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Review article

Impact of blue spaces on the urban microclimate in different climate zones, daytimes and seasons – A systematic review

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A R T I C L E I N F O

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A B S T R A C T

The phenomenon of the urban heat island effect requires urban planning adaptation strategies that mitigate heat stress. While the cooling effect of urban green spaces has been well studied, knowledge gaps remain regarding the cooling potential of urban blue spaces. Particularly, how the cooling intensity of an urban blue space is influenced by its features and the context in which it occurs, such as its size, location, and more broadly the local climate and season, requires closer investigation. To address these gaps, we conducted a systematic review of studies exploring the thermal effect of urban blue spaces on the surrounding urban microclimate. We extracted the cooling or heating intensity of urban blue spaces, while considering how season, time of day, climate zone, water body size and methodological approach may influence results. Through analysis of 67 identified articles, we found that the thermal effect of blue spaces varies between seasons and time of day, with daytime temperatures in the surrounding urban climate cooled by 2.6 °C on average and maximum intensities observed during late spring and early summer. While at night-time in the summer, the thermal effect showed an average urban heating intensity of 0.6 °C. These values differ depending on the methodological approach used, with mean daytime cooling intensities varying considerably by method (field measurements: 1.4 °C; remote sensing: 3.4 °C; numerical modelling: 1.7 °C). The thermal effect also differed by climate zone, with results indicating a cooling intensity during the day with higher values in temperate climate zones. At night, both cooling and heating effects were observed in continental and temperate zones. The few studies reporting on water body size indicated a higher cooling intensity with greater size of the water body. These varying cooling or heating characteristics of urban blue spaces suggest they can be utilised in different planning contexts to achieve desired goals, depending on their features, the time and location, making them valuable nature-based solutions aimed at mitigating urban heat.

1. Introduction

Nature-based solutions, such as urban green and blue spaces, have been identified as means of mitigating climate change and urbanisation-related heating (Kabisch et al., 2015, 2023; Lwasa et al., 2023). Particularly, urban green and blue spaces can cool their surrounding areas and counteract the urban heat island effect (Bowler et al., 2010; Gunawardena et al., 2017). As non-sealed spaces, urban green spaces provide local cooling effects of around 1–2 K (Bowler et al. 2010), even under heat and drought conditions (Kraemer and Kabisch, 2022; Rahman et al., 2022). Yet, comparatively less is known about urban blue spaces, including lakes, ponds, canals and rivers, and given they diverge from green spaces in terms of shading, air movement and wind, and the reflection of solar radiation, the extent to which they may cool their surrounding areas may differ (Ampatzidis and Kershaw, 2020).

Previous studies have identified that urban blue spaces may cool their surrounding areas during the daytime (Heusinkveld et al., 2014; Völker et al., 2013; Wu et al., 2019), but, reversely, heat during the night (Heusinkveld et al., 2014; Hu and Li, 2020; Steeneveld et al., 2014). There is also evidence of seasonal variations, with higher thermal impacts observed during the summer compared to winter (Gupta et al., 2019; Hathway and Sharples, 2012). While previous reviews have begun unravelling these trends, their analyses were based on research published over half a decade ago (see, for instance, Ampatzidis and Kershaw, 2020; Völker et al., 2013; Yu et al., 2020). Conducting a new review considering the most recently published research could update knowledge about the extent to which a blue space's thermal impact is influenced by its characteristics, the time of day, season, and location.

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Determining the thermal impact of a blue spaces requires consideration of its cooling distance and intensity. The cooling or heating distance is defined as the range up to which a change in continuous air or surface temperature as a result of the blue space can be monitored. The difference between the air temperature at this particular point and the water's edge is defined as the cooling or heating intensity and is measured in °C (Jiang et al., 2021) (Fig. 1). Dividing cooling intensity by the cooling distance provides the temperature gradient and is given in °C per m or km (Le Phuc et al., 2022; Sun and Chen, 2012; Yao et al., 2022).

The cooling intensity or distance of a blue space is usually assessed via one of three of methodological approaches: field measurements, remote sensing, or numerical modelling. Field measurement studies, which measure air temperature or humidity at actual physical locals around the blue space, have been used as a method to gather temperature data in particular microclimates since the mid-19th Century (Park et al., 2019). Remote sensing approaches record Land Surface Temperature (LST) through a spectral signal using satellites or drones and provide a spatial overview of the thermal condition of surfaces (Cai et al., 2022). Such approaches have emerged since the 2000s, as technology developed and data from different sensor systems covering large areas, such as Landsat are Sentinel, became more readily available. For example, the Landsat archives opened in 2008 and provided remote sensing images with a high spatial resolution of 30 m from the early 1980s onwards (Wulder and Coops, 2014). Finally, at a somewhat similar time, modelling approaches emerged, which apply scenario development to standard meteorological or infrastructural conditions (Balany et al., 2022; Žuvela-Aloise et al., 2016). While the technology to do modelling has been around since the late 20th Century, it was not until recently that such methods were applied to determining thermal environments around urban blue spaces.

The magnitude of the thermal impact of an urban blue space has been documented to be influenced by both internal and external factors (Steeneveld et al., 2014). Internal factors include the water body depth, area (size), temperature, and shape, also known as the landscape shape index (LSI) (Cai et al., 2022; Steeneveld et al., 2014; Yu et al., 2020). The LSI refers to the circumference of the water body in relation to its area. Rounder water bodies with smaller LSIs are likely to have a greater cooling potential as they have a decreased contact surface with the surrounding area (Cao et al., 2022; Sun and Chen, 2012; Qiu et al., 2021). Deeper blue spaces usually have a higher volume of water and thus a correspondingly higher specific heat storage capacity (Qiu et al., 2021), while shallower blue spaces with low water levels exhibit a reduced cooling effect (Le Phuc et al., 2022). Larger water bodies also take longer to heat up and cool down and thus exhibit a delayed effect on the air or surface temperature of the surrounding area (Heusinkveld et al., 2014; Hu and Li, 2020; Wang et al., 2022). Finally, regarding temperature, water bodies cooler than the surrounding land exhibit the greatest cooling potential (Hathway and Sharples, 2012; Le Phuc et al., 2022; Lin et al., 2022; Yang et al., 2020).

External factors, such as the features of the area surrounding the blue space, may also impact the cooling function. These features include the amount of greenery or sealed surfaces, the ambient air temperature, and the location of the blue space in the urban built environment and in relation to prevailing winds or wind tunnels (Cai et al., 2022; Hathway and Sharples, 2012; Pang et al., 2022; Qiu et al., 2021; Sun and Chen, 2012). For instance, comparisons of blue spaces in built-up, developed areas with those in more natural regions or cropland find more pronounced cooling intensities in the urban areas (Qiu et al., 2021; Sun and Chen, 2012). Cooling intensities and distances are also higher in downwind areas, when compared to those upwind (Jiang et al., 2021; Qiu et al., 2021).

Consequently, in this review, we seek to collate research evaluating the thermal impact of urban blue spaces, in order to inform understandings of the magnitude of urban blue spaces contribution to mitigate the urban heat island effect. Set against this background, the main aim of this study, then, is to systematically review literature examining the thermal effect – cooling or heating – of urban blue spaces, evaluate the impact of relevant internal and external factors in this thermal impact, and determine the relevance and accuracy of various methodological approaches. The following research questions are asked:

- How and to what extent does the thermal impact of urban blue spaces on the urban microclimate differ in the course of the day and throughout different seasons?

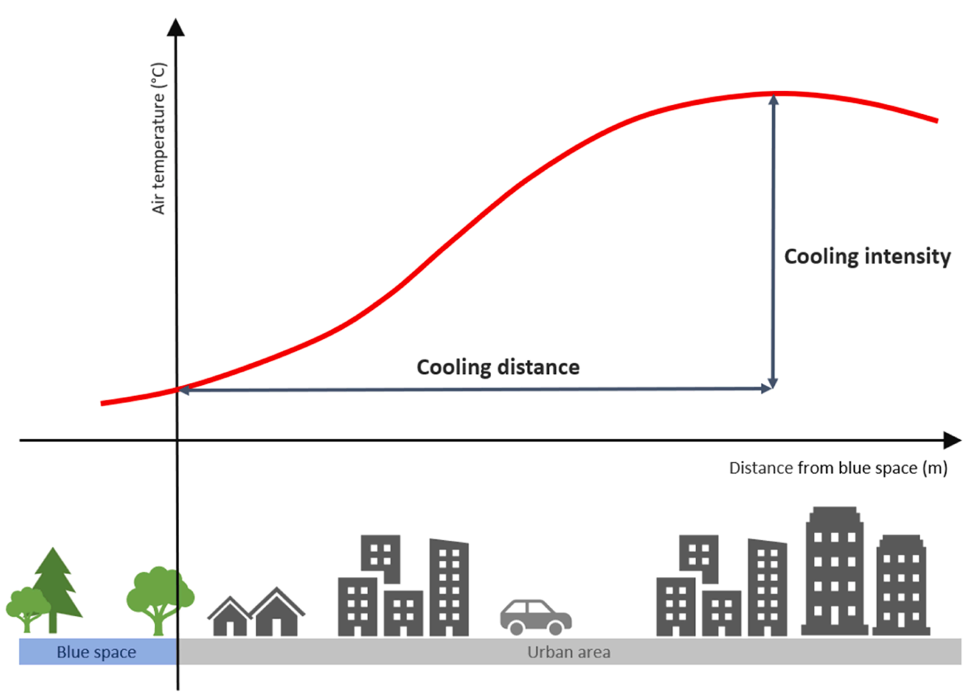

Fig. 1. Schematic illustration depicting the thermal effect of a blue space, including the cooling intensity and distance (exemplary for cooling); adapted from Jiang et al. (2021).

- How are methodological approaches related to the identification of the influence of blue spaces on the urban climate?
- How does the location, in relation to climate zones, and the size of blue spaces affect its thermal impact on the surrounding urban microclimate?

2. Methods

2.1. Search strategy

This review followed PRISMA guidelines (Page et al., 2021) and used the literature database, Scopus, to conduct its search. The process involved: (1) defining search and selection criteria; (2) conducting the search; (3) screening the literature; and (4) extracting relevant data via analysis of the content of the included articles. The search was done in September 2024 and date restrictions were set to the end of August 2024.

In accordance with the research questions, we sought to find articles documenting empirically the thermal impact of blue spaces in urban environments (effect size) on the surrounding urban microclimate, through measuring cooling/heating intensity. Given the focus on quantitative studies reporting empirical values for cooling intensity, we only included articles that provided some numerical value for one of these constructs. Articles that may have measured land surface temperature of water bodies, but not the cooling effects on their surrounding areas specifically, were excluded. The search query was based on the following criteria: (1) urban area; (2) blue space; and (3) service or function. The individual criteria used for each topic, as well as the complete search query, is shown in Table 1. The chosen terms were based on an initial scoping of the existing literature. We restricted our search to articles published in English and excluded research reports, other non-scientific publications, bibliographies, conference proceedings and review papers.

The search resulted in a total of 2051 articles. Screening of the literature's abstracts led to 1677 records being excluded, as they did not satisfy the inclusion criteria. The full-texts of the remaining 374 articles were then assessed, with 309 articles excluded because they did not provide numerical values for cooling or heating intensities or only considered blue spaces as a factor influencing the thermal impact of green spaces, leaving 65 for analysis. Two additional articles were identified through snowballing and inspection of the included articles reference lists. Collectively, 67 articles were included (Fig. 2).

We analysed the 67 articles subsequently by using a standardised data extraction sheet informed by our pre-defined research review questions: (1) study area and climate classification; (2) type and characteristics of the urban blue space; (3) season and time of day the results are based on; (4) method used and data gathered; and (5) indicators and specific results. We used an adapted version of the quality appraisal tool used by Lai et al. (2019) to conduct a risk of bias assessment (see Supplementary Material 1).

Table 1
Structure of the search query used for literature analysis.

	Criteria for assessment	
Area	**Urban blue**	**Service / Function**
Urban	Blue area	Cool Island
City	Blue-green area	Ecosystem function
Peri-urban	Blue infrastructure	Ecosystem service
Suburban	Blue space	Heat island
	Urban lake	Heat stress
	Urban pond	Heat wave
	Urban river	Regulating function
	Surface water	Cooling
	Water area	Warming
	Water body	Regulating service
	Water space	

(TITLE-ABS-KEY ("urban" OR "city" OR "peri-urban" OR "suburban") AND TITLE-ABS-KEY ("blue area" OR "blue-green area" OR "blue infrastructure" OR "blue space" OR "urban lake" OR "urban pond" OR "urban river" OR "surface water" OR "water area" OR "water body" OR "water space") AND TITLE-ABS-KEY ("cool island" OR "ecosystem function" OR "ecosystem service" OR "heat island" OR "heat stress" OR "heat wave" OR "regulating service" OR "warming" OR "regulating function" OR "cooling"))

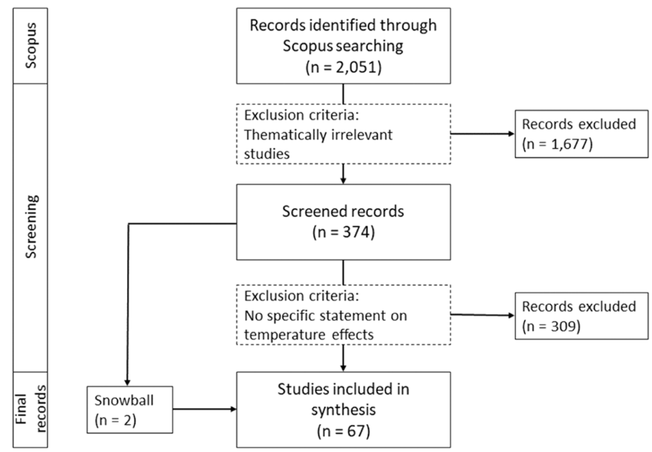

Fig. 2. PRISMA methodology scheme for identifying relevant literature to the urban blue space – cooling topic.

3. Results

3.1. Study characteristics

The publication dates of the 67 included articles ranged from 2012 to 2024. The number of articles published each year tended to increase yearly, indicating that research exploring urban blue spaces and their impact on the urban microclimate is a growing field (Fig. 3).

Fig. 4 shows an overview of the number of articles by location. Around 88 % (n = 59) of the analysed studies were conducted in Asia, particularly in Chinese cities such as Beijing, Shanghai and Wuhan. A smaller selection was conducted in Europe (n = 5), including Vienna (Austria), Sheffield (UK), Bucharest (Romania), and Riccione (Italy), and Australia (n = 2), in Adelaide and Melbourne. One study was conducted in North America, in Madison, USA.

An overview of the data extracted from all studies investigated, including location, climate zone, time of day, cooling or heating intensity, methodological approach, and size of the blue space, is presented in Table 2. Most studies, in determining cooling or heating intensity, recorded temperatures during the summer (n = 63), while a lower number of studies considered spring (n = 17), autumn (n = 12) and winter (n = 15). Nearly one-third of the studies compared results across different seasons (n = 20). Similarly, the majority of articles

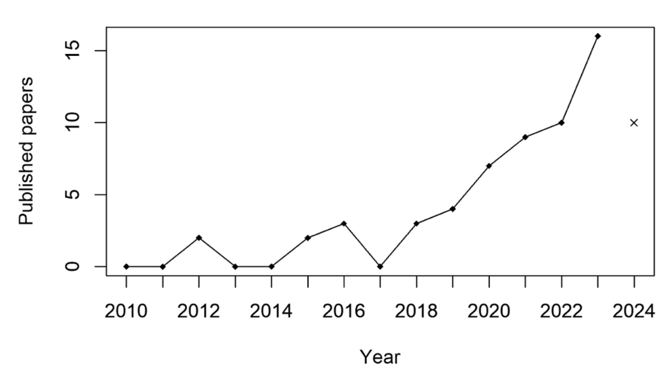

Fig. 3. Number of papers about urban blue spaces per year.

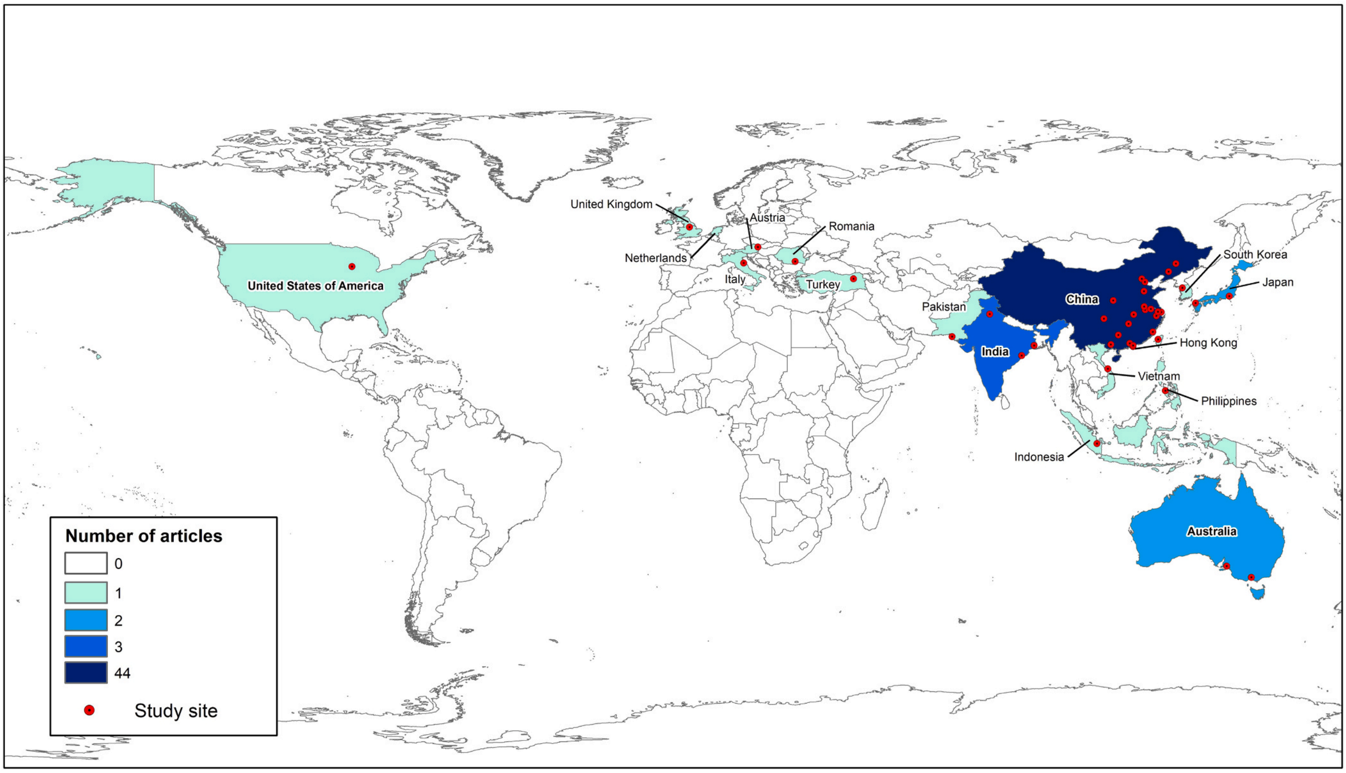

Fig. 4. Spatial distribution of the study sites with regard to the number of articles by each country.

investigated the thermal impact of blue spaces in daytime conditions (n = 44), while 16 compared daytime and night-time. A small selection did not define the exact time of day at which measurement occurred, but for the purposes of this analysis, as they were all remote sensing studies, they were recorded as occurring during the daytime (n = 7). Finally, most of the included studies reported on case studies in temperate climate zones (n = 49), with a lower number of studies for continental (n = 10), tropical (n = 5) and arid (n = 1) zones. One study reported results across multiple climate zones and another one is based on modelling approaches without information on a climate zone. The most frequently used methodological approach adopted across the included studies was the Land Surface Temperatures (LST) approach, derived from remote sensing data (n = 39). In 19 studies, field measurements were conducted and 15 studies applied a numerical modelling approach. Fig. 5 and Fig. 6 show the empirical values obtained for the thermal impact of urban blue spaces identified in each study and sorted by time of day, season and methodological approach.

3.2. *Thermal effect of blue spaces in different seasons and daytimes*

Across all studies investigated the thermal impact of urban blue spaces during the daytime, a mean cooling intensity of 1.9 °C was found (Fig. 5). The 17 studies reporting on the thermal effect at night observed a heating intensity of 0.9 °C on average (Fig. 6). The thermal impact changed across seasons (during the daytime), with mean cooling intensity values in spring of 2.8 °C, followed by summer (2.7 °C), autumn (1.8 °C) and winter (0.9 °C). The magnitude of the cooling effect during the daytime in spring ranged from 0.2 °C in Nanjing, China (Yao et al. 2023a), to 11.18 °C in Hefei, China (Lin et al. 2022). The cooling impact in autumn ranged from 0.0 °C in Nanjing (Yao et al. 2023a), to 7.38 °C in Wuhan, China (Wang and Ouyang, 2021). In winter a thermal effect ranged from 0.02 °C heating in Erzurum, Turkey (Dursun and Yavaş, 2024) to 3.12 °C cooling in Ahmedabad, India (Gupta et al. 2019). The thermal impact of blue spaces during summer show a comparatively high variance, with values between 13.3 °C cooling in Wuhan (Xie et al. 2023) and 2.21 °C heating in a modelling study set in China with no specific city identified (Cai et al. 2022).

Of the articles that measured the thermal impact of blue space at night, the most frequently examined season was summer (n = 11), compared with 3 articles for spring, and 2 articles each for autumn and winter. In contrast to daytime, most studies identified a heating effect during the night, except three studies at Wuhan (Wang et al. 2022), Shanghai (Shi et al. 2024) and Taiwan (Liao et al. 2024), which show exclusively cooling effects between 0.1 °C and 2.4 °C (Shi et al. 2024) and a single study at Taichun City (Taiwan) showing both effects between 1.0 °C cooling and 1.4 °C heating (Liao et al. 2024). Concerning seasonal effects for the night-time assessments, the strongest heating effect was in summer with 3.5 °C (Theeuwes et al. 2013) but ranged from 1.1 °C cooling in Wuhan, China (Wang et al. 2022), to 3.5 °C heating (Theeuwes et al. 2013), with an average value of 0.6 °C heating. The effect was weaker in autumn with 1.1 °C in Nanjing (Yao et al. 2023a) to 1.60 °C in Palembang City, Indonesia (Triyuly et al. 2021), spring with 0.35 °C in Sheffield, United Kingdom (Hathway and Sharples, 2012) to 1.5 °C in Nanjing (Yao et al. 2023a), and winter with 0.30 °C in Fukuoka, Japan (Peng et al. 2021) to 1.4 °C in Nanjing (Yao et al. 2023a).

3.3. *Methodological approaches used to thermal impact of blue spaces*

The measured thermal impact of blue spaces differed depending on the methodological approach used (see Fig. 7 for mean and range values across studies and see Figs. 5 and 6 for individual measurements from these studies during daytime and night-time). Across the 19 studies using field measurements, the average cooling intensity of urban blue spaces during the daytime was found to be 1.4 °C (Fig. 7). This thermal effect ranged from a single morning heating effect of 1.09 °C (Chen et al., 2024) to a cooling of 3.55 °C (Wang et al., 2022). The results during the night-time also varied, with cooling and heating effects observed across studies. On average, a heating effect for night-time of 0.6 °C was identified.

Table 2
Specific results of thermal impact of urban blue spaces.

Author (Year)	Season	Country	City (Study area)	Climate zone	daytime	Thermal effect	Cooling / heating Intensity	Cooling / heating distance (m)	Methodology	blue space	Size
Broadbent et al., 2018	Summer	Australia	Adelaide	C	day and night	Cooling	day: 1.8 °C night: +−0 °C	day: <= 50 m	FM, RS	2 Water courses 2 Lakes	-
Balany et al., 2022	Summer	Australia	Melbourne	C	day	Cooling	0.34 °C (90 cm deep pond) 0.51 °C (100 cm deep pond)	-	NM	Ponds	-
Y. Bin Cai et al., 2022	Summer	China	Fuzhou	C	day	Cooling	May 2010: 4.57 °C September 2015: 7.30 °C July 2020: 9.7 °C	May 2010: 689 m September 2015: 748 m July 2020: 861 m	RS	WB	-
Cai et al., 2018	Summer	China	Chongqing City	C	day	Cooling	max: 4.75 °C	max: 945 m	RS	2 River	-
Cai et al., 2022	Summer	China	34 cities	multiple	day	cooling/ heating	max heating: 2.21°C max cooling: 7.83 °C	430 – 1350 m	RS	WB	-
Cao et al., 2022	Summer	China	Beijing	C	day	cooling	0.813 °C – 2.514 °C	-	NM	WB	0.04 – 0.16 ha
Chen et al. 2024	Summer	Hongkong	Hongkong	C	day	cooling/ heating	Morning; 10 a.m: 0.63–1.09 °C heating Evening, 7 p.m.: 0.22–0.83 °C cooling	-	FM	Blue spaces	-
Cheng et al. 2023	Summer	China	Wuhan	C	day and night	cooling/ heating	Day: 0.184–0.459 cooling night: 0.174–0.448 heating	Day: 7–22 km Night: 23–84 km	NM	Lakes	Area: 867,00 ha
Cheval et al., 2020	Summer	Romania	Bucharest	D	day	cooling	1.10. - 1.7 °C 1.11. 2.5–5.0 °C	30 m 300 m	RS	13 lakes	Area: 921.3 ha; Depth: 1–5 m
Cruz et al., 2021	Summer	Philippines	Iloilo City	A	day and night	cooling/ heating	daytime cooling:.2.63 °C night-time heating: 0.12 °C	max: 200 m	NM	1 River	-
Cureau et al. 2023	Summer/ Winter	Italy	Riccione	C	day	cooling/ heating	Morning: 0.5 °C Midday: 1.3 °C Afternoon: 0.9 °C Winter: heating	-	FM	Sea	-
Du and Zhou, 2022	Summer	China	Shanghai	C	day	cooling	2000: 1.56 – 5.72 °C 2004: 1.63 – 6.15 °C 2007: 1.40 – 5.62 °C 2015: 1.40 – 5.91 °C	2000: 170 – 1670 m 2004: 210 – 1710 m 2007: 310 – 1630 m 2015: 370 – 1470 m	RS	18 WB	> 1 ha
Du et al., 2016	Summer	China	Shanghai	C	day	cooling	1.22–5.91 °C Lakes: 3.49 °C (mean) River: 2.25 °C (mean)	370–1470 m Lakes: 770 m (mean) River: 590 m (mean)	RS	18 lakes 3 rivers	Lakes: 111 – 1218 ha River area: 5464 – 17,153 ha
Dursun, Yavaş, 2024	Summer/ Winter	Turkey	Erzurum	D	day	cooling/ heating	Summer: 5.0 °C cooling Winter: 0.02 °C heating	-	NM	River	-
Feng et al. 2023	Summer	China	Xi'an	D	day	cooling	East bank: 2.8 °C - 3.7 °C; West bank: 1.7 °C - 3.2 °C	East bank: 300 -500m West bank: 400–600 m	RS	River	-
Fung and Jim, 2020	Summer	Hong Kong	Hong Kong	C	day	cooling	Daytime cooling: 0.7 °C (mean)	-	FM	Pond	170 ha
Ghosh and Das, 2018	Spring	India	Kolkata	A	unclear	cooling	0.33–3.3 °C 0.36–3.82 °C	50–100 m 100–150 m	RS	6 WB	150 ha
Guo et al. 2023	Summer	China	Shenyang	D	day	cooling	-	4000 m	RS	River	-
Gupta et al., 2019	Summer/ Winter	India	Chandigarh / Ahmedabad	C	unclear	cooling	Summer / Winter: 7.51 °C / 3.12 °C (Lake) 1.57 °C / 1.71 °C (River; right bank) 0.69 °C / 0.65 °C (River; left bank)	Summer: 900 – 1200 m (Lake) 200–300 m (River) Winter: reduced	RS	1 lake 1 river	Lake: Area: 300 ha, Depth: 4.9 m River: -
Hathway and Sharples, 2012	Spring/ Summer	United Kingdom	Sheffield	C	day and night	cooling/ heating	Daytime cooling: 1.82 °C (avg. May) 0.98 °C (avg. June) Night-time heating:	-	FM	urban river	Width: 22 m

(*continued on next page*)

Table 2 (*continued*)

Author (Year)	Season	Country	City (Study area)	Climate zone	daytime	Thermal effect	Cooling / heating Intensity	Cooling / heating distance (m)	Methodology	blue space	Size
							0.35 °C (avg. May) 1.1 °C (avg. June)				
Hu and Li, 2020	Spring/ Summer/ Autumn/ Winter	USA	Madison	D	day and night	cooling/ heating	Daytime cooling: 0.2 °C (± 0.4) (annual avg.) 0.2–0.7 °C (max; spring/fall) Night-time heating: 1.1 °C (annual avg.) 2.3 °C (max; summer/fall)	Daytime cooling: <= 500 m Night-time heating: <= 1000 m	FM	2 lakes	-
Jiang et al., 2021	Summer	China	Shanghai	C	unclear	cooling	1.72–9.10 °C (mean: 4.47)	72–465 m (mean: 197 m)	RS	1 river	Width: 445–523 m
Kang et al. 2023	Summer	China	Nanjing	C	day	cooling	0.27 °C - 5.78 °C	96.4 m - 445.95 m	RS	35 lakes	-
Le Phuc et al., 2022	Summer	Vietnam	Thenh Noi / Hue City	A	unclear	cooling	0.33–3.5 °C (mean: 1.52 °C)	90–210 m (mean: 150 m)	RS	20 lakes	-
Liao et al. 2024	Spring/ Summer/ Winter	Taiwan	Taichung City	C	day and night	cooling/ heating	Spring: Day: 2.6 °C (cooling) Night: 0.9–1.4 °C (heating) [NM; ENVI MET] Summer: Day: 2.6–3.5 °C [NM; CFD] 2.9–3.2 Cooling [FM] Night: 0.6–1.0 cooling [NM; CFD] 0.3–1.3 cooling [FM]	-	FM NM	Pond	Length: 100 m Width: 70 m Depth: 1.5–2.0 m
Lin et al., 2022	Spring	China	Hefei	C	day	cooling	2005: 7.51 °C (5.21–10.74 °C) 2010: 4.44 °C (2.23–6.41 °C) 2015: 9.43 °C (8.15–11.02 °C) 2020: 8.93 °C (6.71–11.18 °C)	2005: 508.24 m (120–960 m) 2010: 528.88 m (120 – 1080 m) 2015: 431.25 m (120–840 m) 2020: 441.18 m (120 – 1140 m)	RS	17 lakes	16 – 77,590 ha
Liu et al., 2022	Summer	China	Fuzhou	C	unclear	cooling	-	120–150 m	RS	1 lake 3 river	4.7–600 ha
Ma et al., 2021	Summer	China	Xi'an	C	day	cooling	2.93–4.32 °C	150 – 210 m	RS	all WB	-
Mo et al. 2024	Spring/ Summer/ Autumn/ Winter	China	Guilin	C	day	cooling	Spring: 2.25 °C Summer: 3.06 °C Autumn: 1.69 °C Winter: 0.94 °C (LCZ 2)	Spring: 100 m - 500 m Summer: 100–450 m Autumn: 100–500 m Winter: 100–500 m (50 m heating 1 case)	RS	Lakes	-
Pan et al., 2023	Winter	China	Guangzhou	C	day	cooling	Afternoon: 0.23–0.63 °C Evening: 0.15 °C	-	FM	River	-
Pan et al., 2023	Summer	China	Huaihe River Ecological Economic Belt	C	day	cooling	ENVI_MET: 0.6–0.71 WRF: 1.01–2.15 °C	WRF: 400 m	NM	BS	-
Park et al., 2019	Summer	South Korea	Seoul	D	day	cooling	Daytime cooling: 0.46 °C (2 p.m.) 0.37 °C (10 p.m.)	Daytime cooling: 32.7 m (2 p.m.) 37.2 m (10 a.m.)	FM	1 river	-
Peng et al., 2021	Summer/ Winter	Japan	Fukuoka	C	day and night	cooling/ heating	Summer: daytime cooling: 0.61 °C night-time heating: 0.08 °C Winter: daytime cooling: 0.12 °C night-time heating: 0.3 °C	Summer: daytime: 300 – 400 m night-time: 200 – 400 m Winter: daytime: 300 – 400 m night-time: 300 – 600 m	RS	Lakes and River	
Qiu et al., 2021	Summer	China	Changsha	C	unclear	cooling	0.64–4.16 °C (mean: 2.36 °C)	120–970 m (mean: 310 m)	RS	21 WB	1.01–56.83 ha

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Table 2 (*continued*)

Author (Year)	Season	Country	City (Study area)	Climate zone	daytime	Thermal effect	Cooling / heating Intensity	Cooling / heating distance (m)	Methodology	blue space	Size
Qiu et al. 2023	Summer	China	Changsha	C	day	cooling	0.73 °C - 5.04 °C	63.75–370 m	RS	28 WB	1.01–29.99 ha
Shi et al. 2024	Summer	China	Shanghai	C	day and night	cooling	Day: (1) 2.3–2.9 °C (2) 0–0.5 °C (3) 0–0.2 °C Night: (1) 2.0–2.4 °C (2) 0.15 °C (3) 0.1 °C	Day: (1) 450–750 m (2) 140–640 m (3) 260 m Night: (1) 550 m (2) 200–300 m m (3) 220 m	FM	River network	Width: 10 – 500 m
Singh et al. 2023	Summer	India	Odisha	A	day	cooling	3–5 °C	-	NM	BS	11,100 ha
Sun and Chen, 2012	Summer	China	Beijing	D	day	cooling	0.03–2.2 °C / hm mean: 0.54 °C / hm	100 – 1400 m 58 % (of the water bodies): <=100 m 90 % (of the water bodies):<= 700 m	RS	197 WB	> 1 ha - 25.89 ha
Sun et al., 2020	Spring/ Summer	China	Nanjing	C	day	cooling	April 2010: 1.27 °C June 2014: 2.23 °C March 2016: 1.78 °C July 2017: 1.48 °C	April 2010: 503 m June 2014: 919 m March 2016: 1265 m July 2017: 623 m	RS	WB	3–50 ha
Tan et al., 2021	Summer	China	Nanning	C	unclear	cooling	0.08–2.02 °C mean: 0.88 °C	60–390 m (mean: 180 m)	RS	19 BS	0.14–10 ha
Tan et al. 2024	Summer	China	Changsha	C	day	cooling	(1) 2000: 3.87 °C 2009: 7.08 °C 2018: 7.35 °C (2) 2000: 9.51 °C 2009: - 2018: 8.01 °C (3) 2000: 0.41 °C 2009: - 2018: 2.79 °C	(1) 2000: 200 m 2009: 250 m 2018: 300 m (2) 2000: 200 m 2009: - 2018: 350 m (3) 2000: 100 m 2009: - 2018: 100 m	RS	Rivers	-
Theeuwes et al. 2013	Summer	Netherlands	-	-	day and night	cooling/ heating	Daytime cooling: −2.0 - −1.0 °C Night-time heating: 3.5 °C	-	NM	Lakes/ Ponds	-
Tominaga et al., 2015	Summer	Japan	Hadano	C	day	cooling	2.0 °C	100 m	NM	Pond	-
Triyuly et al., 2021	Autumn	Indonesia	Palembang City	A	day and night	cooling/ heating	Night-time heating: 1.2–1.6 °C	-	FM	1 WB	-
Wang et al., 2016	Summer	China	Changchun City	D	day	cooling	ca. 2.0 °C	700 m	RS	all WB	-
Wang et al. 2023	Summer	China	Tianjin	D	day	cooling	5.58 °C	810 m	RS	Lake	195 ha
Wang et al., 2022	Summer	China	Wuhan	C	day and night	cooling	Daytime cooling: 3.55 °C Night-time cooling: 1.1 °C	Daytime cooling: 1741 m Night-time cooling: 1253 m	FM	1 river	Width: 1.3 km
Wang et al. 2024	Summer	China	Hangzhou	C	day	cooling	4.41 °C	-	RS	Blue spaces	-
Wang & Ouyang, 2021	Spring/ Summer/ Autumn	China	Wuhan	C	day	cooling	Spring: 2.74 – 8.47 °C Mean: 5.18 °C Summer: 4.17–10.34 °C Mean: 7.24 °C Autumn: 1.87 – 7.38 °C Mean: 4.40 °C	Spring: 200–1500 m Mean: 606 m Summer: 200 – 1400 m Mean: 578 m Autumn: 200–1300 m Mean: 533 m	RS	36 Lakes	Small < 50 ha Medium >50–500 ha Large >500 ha

(*continued on next page*)

Table 2 (*continued*)

Author (Year)	Season	Country	City (Study area)	Climate zone	daytime	Thermal effect	Cooling / heating Intensity	Cooling / heating distance (m)	Methodology	blue space	Size
Wu and Zhang, 2019	Spring	China	Suzhou	C	day	cooling	3.02 °C	752 m	RS	1 lake	225,000 ha
Wu et al., 2019	Spring/ Summer	China	Wuhan	C	day	cooling	Spring: max: 6.9 °C mean: 4.3 °C urban / 3.3 °C rural Summer: max: 8.0 °C mean: 5.5 °C urban / 2.4 °C rural	Spring: 84–575 m urban lake 440 m rural lake Summer: 28 – 1232 m urban lake 532 m rural lake	RS	Spring: 40 lakes Summer: 42 lakes	3 – 4270 ha
Wu et al., 2020	Spring/ Summer/ Autumn/ Winter	China	Shenzhen City	C	day	cooling	Spring: 1.42 °C Summer: 5.02 °C Autumn: 3.6 °C Winter: 1.19 °C	-	RS	91 WB	> 1 ha
Xie et al. 2023	Summer	China	Wuhan	C	day	cooling	1.1 °C - 13.3 °C	-	RS	36 WB	115,400 ha
Yang et al., 2020	Summer/ Autumn	China	Jinan	C	day and night	cooling	Summer: ~ 1.0 °C (mean) Autumn: ~ 0.3 °C (mean)	-	FM	1 lake	58 ha
Yang and Zhao, 2015	Summer	China	Guangzhou	C	day	cooling/ heating	Daytime cooling: 1.5 °C Night-time heating: slight heating	-	FM	1 pond	Depth: 2 m
Yao et al., 2022	Spring/ Summer/ Autumn/ Winter	China	Fuzhou	C	day	cooling	Spring: 1.35°C Summer: 1.71°C Autumn: 1.07°C Winter: 0.57°C	-	RS	436 WB	> 0.09 ha
Yao et al. 2023a	Spring/ Summer/ Autumn/ Winter	China	Nanjing, Guangzhou	C	day and night	cooling/ heating	Day Spring: −0.4 - +0.2 Summer: 0.1–0.5 °C Autumn: −0.4–0 Winter: 0.3 bis 0.1 Year: 0–0.4 °C cooling Night: Spring 1.1–1.5 °C heating Summer: 1.1–1.3 °C Autumn: 1.1 bis 1.3 °C Winter: 1.4 °C Year: 1.2–1.3 °C	-	FM	Lakes	Xuanwu Lake: Area: 378 ha Depth: 1.6–1.7 m Liuhua Lake: Area: 32.4 ha Depth: of 1.5–2.0 m
Yao et al. 2023b	Summer	China	Nanjing	C	day and night	cooling/ heating	Daytime cooling: 0.6 °C Night-time heating: 1.4 °C	-	FM	Pond	Water area: 0.775 ha Perimeter: 410 m Average depth: 1.0 m
Yu et al., 2020	Spring/ Summer/ Autumn/ Winter	China	Beijing	D	day	cooling	Spring: 5.2 °C Summer: 6.5 °C Autumn: 2.7 °C Winter: 1.7 °C	Spring: 311 m Summer: 383 m Autumn: 317 m Winter: 220 m	RS	9 WB	> 1 ha
Zeeshan, Ali, 2023	Summer	Pakistan	Karachi	B	day	cooling	0.9 °C	-	NM	WB	-
Zhao et al. 2023	Spring/ Summer/ Autumn/ Winter	China	Wuhan	C	day	cooling	Spring: 0.6 Summer: 1.0 Autumn: 0.6 Winter: 0.3	Spring: 300 m Summer: 300 m Autumn: 200 m Winter: 200 m	FM	Lakes Ponds	Summarised water area: 806.8 ha
Zheng et al., 2021	Summer	China	Hangzhou / Nanjing	C	day	cooling	4.78–4.86 °C	336–741 m	RS	2 lakes	Area: 378–638 ha,

(*continued on next page*)

Table 2 (*continued*)

Author (Year)	Season	Country	City (Study area)	Climate zone	daytime	Thermal effect	Cooling / heating Intensity	Cooling / heating distance (m)	Methodology	blue space	Size
Zhou et al. 2023	Spring/ Summer/ Autumn/ Winter	China	Suzhou	C	day	cooling	-	Spring: 50 m - 540 m Summer: 37–616 m Autumn: 0–525 m Winter: 0–523 m	FM RS NM	River	depth: 1.14–2.27 m Area: 101 ha Length: 15,400 m Maximum width: 155 m Average width: 65 m
Zhou et al., 2024a	Spring/ Summer/ Autumn/ Winter	China	Suzhou	C	day	cooling	-	Spring: 43–550 m Summer: 8–601 m Autumn: 50–583 m Winter: 40–467 m	RS	River	River length: 15,400 m
Zhou et al., 2024b	Summer	China	Nanjing	C	day	cooling	10 m width: 0.11 °C 100 m width: 0.75 °C 1000 m width: 2.41 °C	-	RS NM	Rivers	4116 ha
Zhu et al., 2022	Summer	China	Hubei Province / Wuhan	C	day and night	cooling/ heating	Daytime cooling: 9:00: 0.7 °C 14:00: 1.8 °C Night-time heating: 21:00–22:00: 0.3 °C	-	NM	1 river 166 lakes	221,760 ha (total)
Žuvela-Aloise et al., 2016	Summer	Austria	Vienna	C	day and night	cooling/ heating	WT 18°C: 1.75 °C cooling WT 23°C: Night-time heating	-	NM	4 WB	25 ha (each)

Note: A = Tropical climate zone, B = Dry climate zone, C = Temperate climate zone, D = Continental / cold climate zone (Peel et al., 2007); WB= Waterbody; RS = Remote Sensing, FM = Field Measurements, NM= Numerical Modelling

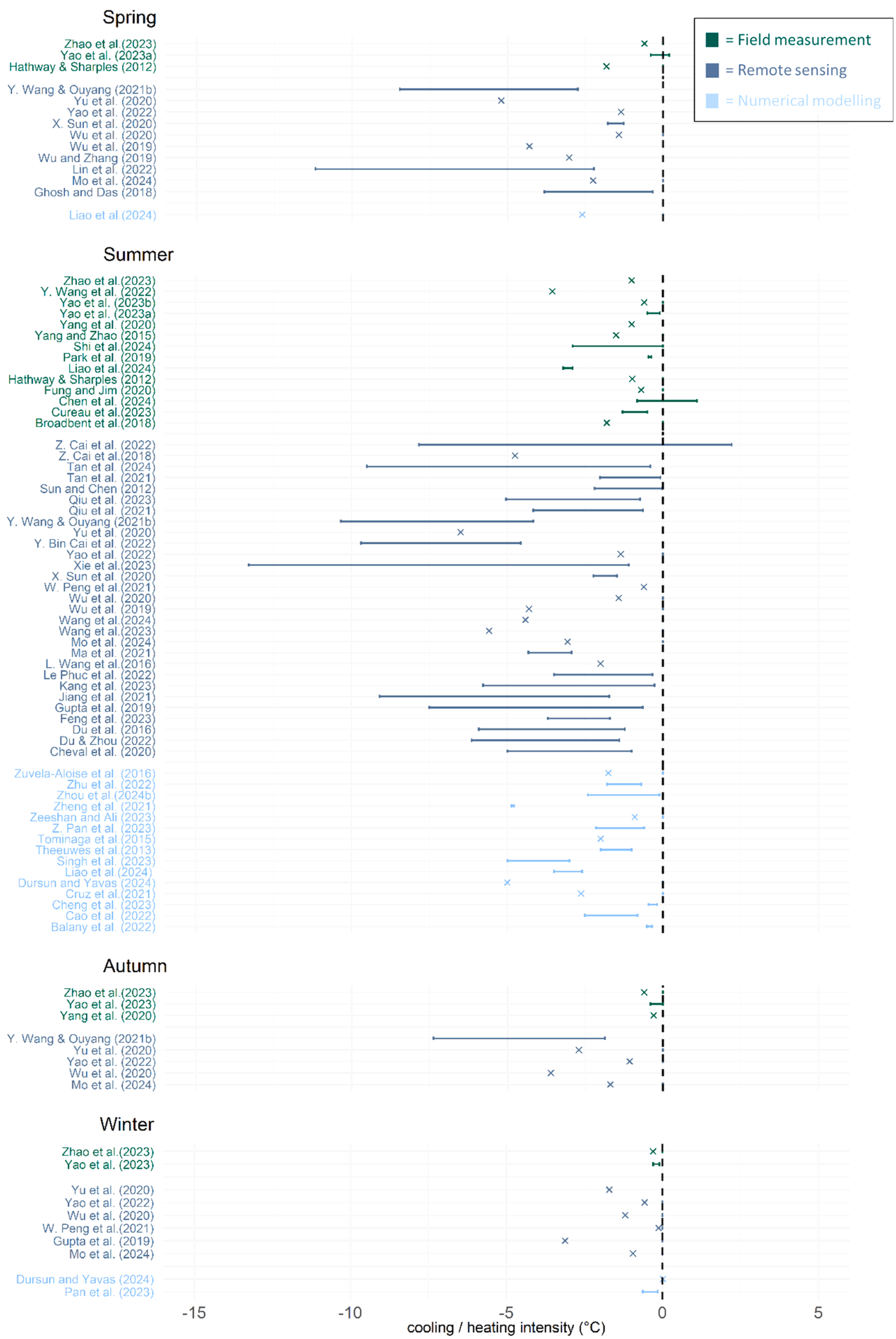

Fig. 5. Comparison of thermal impact of urban blue spaces for daytime. Note that studies are sorted by season and methodology (green= Field measurement, dark blue = Remote sensing, light blue = Numerical modelling). Bars represent a range, crosses single values.

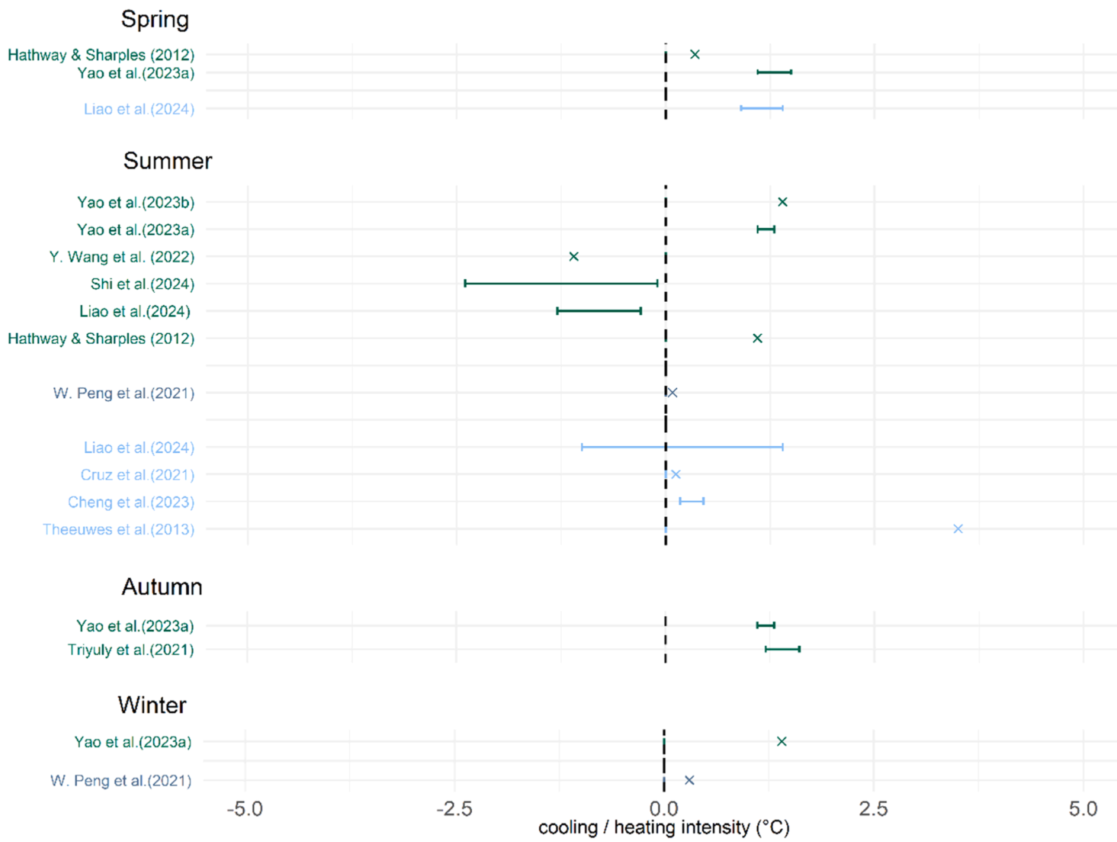

Fig. 6. Comparison of thermal impact of urban blue spaces for night-time. Sorted by season and methodology (green= Field measurement, dark blue = Remote sensing, light blue = Numerical modelling). Bars represent a range, crosses single values.

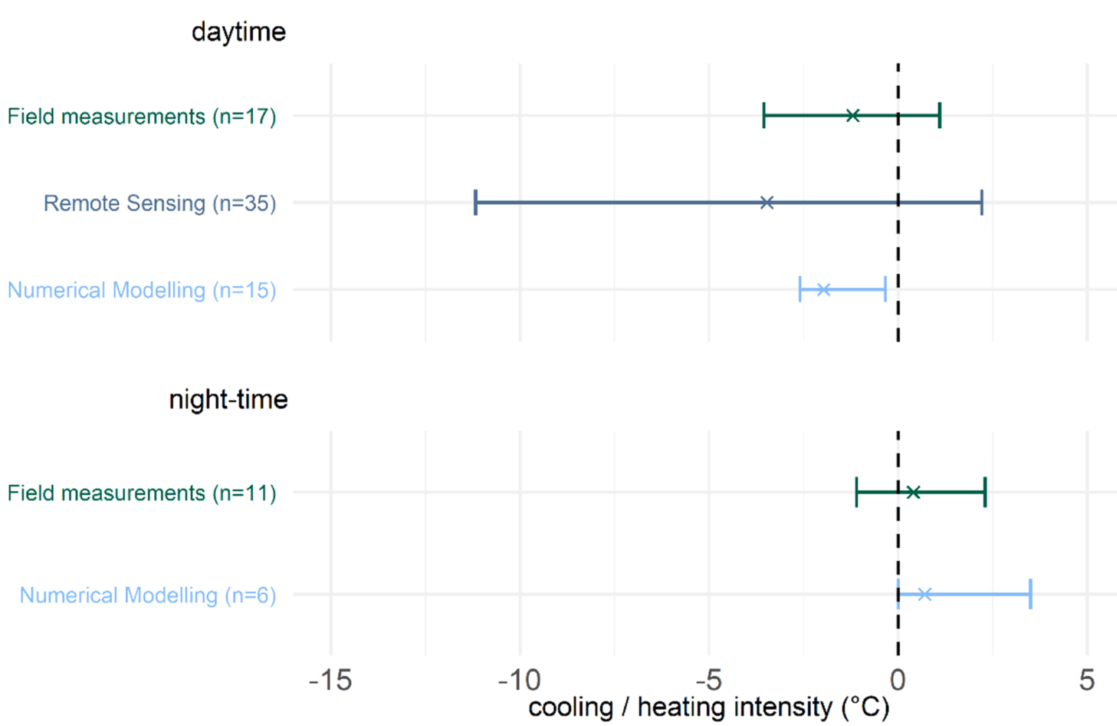

Fig. 7. Range and average value of the thermal effect of blue spaces during day and night-time sorted by methodological approach (green = Field measurement, dark blue = Remote sensing, light blue = Numerical modelling). Note that data for remote sensing at nigh-time is not shown due to low number of studies.

The thermal impact recorded across the 39 studies using remote sensing data during the daytime generally was stronger than field measurement studies, with an average cooling effect of 3.4 °C (Fig. 7). The highest cooling intensity recorded was more than 13 °C in Wuhan (Xie et al. 2023). One study, which considered the thermal impact of blue spaces across 34 cities, found one case of a heating effect during the summer (Cai et al., 2022). This case consisted of a small water body located in a highly dense, inner-city area with a large amount of sealed surfaces surrounding it (Cai et al., 2022). The only study which examined the impact at night-time observed a small heating effect of 0.08 °C in summer and 0.3 °C during the winter (Peng et al., 2021).

Numerical modelling was used in 15 studies, with a variety of different approaches implemented. Seven studies used the ENVI-met modelling approach (Bruse, 2004), five studies used a Weather Research and Forecasting Model (WRF) (NCAR, 2024), four studies computational fluid dynamics (CFD), and one study the urban climate model, MUKLIMO_3 (Sievers, 2016). The modelled scenarios were based on implementations of blue spaces, adjustments to the temperature of the water within the blue space or remodelling of actual conditions. During daytime, only cooling effects were reported, with an average of 1.7 °C (Fig. 7), and ranging from 0.1 °C in Nanjing, China (Zhou et al., 2024b), to 5 °C in Odisha, India (Singh et al., 2023). For night-time, only a heating thermal impact was reported in the models, at an average of 0.7 °C. Within the modelling approaches, some studies showed that cooler (Žuvela-Aloise et al., 2016) and deeper (Balany et al., 2022) water bodies had a higher cooling intensity during the day. Water bodies with a higher water temperature were shown to indicate a heating intensity during the night (Theeuwes et al., 2013, Zhu et al., 2022; Žuvela-Aloise et al., 2016).

3.4. Cooling intensity of blue spaces in different climate zones

Assessing the potential association between different climate zones and the cooling intensity of blue spaces is limited by a lack of studies conducted on continental, tropical and arid zones, particularly as the little research that does exist examining these zones applies different methodologies, thus rendering comparison difficult. Within temperate climate zones, where multiple studies across methods were conducted, the daytime thermal impact varied from 13.30 °C cooling in Wuhan, China (Xie et al. 2023), to 1.09 °C heating in Hong Kong at 10 am in the morning (Chen et al. 2024) (see Fig. 8). Remote sensing had the highest range, with 13.30 °C cooling to 0.12 °C heating, while numerical modelling (3.50 °C cooling to 0.10 °C heating) and field measurements (3.20 °C cooling to 1.09 °C heating) varied less. The only other climate zone where more than three studies were identified using the same methodological approach was the continental climate zone, with five remote sensing studies. Among these, the cooling intensity ranged from 6.5 °C to 1.7 °C, with an average cooling intensity of 3.5 °C. While not displayed in Fig. 8 due to a limited number of studies, the cooling intensity in the five studies of varying methodologies on tropical climate zones ranged from 5 °C in Odisha, India (Singh et al. 2023), to 0.33 °C in Tenh Noi, Vietnam (Le Phuc et al. 2022), and the sole study in an arid zone observed a daytime cooling of 0.9 °C in Karachi, Pakistan (Zeeshan and Ali, 2023).

3.5. Impact of water body type and size on the thermal impact of blue spaces

Broadly, studies tended to investigate either lakes, rivers or both. Studies that investigated the impact of lakes during the daytime (n = 46) found an average cooling intensity of 2.6 °C (Fig. 9), while for rivers (n = 12), the average cooling intensity was 3.2 °C during the day. The maximum cooling intensity for a river during this time was 9.5 °C recorded in Changsha (Tan et al. 2024) and the maximum observed for lakes was 13.3 °C in Wuhan (Xie et al. 2023). Studies examining the night-time thermal impacts of lakes (n = 7) found a maximum cooling intensity of 1.3 °C in Taichung City (Liao et al. 2024) and a maximum heating intensity of 3.5 °C in a modelled scenario (Theeuwes et al. 2013). Rivers at night (n = 4), comparatively, were found to have a maximum cooling of 2.4 °C in Shanghai (Shi et al.2024) and heating of 1.1 °C in Sheffield (Hathway and Sharples, 2012). Given only a small number of studies were conducted for rivers and lakes at night, no average values are reported or displayed in a figure here.

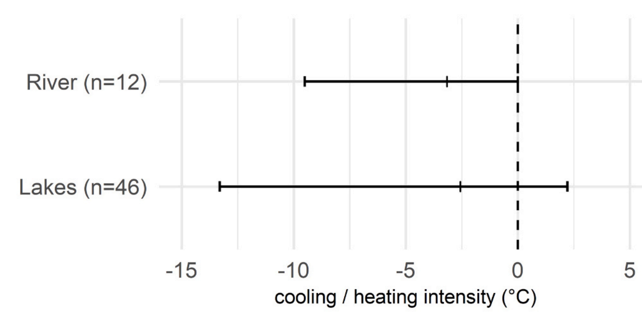

Fig. 9. Cooling and heating intensity of the rivers and lakes observed across included studies during the day.

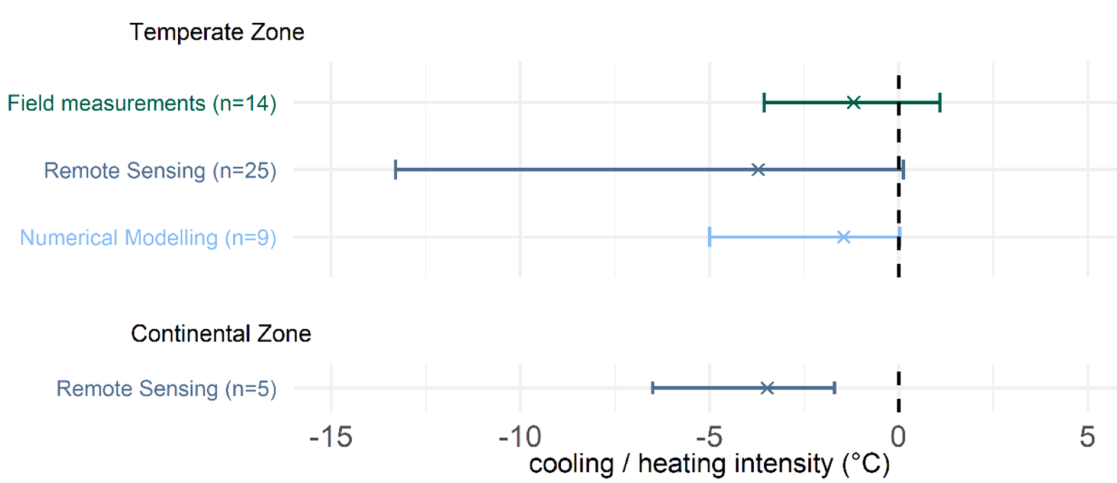

Fig. 8. Comparison of thermal impact of urban blue spaces in different climate zones during daytime. Sorted by methodology (green (left) = Field measurement, dark blue (middle) = Remote sensing, light blue (right) = Numerical modelling). Bars represent a range. Note that night situation and tropical and dry climate zone for day situation are not shown due to limited number of studies.

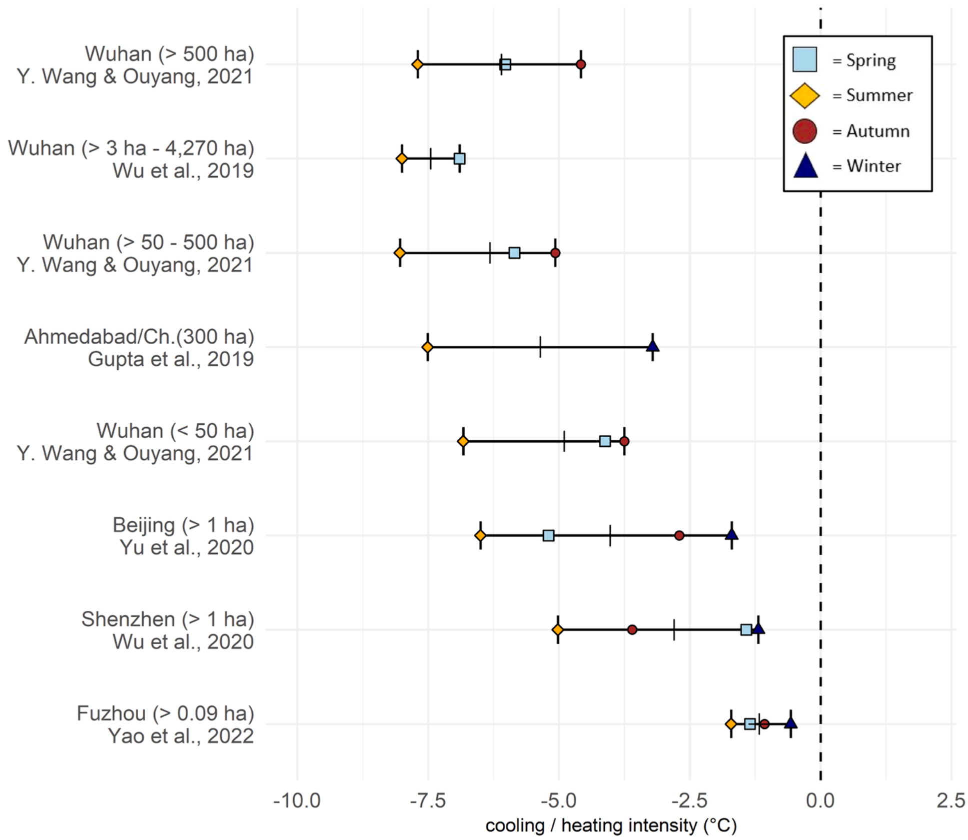

Fig. 10. Seasonal comparison of the cooling intensity of lakes considering water body size.

Six articles reported on the role of the size of individual water bodies, specifically lakes, in influencing the thermal impact of blue spaces (Fig. 10). One study reported differences in the thermal impact examining river width. Within this limited sample examining, those examining daytime conditions observed cooling intensities increased with growing water body size. For instance, in Fuzhou, China, where the water bodies considered were at a minimum 0.09 ha (Yao et al. 2022), mean cooling intensities for each season were significantly lower than the study sites at Shenzhen, China (Wu et al. 2020), or Beijing, China (Yu et al. 2020), where water bodies were at least 1 ha in size. In Wuhan, China, larger lakes (> 500 ha) had a higher cooling intensity (6.03 °C) only in spring when compared with medium (50 – 500 ha; 5.85 °C) and small lakes (< 50 ha; 4.12 °C). During summer and autumn, medium sized water bodies had higher cooling intensities of 0.72 °C and 0.49 °C, respectively. (Wang and Ouyang, 2021). The single study looking at rivers, observed that the cooling effect is positively correlated with river width (Zhou et al., 2024b). The lowest cooling intensity, 0.11 °C, was found for a river of 10 m width, while a river of 100 m width showed a cooling intensity of 0.75 °C, and a 1000 m river a cooling intensity of 2.41 °C.

4. Discussion

This systematic review adds to the growing body of evidence examining the thermal impact of urban blue spaces on the urban microclimate while considering variations by the time of the day, season, climate zone, size and type of waterbody, and methodological approach. Generally, we found that the majority of the studies included in the review reported a cooling effect of blue spaces on their surrounding urban microclimate. However, it is worth emphasising that these studies primarily investigate daytime conditions and that the few studies doing so for night tend to observe a heating effect. We also found that most research was conducted in Asia and that the number of studies has increased in the past few years, perhaps reflecting concern about increasing temperatures and more frequent heatwaves across the globe and the need to combat this heat in urban areas (Klingelhöfer et al., 2023).

In relation to the time of day, we found an average daytime cooling intensity of 2.6 °C across the studies reviewed, while at night, the thermal impact was reversed, with an average heating intensity of 0.6 °C. This confirms previous research on the thermal impacts of blue spaces across the day (Hathway and Sharples, 2012; Hu and Li, 2020; Yao et al. 2023b), but adds more depth by revealing the difference in magnitude between these effects. Particularly, while it is the case that heating does occur at night, we showed that it is of a smaller magnitude than the cooling which occurs during the day.

Across the seasons, the strongest cooling intensities occurred during spring and summer. Again, while previous research has found that the thermal impact does likely change across seasons, particularly warmer ones when more cooling is possible (Yu et al., 2020), our review emphasises how this difference actually manifests across seasons and the magnitude at which they differ, with larger daytime cooling effects in spring (2.75 °C) and summer (2.7 °C) compared to autumn (1.8 °C) and winter (0.8 °C). This difference across seasons may be derived from higher surface evaporation from water bodies in summer as a result of higher solar radiation, which in turn causes greater evaporative cooling in the local area (Yu et al., 2020). Too little research was conducted at night to draw definitive conclusions about how night-time heating may differ across the seasons. It was intriguing that the vast amount of research on blue spaces has been conducted in summer, so we suggest more attention in future research be placed on other seasons, particularly winter, in order to enable more accurate quantitative evaluations of these seasonal differences.

In relation to the climate zones, we observed considerable variance amongst studies examining blue spaces in temperate climate zones during the daytime, with results ranging from cooling intensities below

13 °C to heating intensities slightly above 1 °C. Temperate climate zones themselves generally exhibit moderate seasonal temperature variation, as they are distant from the equator but regulated by nearby large water bodies like seas or oceans. That is, they experience greater temperature differences between summer and winter than tropical or arid zones, but less than continental ones. When the difference between water temperature and air temperature above the surrounding land is greatest, there is greater potential for heat transfer to occur and thus a more intense cooling or heating effect (Gunawardena et al., 2017). So, we might expect that blue spaces in temperate climate zones exhibit some cooling intensity variation, as we observed here. These findings are novel, because little research has been conducted on the influence of blue spaces in different climate zones, although more research is required to draw firmer conclusions.

Beyond this, other climatic factors relating to climate zones should play a role in determining the cooling intensity of blue spaces but it is difficult to unravel here given the limited sample size. When the air temperature is higher as a result of stronger solar radiation, greater evaporation rates will contribute to evaporative cooling and thus a greater cooling impact on the surrounding environment (Katul et al. 2012). Conversely, when humidity is high, the possibility of further evaporation is constrained, limiting the evaporative cooling effect (Gunawardena et al., 2017). Thus, we would expect cooling intensities to be strongest in arid climate zones, with high temperatures and low humidity, but then to vary considerably in the other zones dependent on temperature and humidity. However, we are unable to confirm this as too few studies were conducted on arid or tropical climate zones. Further research is needed to confirm these theorisations.

Amongst studies considering water body size, we observed that the cooling intensities were greater with larger water body sizes and most pronounced during summer and spring. These findings align with broader research, which has found that blue space size is one of the predominant factors predicting cooling intensity and distance (Boehrer et al. 2000; Qiu et al., 2021). During the day, the absorption of short-wave solar radiation induces thermal currents within the water body, leading to thermal mixing. Due to their larger volume, larger water bodies have an increased thermal mass, which enables them to maintain more stable surface temperatures compared to smaller water bodies (Gunawardena et al., 2017). Accordingly, the water surface temperature of smaller lakes tends to heat up faster, leading to higher temperatures during hot periods compared to bigger water bodies (Boehrer et al. 2000).

Water body type (river or lake) was also found to affect cooling intensity, with studies that compared the types finding that lakes often exhibited higher cooling or heating intensities than rivers (Du et al., 2016; Gupta et al., 2019). The thermal impact of blue spaces, it has been theorised, is affected by the extent to which layers of different water temperatures form in the water body, also known as thermal stratification (Boehrer and Schultze, 2008). For deeper or more still water bodies, during the summer when solar radiation is high, the upper layer of the water body (the epilimnion) can become warmer than lower layers when circulation is low (Boehrer and Schultze, 2008). As a consequence, the heated upper layer of the water body, as that having the predominant influence on the surrounding urban microclimate, may limit the cooling potential of these water bodies and even cause stronger heating intensities during the night. This thermal stratification of deeper and more still lakes, then, may in fact limit their cooling intensity, which is supported by broader research finding that a collection of small lakes near one another have a greater cooling intensity collectively than one large lake of equal size (Gunawardena et al., 2017). In contrast, water temperatures in rivers are more uniform with depth and there is greater thermal mixing (Caissie, 2006), which may lead to a more stable temperature across the water body and thus a more regulated impact on the surrounding microclimate. Aligning with this, our results indicated that rivers exhibited a smaller range of cooling intensities and were less likely to heat the surrounding area. Thus, the type and depth of the water body is likely critical for determining its thermal impact.

The majority of studies included in this review used remote sensing data to analyse the thermal effect of urban blue spaces during the daytime by deriving Land Surface Temperature (LST). However, as remote sensing measures surface temperature and not air temperature, it is less suitable to describe thermal comfort or influence on the human body when compared to other methods which do measure air temperature (Cristóbal et al., 2008). Given the land surface has low thermal inertia, it cools and heats more quickly than the air and can thus produce greater cooling intensity values (Ampatzidis and Kershaw, 2020; Mohan et al., 2013). Our findings seem to confirm this association, with the remote sensing studies reporting higher values for both cooling and heating intensities. Due to differences in solar radiation between day and night, remote sensing could report surface temperatures that are higher or lower than air temperatures (Logan et al., 2020), altering the calculated cooling or heating intensity of water bodies at these different times of day. The urban heat island phenomenon has a high temporal variability, rendering remote sensing-based analyses unable to provide a complete understanding of the entire day and night-time thermal impact of blue spaces (Weng and Fu, 2014). The spatial resolution of the remote sensing data is, however, useful for first impressions of the spatial variability of the LST in urban areas and can cover a larger spatial extent (Sun and Chen, 2012; Wang et al., 2022).

Compared to remote sensing, studies using field measurement generated data have the advantage of being able to more accurately choose the time of the investigation or the investigation period as per the research objective (Chen et al., 2019; Yang et al., 2020). Air temperature can be measured throughout the day, enabling better investigation of night-time conditions. Field measurement studies are, however, limited in their spatial range, given that it is much more intensive to gather data (Chen et al., 2019; Park et al., 2019). As a consequence, standardised measurements with regard to the site and the setup of the measurement station are essential to receive comparable data of these parameters (Oke, 2006, Kraemer et al., 2022), and our results demonstrate that field measurements provided consistent and stable measurements of cooling intensity.

Numerical modelling approaches, finally, offer advantages when investigating the thermal effects of blue spaces on the urban climate. On the one hand, the meteorological framework conditions can be specified for the period under investigation. On the other hand, it is possible to adapt an existing situation as required and thus compare various scenarios with each other (Balany et al., 2022) providing results tailored to a certain research question and to certain scenario requirements. Nevertheless, modelling does not show real conditions, but is based on idealised or simplified simulations (Žuvela-Aloise et al., 2016). Given numerical modelling results aligned quite closely with those from field measurement studies, it can also be assumed that they provide valid and valuable results, especially given their practicality in modelling situations that are different to measure in the real world.

4.1. Limitations and prospects for future research

This review had some limitations. First, as only a sole database was used to conduct the search and only articles published in English were included, it is possible that some relevant studies were missed. Second, the limited variety across the included studies, particularly in relation to the number of studies conducted across different climate zones, during winter and autumn, and at night, renders it difficult to completely and accurately estimate the thermal impact of urban blue spaces in these conditions. Finally, the wide variety of blue space types investigated and methodologies used across the different studies can make comparison difficult or even inaccurate.

We found that, as the research currently stands, it is difficult to draw definitive conclusions about how water body type, size, location, etc., influence the thermal impact, given the lack of studies investigating each factor. Future research should concentrate on collecting long-term field measurement data across a variety of different contexts and times in order to more accurately inform understandings of diurnal and seasonal cooling effects, as well as the role of location, size, etc. Given the likely importance of these factors in determining the cooling impact of urban blue spaces, it was surprising that still a relatively few number of studies actually concentrated on non-daytime and non-summer conditions. Not only will conducting such research improve knowledge relating to the thermal impact of blue spaces, but they will also enable more accurate modelling approaches.

5. Conclusions

The rise in temperatures in many urban areas around the world as a result of climate change and urbanisation is rendering nature-based solutions that moderate local temperatures, such as blue spaces, particularly important. Improving understandings of the complex relationship between water, land and air in determining local temperatures, as we have done here, better informs the formation and design of urban spaces that mitigate the urban heat island effect. For instance, in finding that urban blue spaces tend to cool the surrounding area during the day and heat it at night, we demonstrate that urban blue spaces have unique characteristics that should be considered by urban planning. Further, in combination with green spaces, the daytime cooling effect from blue spaces might create an even greater cooling effect, in what is known as a synergistic cooling effect of green-blue space (Cheung and Jim, 2019; Pang et al., 2022; Shi et al., 2020). At night-time, the heating provided by blue spaces could be considered in urban planning strategies for climate adaptation that aim at a cooler local environment during the day, but should ensure that temperature is regulated during the night. The size of these heating and cooling effects depends on the type, location and size of the blue space, as exemplified by the case where several smaller lakes collectively had a stronger cooling intensity than a large lake of similar size (Gunawardena et al., 2017). However, to completely inform urban planning, more in-depth research is needed to unravel the exact contributing of these factors in more detail, as well as other factors like shape, LSI, water temperature and water body depth.

CRediT authorship contribution statement

Lukas Fricke: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nadja Kabisch:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Rupert Legg:** Writing – review & editing, Supervision.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128528.

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