain circumstances, the Helsinki city centre should have been between 0.4–1.0 K warmer than the surrounding areas. Furthermore, he compared a longer series of observations between the city station in Kaisaniemi and a climate station four kilometres to the north. From this relationship, he was able to estimate that the difference in the annual mean air temperature grew by 0.12 K over the course of 45 years.

The study by Fogelberg *et al.* (1973) was the first in Finland to use a car as an instrumental platform for meteorological measurements. Fogelberg carried out his three measurement runs on low-wind, slightly cloudy nights at the end of February (24, 26, and 28. Feb. 1973). The air temperatures were measured by an electrical resistance thermometer, which was kept outside the car during the measurement runs. The registration of the air temperature measurement was done manually with an accuracy of 0.5 K. The measurement runs lasted two to four hours and were carried out on alternating routes in the city centre and the surrounding area at a speed of less than 40 km/h. The analysis of the measurement results was illustrated graphically, where the air temperatures were mapped by isothermal lines on the Helsinki city centre. The results of the three measurement nights were presented in a synthesis map in such a way that it showed the median values determined for each 1 km² city area as the arithmetic mean of the three night's values. Fogelberg *et al.* thus obtained an urban heat island intensity of 8 K for Helsinki at the end of February 1973. Air temperature differences of up to 13 K were established in isolated places due to individual terrain forms. The synthesis map of all three measurement runs further confirmed that there was not only one Helsinki urban heat island, but that in addition to the pronounced urban heat island in the city centre, there were also other weaker sub-centres in the suburbs.

In 1973, a second research project was also carried out in Helsinki. Here, Alestalo (1975) wanted to determine the UHI intensity by means of motor vehicle measurement runs under winter and summer conditions and especially in urban areas near the coast. However, the measurement runs in winter and summer each comprised only

Table 1. Compilation of geographical and demographic data as well as the number of known urban heat island surveys.

City	Coordinates	Population*	Population density**	Land/water areas***	No. of traceable UHI research
Helsinki	60°10´15´´ 24°56´15´´	658 339	3062	215.19 / 500.29	8
Turku	60°27´05´´ 22°16´00´´	195 350	797	245.66 / 60.69	8
Hyvinkää	60°37´50´´ 24°51´35´´	46 686	145	322.69 / 14.08	1
Lahti	60°58´50´´ 25°39´20´´	120 202	262	459.49 / 58.14	1
Joensuu	62°36´00´´ 29°45´50´´	77 284	32	2391,69 / 369,27	1
Oulu	65°01´00´´ 25°28´00´´	209 197	70	2971.14 / 845.13	3

* Number of inhabitants, Statistics Finland 2021

** Number of inhabitants / land area

*** km², National Land Survey of Finland 2021.

one favourable measurement day or measurement night (low cloud, low wind, 12 March and 15–16 August 1973), so that no generally valid statements could be established about Helsinki's urban heat island. The measurement sensor consisted of platinum wire thermocouple, protected from solar radiation, and mounted on the roof of a car at a height of 2.5 metres. The measurement results were recorded with a plotter. During the summer measurement trip, one fixed measurement point each in the city centre and one in the undeveloped suburban area were also available. Alestalo also had a 10-day period around 12 March for comparison, from which there were still some air temperature averages from four urban areas: the city centre, parks, coastlines, and undeveloped areas surrounding the city centre. The means of the air temperature, and the dispersion showed the same characteristics as those of the measurement run of 12 March, only in a smaller dimension. The summer measurements and, above all, the air temperature comparison between the two fixed measurement sites again showed a measured UHI intensity of up to 9.1 K. The two studies (Fogelberg, 1973 and Alestalo, 1975) were carried out independently of each other and there is no indication as to whether they were even aware of each other at the time.

In the analysis of Heino (1978), he described the differences in UHI intensity and other urban climatic parameters for two Finnish cities, Helsinki and Jyväskylä, based on 15-year monthly and annual averages (1961–1975). It was the first time in Finland that besides air temperature, humidity, cloudiness, and precipitation were systematically investigated. For Helsinki, in addition to the climate station in the city centre, Heino had a station to the south, located on an island in the Gulf of Finland, and five others fanned out to the north around the city centre. For Jyväskylä, about 240 kilometres north of Helsinki, a climate station in the city centre and one in the north and south were available for analysis. All stations were operated by the Finnish Meteorological Institute. The measurement results used for his analyses were partly produced with recording instruments (air temperature and humidity) and partly observed manually (cloud cover, precipitation, days with snow cover). His main findings included that the annual mean air temperature in the city centre was 0.4–0.8 K higher and the daily fluctuation of air temperature extremes was 1 K lower. Likewise, the days with frost, a daily air temperature minimum under 0°C, and days with snow cover were 10% less frequent in the urban centres than at the rural stations.

In 2004, Piispa published the results of his 19-month (July 2001 to January 2003) urban heat island study, which he conducted as a thesis for his MSc. degree at the Geography Department at the University of Helsinki. For his study, he installed 10 Optic StowAway temperature loggers in predetermined locations such as gardens, open agricultural areas, public squares, and occasional densely built-up residential areas in simple radiation shields, mainly fixed in trees two metres above the ground. In addition, he used measurement results from seven measuring points of the public services. The air temperatures were measured at half-hourly intervals. Based on this observation material, Piispa created isotherm maps using the IDW interpolation method. However, without additional background data such as distance to the coastline, population density, terrain height above sea level, or land use, it is not possible to approximate the temperature ratios between the measuring points. Therefore, all his results are subjectively influenced by the interpretation method and only give a limited overview of the temperature conditions in Helsinki from 2001–2002.

Between 2002 and 2006 (Drebs 2003; 2005; 2006), a stationary measurement network of up to 20 low-cost recording air temperature data loggers in standard radiation protection was set up at representative locations in the metropolitan area. The aim of this short-term measuring network was to estimate the air temperature distribution under different large-scale weather conditions. For this purpose, special attention was paid to the distribution of the measuring points on a north-south as well as east-west axis. Through these measuring point arrangements, it was possible to confirm certain patterns of the air temperature distributions at the individual seasons in the different weather situations for the metropolitan region. Furthermore, the different air temperature gradients between built-up

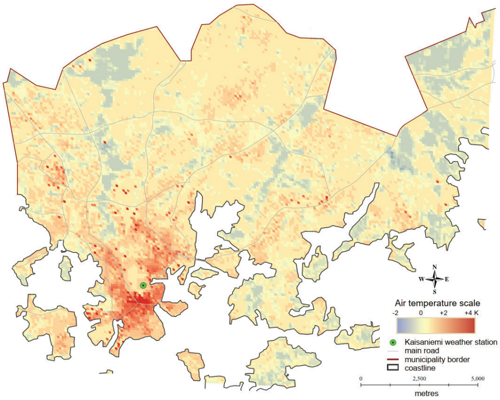

Fig. 1. Mean urban heat island effect in Helsinki, Finland, measured from July 2009 to June 2010, when 104 measurement runs were carried out. The reference station was the synoptic weather station Kaisaniemi (green dot) in the city centre of Helsinki. The analysed temperature differences between the measurement route and Kaisaniemi are presented in 100-metre grids. In addition to the warmer Helsinki city centre, numerous urban sub-centres with increased mean temperatures can be seen (Drebs 2011).

and unbuilt areas confirm another internationally known property of the UHI magnitude for Helsinki as well. This is the relationship of the sky view factor to the UHI magnitude. The sky view factor is the ratio of the width of the street to the height of the building on site, which appears to the observer as an open area of sky when viewed from the ground. For Helsinki, this meant that the UHI magnitude of 9 K was reached (Oke 1987). Depending on the small-scale climatological locations, the distances between the observation points and the distance to the Helsinki coastline, air temperature differences between 8 K and 13 K could generally be observerd. The short-term measurement network was later used to evaluate the Helsinki Testbed Observation Network (Koskinen *et al.* 2011). Later, some of these observation points were part of the Helsinki Testbed observation network (Koskinen *et al.* 2011).

In another published MSc. thesis from the Department of Geography at the University of Helsinki on the UHI phenomenon, Drebs (2011) further explored his previous research on the spatial and temporal distribution of air temperatures. For this purpose, he conducted a 12-month mobile long-term measurement campaign (July 2009–June 2010) on about 100 kilometres of predefined routes with different terrain characteristics such as topography and distance to the coast.

In 104 measurement runs, which were carried out in two parts on each Tuesday of the measurement campaign at 11:00 and at 23:00, 31 kilometres passed through the city centre (speed ~30 km/h) and 75 kilometres through the suburbs (~40 km/h). The air temperature was measured with a ventilated platinum wire thermometer mounted on a van (diesel) at a height of two metres above the ground at an interval of one second. Location information was determined by GPS and stored along with the measurements. In addition, the four components and measurements of short- and long-wave radiation were measured, and the humidity was calculated. Along the routes, 336 fixed points with a diameter of 100 metres were determined to cover the different building and environmental characteristics of the city. In addition, the four components and measurements of short- and long-wave radiation were measured. Along the routes, 336 fixed points with a diameter of 100 metres were determined to cover the different building characteristics of the city. The measurements falling within the fixed-point circle were combined into one measurement. The automatic synoptic weather station Helsinki Kaisaniemi, located in a park, was used as a control station. The difference between the measured values was calculated.

The results were interpolated according to Kriging to 12 monthly and one annual map using additional information such as building characteristics and land use. The interpolated grid size was 100 metres. The annual interpolation as a summary of all measurements shows air temperature differences of up to 2.8 K on an annual basis between the station in Kaisaniemi and several grid points in the Helsinki city centre (Fig. 1). On a monthly basis, the interpolation results did not show such large differences, but effectively reflect the influences of environmental parameters on the local air temperature distribution. The greatest influence on air temperature was in built-up areas, where larger buildings exacerbated the heat island phenomenon. Comparisons of single individual air temperatures at

Table 2. Urban heat island research in Helsinki in chronological order: the research year with the corresponding population, the main researcher, data type, data sources, research area, research period, the maximum temperature difference between the urban and rural area (max $T_{u\text{-}r}$), respectively.

Research year (Population, year)	Main researcher	Data type	Data source	Research area	Period	Duration /Length	Max $T_{u\text{-}r}$
1961 (369 000, 1950)*	Tommila	climatological data	5 observation points	19 km north-south line	3 years (1947–1949)		0.4–1.0 K
1973 (524 000, 1970)*	Fogelberg	mobile	3 different routes	city centre and surrounding areas	3 nights in February 1973	2 to 4 hours drives	~8 K
1973	Alestalo	mobile	predefined route	northern and eastern urban and rural area	1 night in March 1973	no data	~9 K
1973	Alestalo	mobile	predefined routes and 20 observation points	northern and eastern urban and rural area	summer 1973	no data	~9.1 K
1979 (484 000, 1980)*	Heino	climatological data	6 observation points	40 km ~north-south line	15 years (1961–1975)		0.8 K
2004	Piispa	stationary	17 observation points	city area	19 months (07.2001–01.2003)		10.5 K
2006	Drebs	stationary	> 20 observation points	metropolitan area	3 years (2003–2005)		14 K
2011 (588 549, 2010*)	Drebs	mobile	336 points	city area	every Tuesday, 2 runs (midday, midnight) 12 months (07.2009–06.2010)	city centre part, 01:46 h; suburb part 02:26 h	~9.2 K

* Statistics Finland 2021.

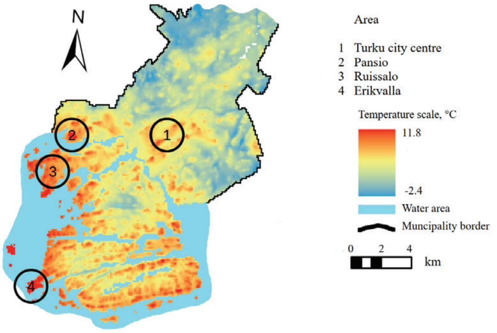

Fig. 2. Temperature in Turku on 21 Sep. 2003 at 02:00 local standard time. The UHI of Turku city centre is detectable (area 1). A warming effect of sea at that moment is even larger than that of the city, and consequently, enhanced by the impact of topography, the high areas in the vicinity of seashore (areas 2,3 and 4) are principally warmer than the city centre (Suomi 2005; TURCLIM database 2022).

the same time in selected locations under favourable meteorological conditions (little wind, clear sky) confirmed an intensity of the urban heat island of up to +9.2 K. An overview of Helsinki's UHI research is compiled in Table 2.

Turku

The local climate of Turku, in the southwest of Finland, has been studied with various study settings from 2005 onwards. The studies have been based on the stationary TURCLIM local climate observation network, established in 2001 by the Department of Geography at the University of Turku. Measurements began with approximately 60 temperature observation sites, and at present, temperature and relative humidity is measured in 75 sites in Turku and neighbouring municipalities. From 2001 to 2010, temperature was measured with Onset HOBO H8 Pro temperature loggers, and from 2011 onwards with Onset HOBO U23-001 Pro v2 temperature/relative humidity loggers. Loggers have been placed inside Onset RS1 radiation shields at a height of three metres, and the observation interval has been 30 minutes since the start of the measurements.

In Turku, the first broader study focused on the UHI intensity and characteristics of spatial-temporal temperature variability in general (Suomi 2005). Temperature data on the 3-year period from 1 Sep. 2001–31 Aug. 2004 was utilised, and the UHI intensity was assessed in different time scales extending from momentary situations to monthly summaries. In monthly summaries, the data on the whole 3-year period was utilised, whereas the short-time analyses were mostly based on the data of the year 2003. Based on preliminary analyses, the temperature data of seven observation sites were analysed in more detail. As one subtopic, the impact of cloudiness and wind speed on UHI intensity was analysed. In September 2003, during one night at two o'clock local time, the combined effect of city, topography and sea caused the marketplace in the city centre to be 11.8 K warmer than the relatively low-lying uninhabited rural site Niuskala, 10 km northeast of the city centre (Fig. 2). On average, the UHI intensity of the respective night defined by the times of sunset and sunrise was 9.1 K.

The focus of later research in Turku has been on understanding the effects of environmental factors such as land use, topography, and proximity to water bodies on variations in temperature across different regions. The effects of environmental factors have been estimated with various GIS data and statistical and spatial modelling methods such as the generalised linear model, the generalised additive model, and the boosted regression tree method (Hjort *et al.* 2011; 2016; Suomi *et al.* 2012; Suomi and Käyhkö 2012; Suomi 2014; Väyrynen *et al.* 2017). Of the environmental factors, land use, i.e., principally, the heating impact of urban land-use types, primarily has the largest effect on spatial temperature differences in Turku, but the impact of water bodies is emphasised in autumn and spring, and that of topography during inversion conditions.

In the research focused on the impact of environmental factors on temperatures, the intensity and spatial aspects of the UHI are included in the analysis, although not as the main focus of the studies. In those studies, the strongest observed UHI intensity was reported by Hjort *et al.* (2016); in February 2006, the urban effect and topography together resulted in the Luostarivuori school yard on the slope of a hill in the city centre to be 12 K warmer than the relatively low-lying rural patch in Kurala, four km ENE of Luostarivuori.

Along with the lengthening observation history, Suomi and Meretoja (2021) studied the change of spatial temperature differences in time during the 17-year period from 2002 to 2018. Trends indicating relative cooling of certain areas, as well as trends showing relative warming of certain areas, were observed. Relative cooling occurred in semi-urban and urban areas that had remained unchanged during the study period. Relative warming trends were most typical at the semi-urban sites at the immediate neighbourhood of the city centre grid plan area. In addition to relative cooling and warming of certain areas, fluctuating variation of spatial temperature differences was observed. The fluctuation was strongly connected with the severity of winter and related sea ice extent. Between 2002 and 2018, the UHI of Turku had a statistically significant intensifying trend of 0.11 K per decade. An overview of Turku's UHI research is presented in Table 3.

Joensuu, Hyvinkää, Oulu, Lahti

Ekholm (1981) studied the local climate of Joensuu, eastern Finland, during the summer of 1980 and winter from 1980 to 1981. During the summer, mobile temperature, relative humidity, and wind measurements were taken using a bicycle, while during the winter, they were taken using a car while driving a pre-determined route. The temperature measurements were made with a resistant thermometer at a height of 1.5 metres. If necessary, linear time corrections for observations were made in relation to the temperatures at the beginning or at the end of the respective measurement session. During calm and clear summer nights, temperatures in the city centre and nearby suburbs were 7.5 K warmer than surrounding areas. The topography caused even more significant spatial temperature differences, as the hilltops of Niinivaara were 9 K warmer than the surrounding valley bottoms. During winter nights, the city centre was 6 K warmer than the average temperature in the area, and 8.5 K warmer than the lakeside of the frozen Lake Pyhäselkä.

Laaksonen (1994) investigated spatial temperature differences in the city of Hyvinkää, southern Finland, during six summer nights in June and July 1988 by conducting mobile temperature measurements at a height of one metre on foot with a digital Sensotherm thermometer 100

Table 3. Urban heat island research in Turku in chronical order: the main researcher, research period, the maximum temperature difference between the urban and rural area (max $T_{\text{u-r}}$), research type, and remarks in the Turku city area with up to 75 observation points.

Year	Researcher	Period	Max $T_{\text{u-r}}$	Research	Remarks
2005	Suomi	3 years (2001–2004)	11.8 K	climatological comparison	long-term and momentary UHI, UHI and weather
2011	Hjort	6 years (2002–2007)	—	statistical analyses	impact of environmental factors
2012	Suomi	6 years (2002–2007)	—	statistical analyses	impact of environmental factors
2012	Suomi	2 years (2006–2007)	—	statistical analyses	impact of environmental factors
2014	Suomi	6 years (2002–2007)	10 K	statistical analyses, climatological comparison	impact of environmental factors, UHI and weather
2016	Hjort	2006 and 2007	12 K	statistical analyses	extreme urban-rural temperatures
2017	Väyrynen	6 years (2002–2007)	—	statistical analyses	impact of sea on temperature
2021	Suomi	17 years (2002–2018)	—	statistical analyses	increasing of UHI intensity

(Digitalthermometer Ni 100) in the inner-city area and nearby open spaces. To reduce the setting time of the thermometer and to increase the measuring accuracy, the thermometer was used in a similar way to a sling thermometer. Calibration measurements were made each night just before and after the actual measurements to take account of the general temperature change during the night. As a result of the combined effect of the city and greater differences in altitude, the largest observed temperature differences between the inner-city areas and the lower-lying clay plains in the immediate vicinity amounted to 9.2 K.

Hara *et al.* (1999) studied the UHI of Oulu in summer and winter from 1996 to 1998. The study was based on hourly observations on three fixed weather stations and six mobile measurement campaigns both in winter and in summer. The mobile measurements were performed with an automobile. Hara *et al.* (1999) concluded that the UHI was detected more clearly in winter than in summer. The strongest UHI, 9.1 K, was, however, observed in summer, whereas in winter, the strongest UHI was 6.2 K. The city centre was the warmest area both in winter and in summer, whereas the areas to the NW of the city centre acted as secondary cores of the UHI. The rural areas to the SE of the city centre were coldest both in summer and in winter. The authors consider the observed temperature differences to be mostly due to the urban effect as the Oulu region is so flat that the effect of topography is minor. Kananen (2011) studied the wintertime urban heat island in the city of Oulu. The study was based on seven separate mobile measurement campaigns performed in January, February, and March 2011. The impact of environmental factors on spatial temperature variation was studied with multiple linear regression models, including explanatory variables for land use and topography. The largest observed UHI intensity was 12.9 K, whereas the average UHI intensity was 9.0 K. At the time of the maximum UHI intensity, the most important environmental factors explaining the temperature differences were the distance from the city centre, relative elevation, built areas and forests and parks. The city centre was the warmest site, whereas the rural areas 8.5 km SE of the city centre were the coldest. Kekkonen (2015) studied the impacts of environmental factors on spatial temperature differences in Oulu with GIS data, hierarchical partitioning, and a linear regression model. The temperature data of the study was collected with a T&D RTR-52A Wireless Temperature Recorder with three mobile measurement campaigns during calm and clear summer nights in July and August 2014. The temperatures were corrected afterwards using a reference temperature from one site to take into account general temperature change during the measurement circuit. The reference temperatures were measured with a Hobo UA-001-64 temperature logger. The city centre was the warmest site during each measurement campaign. The largest temperature difference to the rural site four km SE of the city centre was 8.4 K. Urban land use was the most important environmental factor explaining spatial temperature differences in the area.

Suomi (2018) studied the impacts of environmental factors on large temperature differences (a momentary situation, 99th–100th and 99th–100th percentiles) with open-access GIS data, warmth order of the observation sites and a linear regression model on a monthly basis in the city of Lahti in southern Finland. As temperature data, the 30-minute interval observations of eight sites during a two-year period (June 2014–May 2016) were utilised. Temperature was measured with Onset HOBO U23-001 Pro v2 temperature and relative humidity loggers placed inside Onset RS1 radiation shields a height of three metres. The largest momentary temperature difference occurred during inversion conditions in the morning in February 2015, when the semi-urban hilltop site Kivistönmäki was 11.1 K warmer than the observation site in the detached house area Laune. During the summer season, the city centre was found to be the warmest area. In the autumn and early winter, the harbour on the lakeside of Lake Vesijärvi was the warmest location. Of the various environmental factors, topography had the greatest impact during momentary situations and winter, while the impact of urban heating was at its strongest in the summer and evident at the 99th and 95th percentiles of the ranked spatial temperature differences. In October, the heating impact of the relatively warm Lake Vesijärvi was the most dominant factor. An overview of UHI research in the municipalities Joensuu, Hyvinkää, Oulu, and Lahti is presented in Table 4.

Table 4. Urban heat island research in Joensuu, Hyvinkää, Oulu, Lahti in chronological order: the main researcher, the maximum temperature difference between the urban and rural area (max T_{u-r}), research area, research period, data type, and data sources, respectively.

Year	City	Researcher	Research area	Period	Max. T_{u-r}	Data type	Data source
1981	Joensuu	Ekholm	city centre / suburbs	summer 1980	7.5 K	mobile	drives /bike
1981	Joensuu	Ekholm	city centre / suburbs	winter 1981	6 K	mobile	drives / car
1994	Hyvinkää	Laaksonen	city centre / surrounding areas	summer 1988	9.2 K	mobile	8 areas / foot
1999	Oulu	Hara	city centre / rural areas	summer 1996–1998	9.1 K	stationary and mobile	3 points and 5 drives
1999	Oulu	Hara	city centre / rural areas	winter 1996–1998	6.2 K	stationary and mobile	3 points and 5 drives
2011	Oulu	Kananen	city area	winter 2011	12.9 K	mobile	7 drives
2015	Oulu	Kekkonen	city area	summer 2014	8.4 K	mobile	3 drives
2018	Lahti	Suomi	city centre / suburbs	24 months 2014–2016	11.1 K	stationary	8 points

Discussion and Conclusions

The effects of the urban heat island phenomenon are fourfold at higher latitudes. First, in winter the UHI phenomenon reduces the amount of heating required for residential and public buildings, but increases, for example, maintenance costs for the public road network due to more frequent crossing of the zero-degree line caused by constant freezing and thawing. Research in Slovenia on the relationship between large-scale weather patterns and UHI in a small town showed an increase in UHI intensity of 0.6 K for anticyclonic weather patterns (Ivajnšic and Žiberna 2018). Winter high-pressure weather conditions increase the UHI intensity due to low-cloud and low-wind phenomena. However, such weather patterns are not the predominant winter weather patterns. Yang and Bou-Zeid (2018) demonstrated that anthropogenic waste heat from the buildings of 12 North American cities contribute more than 30% of UHI intensification during winter.

Secondly, the urban heat island extends the growing season in spring and autumn. More detailed studies on the extension of the growing season for Finnish cities are not yet available. In Madison, Wisconsin, USA, Schatz and Kucharik (2016) found a 14% increase in vegetation length comparing rural and urban areas. Aalto *et al.* (2022) observed an increase in the growing season for northern Europe of 3.3 days per decade for the period from 1990–2019. Higher temperatures also increase the vulnerability of urban green infrastructure to diseases and infestation by pest insects (Lehmann *et al.* 2020). Preventive urban planning must already think about introducing more climate-resistant shrubs and trees so that the green infrastructure has enough time to acclimatise.

Thirdly, the urban heat island in summer contributes to a significant increase in the occurrence of heat waves and thus to the increased incidence of thermal health stresses with possible premature mortality in human risk groups (Ruuhela *et al.* 2021). Ward *et al.* (2016) discovered that northern European cities are more vulnerable to heat waves than their southern European counterparts. The impact of summer heat waves on the population is increasingly related to thermal conditions in buildings. Here, risk groups such as the sick, children and the elderly are particularly affected by thermal conditions. Finally, the effects of the urban heat island on the building material are still largely unexplored. The urban building fabric, which was designed and built for different climatic conditions, is a particular focus of urban planning in view of the increasing development of the urban heat island and climate change. For example, it is assumed that precipitation amounts could increase by up to 60% in winter months in the worst cases (Ruosteenoja *et al.* 2016). This can lead to an increase in water damage to buildings, which in turn can lead to mould and rotting of residential and public buildings due to inadequate air conditioning and ventilation.

The UHI research can be divided into two groups, mobile and stationary measurements. Mobile measurements can represent high spatial and temporal resolution but only via the measurement route, while stationary measurements can represent high temporal resolution and long data sets, but only in a specific point. The mobile measurements are typically considered only in weather conditions that are favourable for the studies (e.g., light cloud cover, i.e., < 2/8 sky cover, low wind), while all stationary measurements are commonly used for the heat island calculations. Different mobile measurement studies established in the same city (e.g., those of Fogelberg *et al.* 1973 and Alestalo 1975) in practice always represent a different measurement route and a small number of measurement trips. A combination of mobile and stationary methods has also been used (Drebs (2011). The results from the stationary methods in a specific city are similar to those from the mobile investigations. For instance, in Helsinki, the urban heat island's long-term average temperature ranges from 0.8 K (Tommila 1961) to 2.8 K (Drebs 2011).

Despite the complexity of the individual UHI studies and the assumption that all of them were carried out independently of each other, the result of our analysis shows surprisingly high agreement. Therefore, the individual studies established in Helsinki from 1961 to 2011 can be summarised into an overall picture according to the used methodology, data sources and the primary results, respectively. In Finland, notable impact on the UHI characteristics comes from the vicinity of the city to a water body. Similar to Helsinki, Oulu and Turku are coastal cities of the Baltic Sea, whereas inland towns Joensuu and Lahti have relatively large lakes in their immediate vicinity. Of the cities/towns studied in this paper, Hyvinkää has the fewest water bodies in its surroundings (Table 1). However, most large urban areas in Finland are close to either a sea or a lake. Regarding topography, Finland does not exhibit extreme elevations, and therefore the topographical effects to UHI are not very large but should not be neglected. With respect to elevation, in the most variable town, Lahti, the differences in relative elevation are up to 150 m, whereas in the other end, the Oulu area is generally very flat. In the UHI studies of Lahti, Oulu and Turku, the impacts of topography and water bodies on temperatures have been recognised, statistically analysed, and interpreted. In the studies of Helsinki and Joensuu, the roles of topography and water bodies have been noticed. In Hyvinkää, the impact of topography has been interpreted, whereas due to the scarcity of water bodies, their impact has not been assessed. In summary, the previously mentioned UHI studies can be considered comprehensive in a way that in addition to the impacts of a city, they have recognised and assessed the roles of other relevant local factors on spatial temperature variability. In Turku, where the studies have been based on a stationary observation network, the impact of water bodies on spatial temperature differences is generally at its largest in spring and autumn (Suomi and Käyhkö 2012; Väyrynen *et al.* 2017). In Lahti, the impact of Lake Vesijärvi is emphasised in autumn (Suomi 2018). To get more information on seasonal variability of UHI, it would be interesting to perform measurement campaigns during suitable conditions in spring and autumn, especially in Joensuu and Oulu, where the impact of water bodies on spatial temperature differences could be emphasised in a similar manner to the approach in Lahti and Turku.

As the studies in Helsinki have followed traditional UHI research by focusing mainly on UHI intensity and its spatial characteristics, the studies performed in Turku have principally concentrated on the impacts of environmental factors on spatial temperature variability. As the seasonal and diurnal differences in the relative importance of land use, topography and water bodies have been studied with various time periods and various statistical methods, the principal observations on their weights have been reminiscent of one another, an observation which can be considered to strengthen the reliability of the results. As the impact of urban land use has been, without exception, a warming one (Hjort *et al.* 2011; Suomi and Käyhkö 2012; Suomi *et al.* 2012; Hjort *et al.* 2016; Väyrynen *et al.* 2017), the direction of the impact of the water bodies is twofold, characterised by daytime cooling in spring and general heating in autumn (Hjort *et al.* 2011; Suomi and Käyhkö 2012; Väyrynen *et al.* 2017). The impact of topography is for the most part rather weak, but its impact is emphasised during inversion conditions, when the cold air pooling is often the strongest agent behind the spatial temperature differences (Hjort *et al.* 2016).

In the studies of Turku dealing with the impacts of environmental factors, remarkable time- and factor-specific variation in the size of the footprint area that best reflects the thermal impact of the factor has been observed. For urban land use/land cover types, the optimal footprint area has been between 100–1000 m in radius, whereas for non-urban factors, the footprint area has been on average larger, and more variable, extending from 100 m up to 20 000 m (Suomi *et al.* 2012; Hjort *et al.* 2016). The observations on the optimal footprint area for urban land use types is in line with Oke's (2006) considerations on 500 m as an appropriate footprint area for screen-level temperature measurements. The larger footprint area for non-urban factors is supported by the statements of Giridharan and Kolokotroni (2009) and Stewart and Oke (2009), who suggest a larger footprint area for sparsely built and natural environments. Seasonally, the footprint area of non-urban factors is larger in summer than in winter, both in long-term average temperatures and during momentary situations, whereas for urban factors, the footprint area is larger in summer in long-term average temperatures, but during momentary situations, the footprint area of urban factors is larger in winter (Suomi *et al.* 2012; Hjort *et al.* 2016). In the Turku area, stationary temperature measurements have continued since the summer of 2001. Lengthening the observation period will form a good basis for climate change-related UHI studies in the future. So far, the best view of temporal change of UHI can be obtained by the study of Suomi and Meretoja (2021), who detected an intensifying trend of UHI by 0.11 K per decade during the 17-year period from 2002–2018. The observation is in line with that of Wilby (2007), who predicted an intensifying trend of UHI because of climate change but is the opposite of Oleson *et al.* (2011), who predicted a weakening trend of UHI in the future. The population of Turku grew from 174 000 to 191 000 during the 17-year period, but the surroundings of the marketplace that presented the core area of UHI in the study, remained rather unchangeable. To summarise, a 17-year period is too brief to reliably estimate the factors behind the intensifying UHI in Turku, and further research is needed.

Accurate knowledge of thermal conditions in cities and peri-urban areas enables sustainable urban and environmental planning; this can also be seen as one of the main drivers for the past UHI research in Finland analysed in this paper. Common UHI features in high-latitude urban areas are the significant seasonal differences (even up to 14 K) and the somewhat constant nature of UHI intensity during the recent decades; only recently has the UHI intensity shown increasing features. Also, an important finding is that the previous studies have been established with similar methods, suggesting that these early research results are also valuable for current UHI research.

As can be seen from the review of existing studies, UHI research has been a combination or mix of different kinds of methods, mobile and static in-situ observations. We can safely say that each method has its benefits but also downsides. While mobile measurements provide the possibility to have spatially detailed observations from the route, the measurement represents only one timestep. On the other hand, while static in-situ measurements may provide detailed temporal time series, the observations represent only a single fixed point. This suggests that the complete or optimal understanding of the climatic characteristics of urban areas can be achieved only with the combination of different types of methods.

Acknowledgements: The authors would like to thank Professor Miska Luoto from the University of Helsinki's Department of Geosciences and Geography for his objective criticism of the content and form of this publication. Furthermore, we wish to thank two anonymous reviewers for their critical and helpful comments that improved the manuscript. This work was financially supported by LIF17 IPC/FI/000002/LIFE-IP CANEMURE-Finland and by the CLIHE programme of the Academy of Finland (Consortium HEATCLIM, funding decision 329307).

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