Sprawl or compactness? How urban form influences urban surface temperatures in Europe

City and Environment Interactions 16 (2022) 100091

Contents lists available at ScienceDirect

City and Environment Interactions

journal homepage: www.sciencedirect.com/journal/city-and-environment-interactions

Sprawl or compactness? How urban form influences urban surface temperatures in Europe

Jonas Schwaab

ETH Zurich, Institute for Atmospheric and Climate Science, Switzerland

A B S T R A C T

The surface of cities is often warmer than the surface of their surroundings. This phenomenon is known as the surface urban heat island (SUHI) effect and has several adverse implications. Studies have shown that the SUHI effect tends to be weaker if urban form is characterized by sprawl or polycentrism. These findings suggest that urban heat could be mitigated if a city is less compact. By analyzing high-resolution remote-sensing land surface temperature (LST) and land-cover data for 293 European cities, this study shows that — contrary to many previous findings — sprawling or polycentric urban forms do not necessarily lead to a decrease of LSTs over urban areas. In southern European cities, sprawl could even lead to the warming of urban areas during specific daytimes, highlighting the importance of considering environmental and regional contexts when determining the role of urban form in heat mitigation. It is also crucial to consider the predominant type of land cover surrounding a city since sprawl into forested areas could have a very different effect than sprawl into agricultural areas. These results illustrate the complexity of urban form related heat mitigation and that policy- and decision-makers have to consider local and regional contexts when steering urban form.

Introduction

Heat in urban areas leads to increased energy consumption [54], human health problems including increased mortality [45,40], and further adverse impacts [30,70]. Urban growth as well as climate change exacerbate heat in cities and expose an ever increasing fraction of the global population to heat [38,26]. Heat in cities is controlled by a variety of factors including among others albedo, vegetation, water and urban form (e.g. [20]). To understand the influence of these factors and designing adequate heat mitigation strategies is challenging because their effect can strongly vary over time and space. For example, it has been shown that vegetation in European cities can have a higher or lower effect on temperatures depending on regional environmental conditions [41,36]. While urban heat mitigation measures are implemented locally, it is important to understand their effectiveness in different regional contexts and which factors should be taken into account when transferring knowledge based on local case studies.

The management of urban development and urban form is important in mitigating urban heat and its adverse impacts [63,32,33]. Small, disperse, stretched, polycentric or discontiguous cities (henceforth summarized in a simplified way as “sprawling urban areas”) have been shown to be preferable for reducing urban heat over compact cities in Europe, the USA and China [58,12,69,32,34]. One reason why sprawling urban areas can be beneficial are that they are intermingled with vegetated areas that can exert cooling on neighboring urban areas [21,61,68]. However, the cooling of vegetated areas through transpiration may not always be equally high and may decline towards dry regions and periods [3,57,36,28], particularly if vegetated areas are or cannot be properly irrigated [49]. Less temperature reduction by vegetated areas is one reason why urban cool islands (UCIs - denoting that urban areas are cooler than their surroundings), have been observed in arid regions [10,29,64,16,18]. In addition, it has been shown that increased building heights and densities in dry regions can reduce daytime temperatures, particularly through shading [13,4,42]. The latter finding and a potentially reduced cooling provided by vegetation in certain regions raise the question of whether and where sprawl would indeed lead to reduced urban heat.

To better understand the impact of different urban forms on urban temperatures across different climates, high-spatial-resolution LST and LULC data was used for 293 European cities and their surroundings. For each city, all urban patches, were separated and the size (i.e., area) of these patches was calculated. After that the difference in spatial mean temperature was calculated between large contiguous urban patches (indicating compactness and contiguity) and small disperse urban patches (indicating sprawl and discontiguity) that are either surrounded primarily by forest or agriculture.

Methods

Temperatures of small and large urban patches and the temperatures of urban patches that are either mainly surrounded by forested or agricultural land were compared. All analysis were performed using R

E-mail address: jonasschwaab@ethz.ch.

https://doi.org/10.1016/j.cacint.2022.100091
Received 11 July 2022; Received in revised form 7 November 2022; Accepted 9 November 2022
Available online 9 November 2022

Statistical Software (v4.1.2, [50]). To calculate the size of urban patches and the fraction of forest or agriculture in their surroundings, a land-use/land-cover dataset was used, which is denoted as the "Urban Atlas (UA, https://land.copernicus.eu/local/urban-atlas, European Commission [14]) The UA is available for large European cities and their surroundings. The UA data, which are in their original form provided as spatial polygons, was rasterized to a spatial resolution of 250 m via the rasterize R package [23] and afterward, only areas that are categorized as urban fabric or as industrial/commercial (henceforth referred to as urban areas) were selected (more details in Table S 1 and Figure S 1). The urban fabric category includes all built-up areas and their associated land including, e.g., infrastructure and urban gardens. All urban areas were split into separate patches based on the connectedness within a neighborhood space defined by 8 surrounding cells (function clump, raster package, [23]). For each urban patch, its size, its mean elevation, the fraction of forested and agricultural land in the surroundings of each patch, and the LST of each patch was calculated (Figure S 2). The LSTs were calculated as spatial mean temperatures for each patch based on Landsat data. Landsat LST data were extracted for each selected European city between 2006 and 2018 for every month available (https://rslab.gr/downloads_LandsatLST.html, Parastatidis et al. [44]. On average, 408 Landsat scenes were available per city.

For each city, temperature differences between large and small patches were calculated for high background temperatures. Scenes with high background temperatures were determined by calculating the spatially averaged LST of each Landsat scene and selecting those Landsat scenes for which temperatures were ranking among the highest 5 %. Large patches were defined as the 50 % of patches that are larger than the median patch size and small patches are the 50 % of patches that are smaller than the median patch size. In addition, the smallest 50 % of patches were either defined as mainly surrounded by agricultural land (more than 50 % of the surroundings) or as patches that were mainly surrounded by forest (more than 50 %). Cities for which there were no urban patches surrounded by more than 50 % forested areas or agricultural areas were excluded, since differences in temperatures due to different LULC surroundings of urban patches cannot be estimated in a robust way in these cities. To reduce the effect of elevation on temperatures, patches were only selected if they were less than 200 m in altitude from the average elevation of all patches. In summary, for each city, the following was calculated (1) a temperature difference between large urban patches minus small urban patches mainly surrounded by agriculture and (2) a difference between large urban patches minus small urban patches mainly surrounded by forest. The temperature differences calculated for each city were compared for three regions (Fig. 1), including North Europe (NEU), Central Europe (CEU) and the Mediterranean (MED). Even though these three regions are quite large and diverse, they allow for a broad distinction between climates [46,56,6]: The region NEU can be characterized as a mainly boreal region with cold winters and short summers. The region CEU can be characterized as a temperate region which includes oceanic and continental climates. The continental climate (towards eastern Europe) is characterized by hot and dry summers and cold winters. The oceanic climate (towards western Europe) is characterized by warm summers and mild winters and high precipitation throughout the year. The region MED includes temperate climates, but can be mainly characterized as arid. Summers in the Mediterranean are hot and dry, winters are mild and most annual rain is received during winter.

Results and discussion

This study found that small urban patches can be warmer than large urban patches at Landsat observation time (approx. 10:15 a.m.) in parts of the Mediterranean (Fig. 1 and Fig. 2). This indicates - in contrast to many previous findings - that sprawl may not always lead to reduced temperatures over urban areas in these regions and during that time. In particular, small urban patches were often warmer than large urban patches, if the small patches were surrounded by agricultural land. However, there was a substantial spread in the temperature difference of −5 °C to 7.5 °C between small agriculturally surrounded and large patches in the Mediterranean (Fig. 1 b, Fig. 2 b), indicating that the Mediterranean region (as defined in this study) is a broad category and does not allow to single out cities where temperature differences between patches are clearly positive. If surrounded by forest, a sprawling pattern could be beneficial during specific times of the day even if a city is located in the Mediterranean, since small forest surrounded patches can be cooler than large urban patches (Fig. 1 a Fig. 2 a). In central and northern Europe, smaller urban patches are cooler than larger urban patches in almost all cities no matter whether the small urban patches are surrounded by agriculture or forest (Fig. 1, Fig. 2), which could indicate that sprawl is mostly reducing heat in urban areas in these regions and during Landsat observation time. In summary, these results show that the temperature differences between small and large urban patches vary substantially between regions and according to the dominant LULC type (i.e. forest vs agriculture) in the surrounding of urban

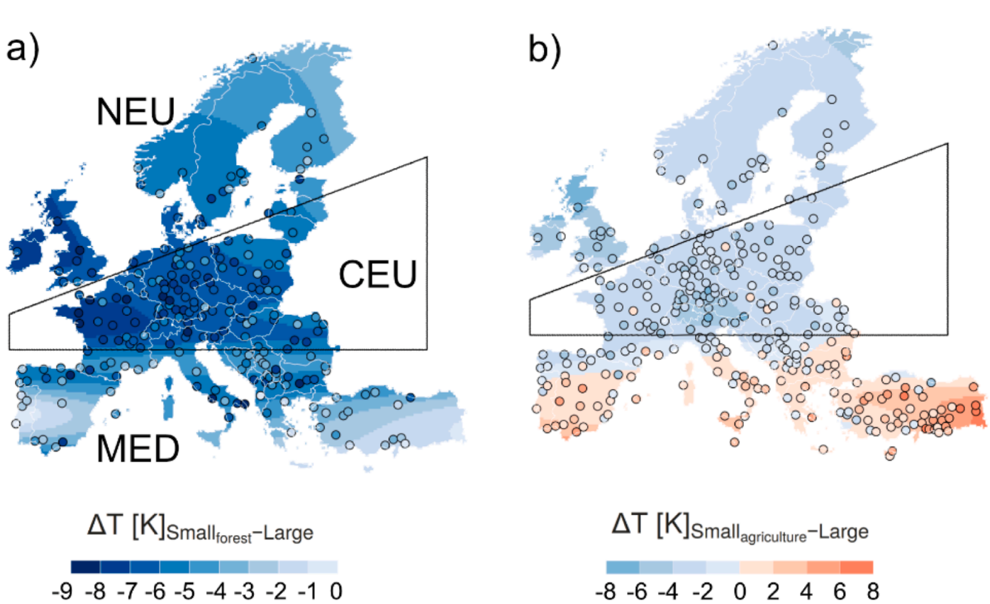

Fig. 1. The maps show smoothed spatial trends of temperature differences between small and large urban patches, and each dot represents the temperature difference in a specific city. Negative temperature differences indicate that the temperature of small urban patches is lower than that of large urban patches. a) Temperature differences between the smallest 50% of urban patches surrounded by forest and the largest 50% of urban patches. b) Temperature differences between the smallest 50% of urban patches surrounded by agricultural land and the largest 50% of urban patches.

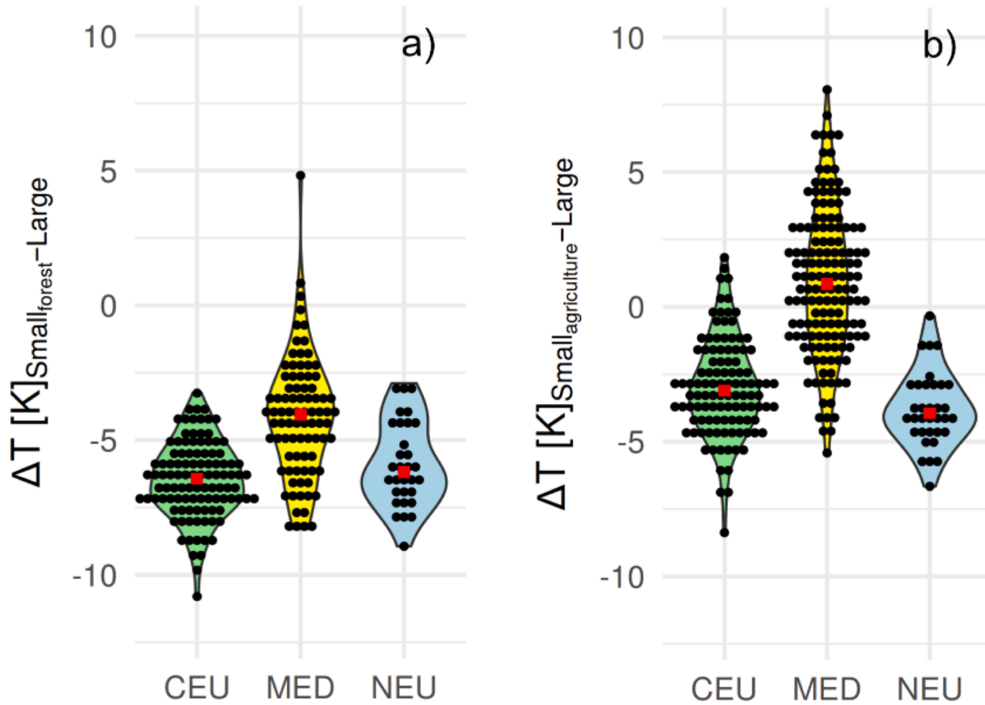

Fig. 2. A) violin plots indicating the temperature differences between the smallest 50% of urban patches surrounded by forest and the largest 50% of urban patches in the three different regions neu – north europe, ceu – central europe, and med - mediterranean. b) violin plots indicating the temperature differences between the smallest 50% of urban patches surrounded by agricultural land and the largest 50% of urban patches in regions neu, ceu, and med.

areas.

The obtained results can be partly explained with the help of existing literature, by considering geographically varying climatic and environmental conditions and by looking at the different ways of how trees and agricultural areas affect the climate. Analysis of SUHIs in arid regions - such as parts of the Mediterranean - show that temperatures of urban areas are often not much higher or even lower (forming UCIs) than temperatures in their surroundings [10,22,29,9,1]. A main reason for this is that the levels of evapotranspiration in the surrounding of cities in dry regions are low (if not irrigated), due to low soil moisture and reduced fraction of vegetation [29,31]. In Europe, additional effects leading to UCIs could be that the albedos of urban areas in Mediterranean regions tend to be higher than in other European regions [57] and that irrigation of vegetation inside cities may be high in comparison to outside of cities [51]. In addition, higher surface roughness and, accordingly, lower aerodynamic resistance of built-up areas in relation to flat surfaces could reduce temperatures in Mediterranean cities compared to their surroundings [66,17].

While the SUHI may explain why sprawl leads to reduced urban heat in some regions, the results of this study also show that the land cover which surrounds a city must be considered to understand the potential climatic benefits of sprawl. Summarizing the results of Schwaab et al. [57] it can be shown that LSTs of forests are generally lower than of urban areas across Europe, but agricultural areas in the Mediterranean are often warmer than urban areas (Figure S 3). Forests during the day are cooler than agricultural areas in southern Europe because they seem to be able to maintain higher evapotranspiration levels and have a higher surface roughness than agricultural land [65]. Higher evapotranspiration levels may be explained by the larger root depth of trees, allowing them to maintain a higher ET even during hot extremes [8,55]. A higher surface roughness leads to more efficient heat convection and, hence, lower temperatures [52]. The are probably two main ways in which the different LULC and vegetation types influence temperatures: On the one hand, it is likely that advection effects are relevant. This means that the land surface temperatures of the urban patches are influenced by air temperature changes caused by the vegetated surrounding of the urban patches. These effects have been recognized and shown to be relevant in many different settings [27,71,11,2,7]. On the other hand, it is not possible to perfectly isolate urban patches that are of the same urban fabric and do not include vegetated areas. For example, a substantial part of urban patches will not only be comprised of, e.g. same height buildings and equal road surfaces, but also of forest and agricultural areas or even other LULC types. Thus, the observed temperature differences will often not just be the temperature difference between the same urban fabric and LULC type (influenced only by their surroundings), but include the temperature difference between different urban fabric and LULC types.

The use of Landsat data allows for a comparison of LSTs of urban patches in different geographic regions, but has several major limitations. Most importantly these are that the data cannot resolve the diurnal cycle of temperatures and that LST and the surface urban heat island are often related in complex and counter-intuitive ways to near-surface air temperatures and the canopy level urban heat island [53,60]. For example, the daytime canopy urban heat island is usually very small in comparison to the surface urban heat island and the canopy urban heat island can even switch signs during morning hours [38]. The existing relationship between surface temperatures and canopy level temperatures [37,19,47], would need to be further explored including in-situ observations and modelling experiments to better understand the effect of sprawl in different climates, with relation to varying vegetation and during different times of the day. For example, while the analysis of LST data indicates a surface urban cool island during the day in dry regions, there can still be a nighttime surface urban heat island [10,1], which could mean that sprawl could lower nighttime temperatures in urban areas in dry regions.

In this study, a simple indicator of urban sprawl (i.e., small disperse urban patches) and compactness (i.e., larger contiguous urban patches) was used when identifying temperature patterns. The separation into small and large patches leads to different patch sizes in each city and can be carried out in various ways (Figure S 5). However, different ways of separating small from large patch sizes do not have substantial effect on the main results (Figure S 4). Analyzing additional measures of urban form, having an improved understanding of the climatic impacts of dense and high-rise urban areas (i.e., three-dimensional considerations, Li et al. [32] and isolating the effects of urban form and fabric from geography [43] have been shown to be crucial. Last but not least, it is important to note that the complex 3d structure of cities lead to anisotropy effects (i.e. directional variation in upwelling thermal radiation) and that these effects may vary between smaller and larger urban patches [62,24] and hence influence the observed LST differences.

Urban expansion is a dominant process of present and future land changes [59,35] causing intensification of urban heat islands [25,38]. Identifying suitable urban forms and supporting policymakers in their efforts to establish sustainable urban growth trajectories is a major challenge [5]. Since heatwave events are expected to increase in both intensity and frequency in the future [48,39], there is a pressing need for more evidence on how urban form can help to mitigate heat in urban areas. In this study, it is shown that the effect of urban form on land surface temperatures depends on regional and local factors. Two important factors are background climate and the predominant land-cover in the surrounding of urban areas. Accounting for these two factors complements previous findings showing that sprawl may be helpful in reducing land surface temperatures in European cities [58,67,33] by showing that the relationship between sprawl and urban temperatures is complex and particularly needs further investigation in dry regions. While exploring the relationship between urban form and urban heat mitigation is essential, of course many other objectives and potential trade-offs need to be considered when striving for sustainable urban forms (e.g. [15,5].

Author statement

There is only one author of this study (Jonas Schwaab).

Declaration of Competing Interest

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

Acknowledgements

Funding is acknowledged from the Swiss National Science Foundation (SNSF) and the Swiss Federal Office for the Environment (FOEN) through the CLIMPULSE project (http://p3.snf.ch/Project-172715; grant no. 200021_172715). The funding sources did not participate in the study design, data analysis and result interpretation.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2022.100091.

References

[1] Alahmad B, Tomasso LP, Al-Hemoud A, James P, Koutrakis P. Spatial distribution of land surface temperatures in Kuwait: Urban heat and cool islands. Int J Environ Res Public Health 2020;17:12.
[2] Algretawee H, Rayburg S, Neave M. Estimating the effect of park proximity to the central of Melbourne city on Urban Heat Island (UHI) relative to Land Surface Temperature (LST). Ecol Eng 2019;138:374–90.
[3] Allen MA, Roberts DA, McFadden JP. Reduced urban green cover and daytime cooling capacity during the 2012–2016 California drought. Urban Clim 2021;36: 100768.
[4] Alobaydi D, Bakarman MA, Obeidat B. The impact of urban form configuration on the urban Heat Island: the case Study of Baghdad, Iraq. Procedia Eng 2016;145: 820–7.
[5] Artmann M, Inostroza L, Fan P. Urban sprawl, compact urban development and green cities. How much do we know, how much do we agree? Ecol Ind 2019;96: 3–9.
[6] Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 2018;5:180214.
[7] Blachowski J, Hajnrych M. Assessing the cooling effect of four urban parks of different sizes in a temperate continental climate zone: Wroclaw (Poland). Forests 2021;12:1136.
[8] Canadell J, Jackson RB, Ehleringer JB, Mooney HA, Sala OE, Schulze ED. Maximum rooting depth of vegetation types at the global scale. Oecologia 1996; 108:583–95.
[9] Chakraborty T, Lee X. A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability. Int J Appl Earth Observ Geoinformation 2019;74: 269–80.
[10] Clinton N, Gong P. MODIS detected surface urban heat islands and sinks: Global locations and controls. Remote Sens Environ 2013;134:294–304.
[11] Cohn AS, Bhattarai N, Campolo J, Crompton O, Dralle D, Duncan J, et al. Forest loss in Brazil increases maximum temperatures within 50 km. Environ Res Lett 2019;14:084047.
[12] Debbage N, Shepherd JM. The urban heat island effect and city contiguity. Comput Environ Urban Syst 2015;54:181–94.
[13] Emmanuel R, Fernando HJS. Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. Clim Res 2007;34:241–51.
[14] EUROPEAN COMMISSION 2012. Mapping Guide v4.7 for a European Urban Atlas (https://land.copernicus.eu/user-corner/technical-library/urban-atlas-2012-mapping-guide-new/).
[15] Ewing R, Hamidi S. Compactness versus Sprawl: a review of recent evidence from the United States. J Plan Literature 2015;30:413–32.
[16] Fan C, Myint SW, Kaplan S, Middel A, Zheng B, Rahman A, et al. Understanding the impact of urbanization on surface urban heat islands—a longitudinal analysis of the oasis effect in subtropical desert cities. Remote Sens 2017;9:672.
[17] Fitria R, Kim D, Baik J, Choi M. Impact of biophysical mechanisms on urban heat island associated with climate variation and urban morphology. Sci Rep 2019;9: 19503.
[18] Goncalves A, Ornellas G, Ribeiro AC, Maia F, Rocha A, Feliciano M. Urban Cold and Heat Island in the City of Braganca (Portugal). Climate 2018;6:14.
[19] Good EJ, Ghent DJ, Bulgin CE, Remedios JJ. A spatiotemporal analysis of the relationship between near-surface air temperature and satellite land surface temperatures using 17 years of data from the ATSR series. J Geophys Res: Atmosp 2017;122:9185–210.
[20] Guerri G, Crisci A, Messeri A, Congedo L, Munafò M, Morabito M. Thermal summer diurnal hot-spot analysis: the role of local urban features layers. Remote Sens 2021; 13:538.
[21] Gunawardena KR, Wells MJ, Kershaw T. Utilising green and bluespace to mitigate urban heat island intensity. Sci Total Environ 2017;584–585:1040–55.
[22] Haashemi S, Weng QH, Darvishi A, Alavipanah SK. Seasonal Variations of the Surface Urban Heat Island in a Semi-Arid City. Remote Sens 2016;8:17.
[23] HIJMANS RJ. Raster: Geographic Data Analysis and Modeling; 2020. R package version 3.1-5. https://CRAN.R-project.org/package=raster.
[24] Hu L, Monaghan A, Voogt JA, Barlage M. A first satellite-based observational assessment of urban thermal anisotropy. Remote Sens Environ 2016;181:111–21.
[25] Huang K, Li X, Liu X, Seto KC. Projecting global urban land expansion and heat island intensification through 2050. Environ Res Lett 2019;14:114037.
[26] IPCC 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Masson-Delmotte V, P. Zhai, A. Pirani SL, Connors CP, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. & Matthews, T. K. M., T. Waterfield, O. Yelekçi, R. Yu, B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press.
[27] Jaganmohan M, Knapp S, Buchmann CM, Schwarz N. The bigger, the better? the influence of urban green space design on cooling effects for residential areas. J Environ Qual 2016;45:134–45.
[28] Kraemer R, Kabisch N. Parks under stress: Air temperature regulation of urban green spaces under conditions of drought and summer heat. Front Environ Sci 2022;10.
[29] Kumar R, Mishra V, Buzan J, Kumar R, Shindell D, Huber M. Dominant control of agriculture and irrigation on urban heat island in India. Sci Rep 2017.
[30] Lai L-W, Cheng W-L. Air quality influenced by urban heat island coupled with synoptic weather patterns. Sci Total Environ 2009;407:2724–33.
[31] Li D, Liao W, Rigden AJ, Liu X, Wang D, Malyshev S, et al. Urban heat island: Aerodynamics or imperviousness? Sci Adv 2019;5:eaau4299.
[32] Li Y, Schubert S, Kropp JP, Rybski D. On the influence of density and morphology on the Urban Heat Island intensity. Nat Commun 2020;11:2647.
[33] Li Y, Zhou B, Glockmann M, Kropp JP, Rybski D. Context sensitivity of surface urban heat island at the local and regional scales. Sustain Cities Soc 2021;74: 103146.
[34] Liu H, Huang B, Zhan Q, Gao S, Li R, Fan Z. The influence of urban form on surface urban heat island and its planning implications: Evidence from 1288 urban clusters in China. Sustain Cities Soc 2021;71:102987.
[35] Mahtta R, Mahendra A, Seto KC. Building up or spreading out? Typologies of urban growth across 478 cities of 1 million+. Environ Res Lett 2019;14:124077.
[36] Marando F, Heris MP, Zulian G, Udías A, Mentaschi L, Chrysoulakis N, et al. Urban heat island mitigation by green infrastructure in European Functional Urban Areas. Sustain Cities Soc 2022;77:103564.
[37] Mohan M, Kikegawa Y, Gurjar BR, Bhati S, Kolli NR. Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. Theor Appl Climatol 2013;112:647–58.

[38] Mohan M, Sati AP, Bhati S. Urban sprawl during five decadal period over National Capital Region of India: impact on urban heat island and thermal comfort. Urban Clim 2020;33:100647.
[39] Molina MO, Sánchez E, Gutiérrez C. Future heat waves over the Mediterranean from an Euro-CORDEX regional climate model ensemble. Sci Rep 2020;10:8801.
[40] Mora C, Dousset B, Caldwell IR, Powell FE, Geronimo RC, Bielecki Coral R et al. 2017. Global risk of deadly heat. Nat Clim Change 7, 501–506.
[41] Morabito M, Crisci A, Guerri G, Messeri A, Congedo L, Munafò M. Surface urban heat islands in Italian metropolitan cities: Tree cover and impervious surface influences. Sci Total Environ 2021;751:142334.
[42] Nassar AK, Blackburn GA, Whyatt JD. What controls the magnitude of the daytime heat sink in a desert city? Appl Geogr 2017;80:1–14.
[43] Nice K, Nazarian N, Lipson M, Hart M, Seneviratne S, Thompson J, et al. Isolating the impacts of urban form and fabric from geography in assessing heat mitigation strategies. Earth Space Sci Open Arch 2022;23.
[44] Parastatidis D, Mitraka Z, Chrysoulakis N, Abrams M. Online global land surface temperature estimation from landsat. Remote Sensing 2017;9:16.
[45] Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. Nature 2005;438:310–7.
[46] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 2007;11:1633–44.
[47] Peng W, Wang R, Duan J, Gao W, Fan Z. Surface and canopy urban heat islands: does urban morphology result in the spatiotemporal differences? Urban Clim 2022;42:101136.
[48] Perkins-Kirkpatrick SE, Lewis SC. Increasing trends in regional heatwaves. Nat Commun 2020;11:3357.
[49] Potchter O, Cohen P, Bitan A. Climatic behavior of various urban parks during hot and humid summer in the mediterranean city of Tel Aviv, Israel. Int J Climatol 2006;26:1695–711.
[50] R CORE TEAM 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria (http://www.R-project.org/).
[51] Reyes-Paecke S, Gironas J, Melo O, Vicuna S, Herrera J. Irrigation of green spaces and residential gardens in a Mediterranean metropolis: Gaps and opportunities for climate change adaptation. Landscape Urban Plann 2019;182:34–43.
[52] Rotenberg E, Yakir D. Contribution of semi-arid forests to the climate system. Science 2010;327:451–4.
[53] Roth M, Oke TR, Emery WJ. Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. Int J Remote Sens 1989;10:1699–720.
[54] Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—a review. Energy Build 2015;98:119–24.
[55] Schenk HJ, Jackson RB. The global biogeography of roots. Ecol Monogr 2002;72:311–28.
[56] Schneider C, Laizé CLR, Acreman MC, Flörke M. How will climate change modify river flow regimes in Europe? Hydrol Earth Syst Sci 2013;17:325–39.
[57] Schwaab J, Meier R, Mussetti G, Seneviratne S, Bürgi C, Davin EL. The role of urban trees in reducing land surface temperatures in European cities. Nat Commun 2021;12:6763.
[58] Schwarz N, Manceur AM. Analyzing the influence of urban forms on surface urban heat Islands in Europe. J Urban Plann Dev 2015.
[59] Seto KC, Guneralp B, Hutyra LR. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. In: Proceedings of the National Academy of Sciences of the United States of America; 2012. Vol. 109. pp. 16083-16088.
[60] Stewart ID, Mills GM. The urban heat Island: a guidebook. Amsterdam, Netherlands: Elsevier; 2021.
[61] Toparlar Y, Blocken B, Maiheu B, van Heijst GJF. The effect of an urban park on the microclimate in its vicinity: a case study for Antwerp, Belgium. Int J Climatol 2018;38:e303–22.
[62] Voogt JA, Oke TR. Thermal remote sensing of urban climates. Remote Sens Environ 2003;86:370–84.
[63] Xu L, Cui S, Tang J, Nguyen M, Liu J, Zhao Y. Assessing the adaptive capacity of urban form to climate stress: a case study on an urban heat island. Environ Res Lett 2019;14:044013.
[64] Yang XY, Li YG, Luo ZW, Chan PW. The urban cool island phenomenon in a high-rise high-density city and its mechanisms. Int J Climatol 2017;37:890–904.
[65] Yosef G, Walko R, Avisar R, Tatarinov F, Rotenberg E, Yakir D. Large-scale semi-arid afforestation can enhance precipitation and carbon sequestration potential. Sci Rep 2018;8:996.
[66] Zhao L, Lee X, Smith RB, Oleson K. Strong contributions of local background climate to urban heat islands. Nature 2014;511:216–9.
[67] Zhou B, Rybski D, Kropp JP. The role of city size and urban form in the surface urban heat island. Sci Rep 2017;7:4791.
[68] Zhou W, Cao F, Wang G. Effects of spatial pattern of forest vegetation on urban cooling in a compact megacity. Forests 2019;10:282.
[69] Zhou W, Wang J, Cadenasso ML. Effects of the spatial configuration of trees on urban heat mitigation: A comparative study. Remote Sensing of Environment; 2017.
[70] Zipper SC, Schatz J, Kucharik CJ, Loheide II SP. Urban heat island-induced increases in evapotranspirative demand. Geophys. Res. Lett. 2017;44:873-881.
[71] Ziter CD, Pedersen EJ, Kucharik CJ, Turner MG Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proceedings of the National Academy of Sciences; 2019.