Urban Sustainability

Ali Cheshmehzangi
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Climate Change and Cooling Cities

Springer

Urban Sustainability

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Editors

Climate Change and Cooling Cities

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***Ali Cheshmehzangi** dedicates this book to all his recent collaborators from the industry, governmental organisations, and academia who have been actively engaged with project workshops, surveys, data collection, and stakeholder discussion sessions.*

***Bao-Jie He** dedicates this book to all his collaborators on urban climate and sustainable built environment for their support on questionnaire survey, interview, workshop, seminars, roadshow, and project demonstration.*

***Ayyoob Sharifi** dedicates this book to all researchers and policy makers interested in taking actions towards urban heat adaptation and mitigation.*

***Andreas Matzarakis** dedicates this book to all his collaborators and colleagues at the Research Centre Human Biometeorology and the University of Freiburg. Also dedicated to all young researchers willing to contribute to this topic.*

Lastly, we collectively dedicate this book to climate change activities around the globe *and we hope they get more attention and support as they continue their battle against the current flows.*

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About This Book

With ever-increasing climate change impacts on our living environments and continuous calamities and natural disasters around the world, we urge for new approaches, apt action, and adequate support to boost cooling strategies for the built environments. To achieve this goal, research, practice, and policy could do much more to provide us with new pathways to achieve sustainable development. This collection helps to put together an excellent set of global case studies from regional contributors, exploring new cooling design, planning, and directions in cities, communities, and the built environments.

Climate Change and Cooling Cities is a comprehensive collection of theoretical perspectives and global case study examples focused on three core areas of (1) concepts, theories, and trends, (2) mitigation and adaptation strategies, and (3) policies. This edited volume provides a solid foundation for future research on cooling cities, climate change impacts on cities and urban environments, and innovative mitigation and adaptation strategies. The book will be of use to various stakeholders, and more importantly to urban specialists, planners and designers, policy makers, academics, practitioners, and developers. We urge them to mitigate climate change before it gets too late. We are confident that the book could provide readers with new ideas, strategies, and directions that could lighten up the path towards new actions, policies, and innovation.

This volume addresses cooling strategies in cities to combat climate change, looking at multiple aspects, scenarios, opportunities, and directions in making cities cooler and mitigating the climate change impacts as much as possible. This timely book has arisen partly from year-long discussions, activities, dialogues, and exchanges between all four editors (from China, Japan, and Germany) and contributing authors from various parts of the world. Through many global case study examples, its contributors address cooling and explore ways of reducing cooling demand, heat island effects, etc. We hope this book's up-to-date materials and case study examples remain valid and beneficial for many years ahead.

Ali Cheshmehzangi
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Contents

Part III Policies

Editors and Contributors

About the Editors

Ali Cheshmehzangi is the World's top 2% field leader, recognised by Stanford University. He has recently taken a senior leadership and management role at Qingdao City University (QCU), where he is a Professor in Architecture and Urban Planning; Director of the Center for Innovation in Teaching, Learning, and Research; and Advisor to the school's international communications. Over 11 years at his previous institute, Ali was a Full Professor in Architecture and Urban Design, Head of the Department of Architecture and Built Environment, Founding Director of the Urban Innovation Lab, Director of Center for Sustainable Energy Technologies, and Director of Digital Design Lab. He was Visiting Professor and now Research Associate of the Network for Education and Research on Peace and Sustainability (NERPS) at Hiroshima University, Japan. Ali is globally known for his research on 'urban sustainability'. So far, Ali has published over 300 journal papers, articles, conference papers, book chapters, and reports. To date, he has 17 other published books.

Bao-Jie He is a Professor of Energy and Sustainable Built Environment at School of Architecture and Urban Planning, and the leader of the Centre for Climate-Resilient and Low-Carbon Cities, Chongqing University. Bao-Jie is also the Research Fellow at Network for Education and Research on Peace and Sustainability, Hiroshima University, Japan. Bao-Jie He was a Postdoc Research Fellow, Research Associate, Ph.D. researcher, at UNSW Sydney, Australia. Bao-Jie is working on the technologies of Cool Cities and Communities and Net Zero Carbon Built Environment. Bao-Jie has published more than 110 peer-reviewed papers in high-ranking and delivered invited talks in reputable conferences. Bao-Jie has a H-index of 42 (Scopus). Bao-Jie has been involved in several large research projects on energy and built environment in Australia. Bao-Jie has been invited to act Topic Editor-in-Chief, Leading Guest Editor, Associate Editor, Editorial Board Member, Conference Chair, Sessional Chair, Scientific Committee of a variety of reputable international journals and conferences. Bao-Jie received the Highly Cited Researcher Title (Clarivate) in 2022, the Sustainability Young Investigator Award in 2022, the Green Talents Award (Germany) in 2021, and National Scholarship for Outstanding Foreign Students (China) in 2019. Bao-Jie was ranked as one of the Single-year & Career 100,000 global scientists (2%) by the Mendeley in 2020, 2021, and 2022.

Ayyoob Sharifi is a Professor at the IDEC Institute, Hiroshima University. His research is mainly at the interface of urbanism and climate change mitigation and adaptation. He has published over 100 articles on issues related to urban planning, design, and management. Ayyoob actively contributes to global change research programs such as the Future Earth and has served as a lead author for the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). Before joining Hiroshima University, he was the Executive Director of the Global Carbon Project (GCP)-a Future Earth core project- leading the urban flagship activity of the project which is focused on conducting cutting-edge research for supporting climate change mitigation and adaptation in cities.

Andreas Matzarakis studied meteorology at the Ludwigs-Maximilians-Universität (LMU) Munich, and completed his dissertation on the bioclimate of Greece in 1995 at the Aristoteles University in Thessaloniki. Between 1995 and 2001, he served as a research assistant for the Meteorological Institute of the University of Freiburg. He wrote his habilitation on the 'thermal component of the urban climate'. Between October 2001 and July 2015, he was a senior research associate at the University of Freiburg, and was subsequently appointed an extraordinary Professor in October 2006. Since August 2015, he has served as the head of the Research Centre Human Biometeorology of the German Meteorological Service. Between 1996 and 2014, he chaired the commission for climate, tourism, and recreation of the International Society of Biometeorology, and served as the vice-president of the International Society of Biometeorology between 2006 and 2009. Since 2016, he is the chairman or the German Society for the advancement of medical-meteorological research. He is the editor in Chief for the *Section of Biometeorology of the Atmosphere Journal.* From 2022 onwards, he has acted as the external member of the Administration Council of the Democritus University of Trace in Greece.

His publications cover more than 300 review papers and journal articles, many books and book chapters. Core research interests relay to human bioclimatology and urban climatology, climatology of tourism and climate change impact research. A further research focus is the development of models and tools for applied climatology and biometeorology (e.g. the RayMan model, SkyHelios model, and CTIS [Climate-Tourism-Information-System]).

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Chapter 1
Climate Change, Cities, and the Importance of Cooling Strategies, Practices, and Policies

Ali Cheshmehzangi, Bao-Jie He, Ayyoob Sharifi, and Andreas Matzarakis

Abstract Cities, the prominent place of human settlements, face various mega challenges. Among them, extreme heat challenge, the combined effect of heat waves and heat islands, is the deadliest disaster (Anderson and Bell in Environmental Health Perspectives 119(2):210–218, 2011; City of Sydney, Adapting for climate change: A long term strategy for the city of Sydney, 2015; De Bono et al., Environment Alert Bulletin, 2:4, 2004). For instance, the extreme heat event in Europe in 2003 killed about 72,000 people (WMO, United Nations News, 2021), and the extreme heat event in June–August 2022 caused more than 53,000 deaths.

1 Prologue: Climate Change and Cooling Cities

Cities, the prominent place of human settlements, face various mega challenges. Among them, extreme heat challenge, the combined effect of heat waves and heat islands, is the deadliest disaster (Anderson & Bell, 2011; City of Sydney, 2015; De Bono et al., 2004). For instance, the extreme heat event in Europe in 2003 killed about 72,000 people (WMO, 2021), and the extreme heat event in June–August 2022 caused more than 53,000 deaths (EU, 2022). Beyond health and lives, extreme

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heat is evidenced as the culprit of excessive energy and water consumption, environmental deterioration, economic losses, social inequality, biodiversity loss, etc. (Butters & Cheshmehzangi, 2018; Cheshmehzangi & Butters, 2015; Cheshmehzangi et al., 2021; He et al., 2021). What's worse, extreme heat challenges will be more frequent, severe, and intense, along with climate change and urbanization. Therefore, addressing global warming or urban warming is urgent to ensure human survival and prosperity.

Moreover, extreme heat and its impacts are interlinked with many other mega challenges. Through the lens of Sustainable Development Goals proposed by the United Nations, extreme heat deteriorates goals of Good health and well-being (Goal 3), Gender Equality (Goal 5), Clean water and sanitation (Goal 6), Affordable and clean energy (Goal 7), Decent work and economic growth (Goal 8), Reduced inequalities (Goal 10), Sustainable cities and communities (Goal 11), Climate Action (Goal 13), and Peace, justice, and strong institutions (Goal 16) (Khosla et al., 2021). Accordingly, taking action to address urban heat challenges is an approach to promoting and securing urban sustainability. Such an argument is true since extreme heat is or will be a new normal for many cities in the coming years.

Since Howard identified the heat island phenomenon in London in 1818, numerous scholars and experts have made efforts to address heat-related challenges in cities and have shaped extreme heat studies as a transdisciplinary subject consisting of urban meteorology, urban physics, landscape ecology, planning and design, urban governance, and public health (He et al., 2023). For instance, in the 1930s–1980s, urban meteorologists focused on the confirmation of the heat island phenomenon across cities in North America, Europe, and East Asia (He et al., 2023), and some scholars, represented by Oke (1988), explored the surface energy balance model to explain heat island formation. Afterward, scientific efforts emerged into four clusters, including (He et al., 2023):

- Heat island impact assessment and cause identification, characterized by the understanding of the spatiotemporal variations of land surface temperature based on "remote sensing" techniques and datasets and its relationship between land use/land cover (Fletcher et al, 2021) or typically local climate zones (Stewart & Oke, 2012).

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- Microclimate regulation and human thermal comfort assessment, characterized by analysis of microclimatic parameters such as airborne temperature, wind speed, relative humidity, and mean radiant temperature based on fixed or mobile measurement, and assessment of human thermal comfort based on thermal comfort indicators (e.g., PET, UTCI) (Matzarakis et al., 1999; Mayer & Höppe, 1987; Staiger et al., 2019) and analytical models (e.g., RayMan, ENVI-met) (Bruse & Fleer, 1998; Matzarakis et al., 2007, 2021).
- Climate-related health impact assessment and adaptation, characterized by the analysis of heat-related vulnerability, health, mortality, and air pollution based on long-term data from professional or governmental authorities (e.g., medical centre, hospitals, statistical bureau, public health department) (Hatvani-Kovacs et al., 2016; Matzarakis, 2020; Matzarakis et al., 2020; Santamouris, 2020), and the development of adaptation plans based on an education campaign for awareness and knowledge enhancement (Kotharkar & Ghosh, 2022; Matzarakis, 2021; Yang et al., 2021).
- Mitigation strategy and technique development and performance assessment, characterized by the development of reflective, retro-reflective materials, chromic materials, super cool materials, and permeable materials based on laboratory experiments and field experiment (Santamouris & Yun, 2020; Wang et al., 2022), and the analysis of the energy saving potential based on numerical simulation (Cui et al., 2017; Santamouris & Kolokotsa, 2015).

However, the arrival of various subjects brings diverse goals and targets, making the efforts for addressing urban heat challenges isolated and delayed to force the transformation from research into practice for creating cool cities and communities on site (Cheshmehzangi & Butters, 2017; Dawodu & Cheshmehzangi, 2017; He et al., 2023; Matzarakis, 2021). How to eliminate the gaps, conflicts, and disputes that hinder the integration of cooling strategies and techniques into urban planning and design is a critical issue for consideration. To achieve so, we are dedicated to mainstream urban cooling into urban planning, design, construction, operation, and maintenance through the collective action of (i) assessment, identification, and projection of extreme heat, (ii) development and performance assessment of mitigation and adaptation strategies and techniques, and (iii) piloting projects and promoting the application of mitigation and adaptation strategies and techniques through addressing social, economic, technical and policy barriers.

2 The Aim and Objectives of the Book

This book aims to bring together the latest research outcomes on climate change and cooling cities for a comprehensive framework for urban cooling implementation in order to address gaps, barriers, conflicts, and disputes in mainstreaming urban cooling. In particular, the development of such a framework is in alignment with the Sendai Framework by balancing mitigation and adaptation actions to enhance prevention, mitigation, preparedness, response, recovery, and rehabilitation capacity on the one hand and to enhance awareness and knowledge of disaster risk, promote behavioural and operation change, strengthen disaster risk governance, and invest in disaster reduction on the other. Given this, the objectives of this book include:

- Presenting emerging, innovative and comprehensive thoughts on climate change and cooling cities;
- Showcasing the applications of mitigation and adaptation strategies in different; contexts, accompanied by reporting the cooling performance in temperature, thermal comfort, and energy saving; and
- Exploring drivers to the extreme heat challenges to inform urban development policy, governmental regulations, planning practice, and design schemes.

Overall, this book is innovative in demonstrating a scientific roadmap to achieving targets covering emerging concepts, theories, trends, strategies, techniques, methods, models, policies, and regulations. This book is also advantageous to provide governmental and built environment professionals with insights into actual actions on urban planning and design by demonstrating practical cases in the context of developing and developed cities across the world.

3 Structure of the Book

The book is intentionally divided into three parts, addressing key aspects related to concepts and trends, mitigation and adaptation strategies, and policies. For each part, we have invited contributors from around the globe, where they present their study findings, case study work, or specific concepts, strategies, and policies. These three parts are structured as:

1. Concepts, Theories and Trends;
2. Mitigation and Adaptation Strategies; and
3. Policies (Fig. 1).

PART I: Concepts, Theories, and Trends

The first part looks into four examples of 'concepts, theories, and trends', exploring four key areas of urban heat mitigation strategies, biophilic design and nature-based techniques, urban thermal field variance index under rapid urbanization, and Urban Heat Island (UHI) implications. Below is the summary of the four chapters included in this part.

Chapter 2: Urban Heat Mitigation Strategies

By: Jinda Qi, and Bao-Jie He

Urban heat has been detected in many cities worldwide and has negatively impacted the urban environment and human well-being. Many strategies have been developed to mitigate urban heat, collectively called urban heat mitigation strategies (UHMSs).

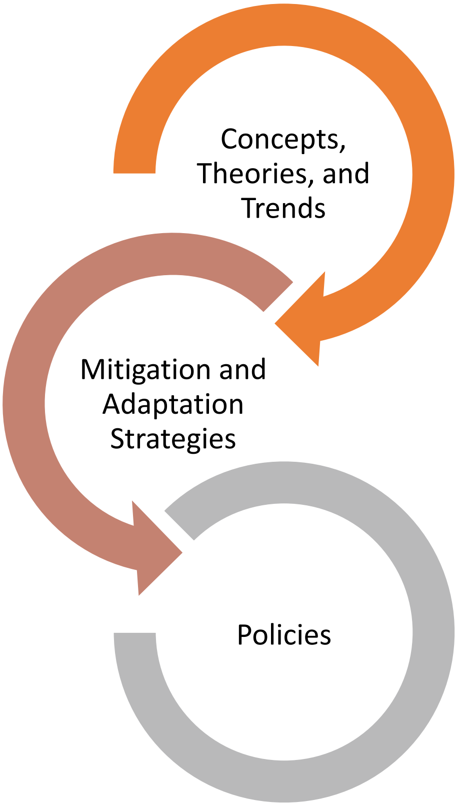

Fig. 1 Summary of three parts of the book

This study reviewed the four types of passive UHMSs (i.e., greenery, cool materials, evaporation techniques, and shading devices) from an implementation perspective to support urban heat mitigation. The definitions, mitigation performance, planning and design variables, and cost-benefits of these UHMSs are elaborated from three categories, according to the place of application: private realm, public realm, and combinations. The results show that green infrastructures have high performance in cooling and energy saving in private and public realms, and their effectivenesses are affected by many factors, such as vegetation species. For cool materials, reflective materials generally have higher cooling potentials and lower costs than heat storage materials and heat harvesting materials. The predominant planning and design variables for cooling effectiveness are the colour and construction materials, and coating materials. The evaporation techniques can reduce ambient temperature significantly due to the high cooling potential of latent heat. The main variables include water flow rate, water particle size, area and shape of water bodies etc. To achieve optimal cooling performance, it is required to properly define the surface temperature of the evaporative cooling pads for evaporative cooling towers and shading structures and slat angles for shading. Also, UHMS combinations can have higher mitigation performance than a single one. All these findings help decision-makers better understand the implementation of UHMS in detail, supporting the proper selection and application of strategies for urban heat mitigation.

Chapter 3: Biophilic Design: Pinpointing Nature-Based Techniques in Urban Areas to Combat Global Warming

By: Abdollah Baghaei Daemei, Masoumeh Mazandarani, and Mahshid Motamed

The rate of global warming has increased rapidly in recent decades, and experts agree that climate change is exacerbating dangerously high temperatures around the world, which will ultimately lead to an increase in urban heat islands (UHI), longer warm seasons, and severe health-related issues. This study aims to provide strategies, exemplars, and approaches to tackle the mentioned problems. Hence, this research proposed biophilic design elements as a promising technique to mitigate UHI resulting from global warming, to examine the importance of vegetation and plants in urban areas. The Rhino software, and Grasshopper and Ladybug plug-ins have been deployed to simulate UHI; referred to as Urban Weather Generator (UWG). The humid climate of Rasht was selected as an example of the study area in this research. Thus, findings showed that adequate vegetation could help drop the average monthly temperature by approximately 2 °C, and this mean temperature could vary between 9 and 19 °C annually.

Chapter 4: Warming Cities in Pakistan: Evaluating Spatial–Temporal Dynamics of Urban Thermal Field Variance Index Under Rapid Urbanization

By: Mirza Waleed, and Muhammad Sajjad

With ~57% of the world population living in cities, the global urban population is increasing at an alarming rate, which further stimulates the urbanization process. Consequently, the increasing impervious surfaces in cities and associated variabilities in local/regional climatic characteristics pose several challenges to citizens (i.e., heat-related health issues, higher energy demands, and flooding among many others). Currently, cities contribute 75% of Green House Gases emissions, which is further worsening climate change impacts through global warming. Pakistan, the 6th most populated country globally, with ~220 million people, is among the top 10 most-affected nations vulnerable to climate change. Hence, studies addressing climate variability in local geographical regions have important implications to address the adverse urbanization-associated challenges, such as sustainability of the land resource and mitigating urban heat island (UHI) impacts in the context of climate change mitigation/adaptation. Due to temperature differences between urban, suburban, and rural areas, mapping city zones prone to the UHI effect is essential to provide actionable references. In connection with this, the present study analyses 15 megacities in Pakistan regarding their temperature variability in response to built-up area increment and highlights heat stress zones using the Urban Thermal Field Variance Index (UTFVI). The cloud-computing-based Google Earth Engine platform is employed to explore spatial–temporal variation in Land Surface Temperature (LST), which further leads to the identification of top-15 cities in terms of LST increase and the further evaluation of UTFVI for each city. The findings of this study suggest that the strongest UTFVI zones are concentrated around city-core areas, which are pure impervious surfaces with little or no green space. Moreover, in the last three decades (1990–2020), most of the weak and strong-strength UTFVI areas have been converted into the strongest strength primarily because of a rapid increase in the built-up areas. The findings of this study can help urban policymakers to identify priority intervention areas and design/implement strategies to counter the UTFVI and associated challenges. With proper land-use planning and on-time policy implementation, people residing in higher UTFVI zone areas can be safeguarded from noxious heatstroke-like health consequences along with mitigating and adapting to changing environmental conditions in cities.

Chapter 5: Urban Heat Island (UHI) Implications and a Holistic Management Framework

By: Hafiza Saba Islam, Talib Elahi Butt, Shaker Mahmood Mayo, Siddiqa Amin, and Maria Ali

The Urban Heat Island (UHI) effect is one of the most debated phenomena among the urban researchers and city planners. In addition to fast urbanization, climate change actors are rendering major cites thermal hubs of the modern global civilization. Climate models consistently predict that the frequency, severity, and duration of extreme weather conditions which also include heat wave are on the increase and would be significantly by the end of the twenty-first century. Therefore, there is an emergent and urgent need to rethink the assessment and management of the UHI phenomenon (Cheshmehzangi et al., 2022). This study aims to establish the existing knowledge regarding UHI implications by categorically identifying and systematically grouping the factors and sub-factors that contribute UHI phenomenon. The aforesaid aim is based on the literature review, investigation of models, and the thematic analysis. Some new insights are produced by categorizing UHI implications into two main groups climate change and non-climate change related. This leads to a more comprehensive conceptualization of UHI at different tiers which is discussed and presented schematically. Founding on this conceptualization a new, integrated and holistic framework of the assessment and management of UHI is developed. The UHI framework is also schematically delineated. This UHI framework can be used as a basis for further research and development in the form of a ready-to-use/off-the-shelf tool for urban planners, decision-makers, and other associated stakeholders. The framework can also be communal platform of effective communication between diverse stakeholders with varying background and interests.

PART II: Mitigation and Adaptation Strategies

In the second part, we focus more on ‘practices’, mainly from the mitigation and adaptation strategies. We particularly explore best practices that are considered as urban planning interventions, urban design innovations, and new approaches to either mitigate or adapt climate change impacts on cities. This part includes seven case study chapters. These include a wide range of topics such as UHI effect mitigation, densification strategies, traditional dwellings, climate-responsive design, bioclimatic design, etc. Below is the summary of the seven chapters included in this part.

Chapter 6: Contribution of Bodies of Water to the Mitigation of UHI Effect in Urban Canyon: A Parametric Study Approach

By: Nedyomukti Imam Syafii, and Masayuki Ichinose

To find effective design solutions for bodies of water for better urban thermal environment, a series of comprehensive studies have been conducted utilising an outdoor scale model canopy in Saitama, Japan, and coupled numerical model. The simple form of the outdoor scale model has the advantages of enabling the observation of various physical phenomena under actual climate conditions and conducting comprehensive measurements of a relatively uniform area, thus providing results that are easy to interpret. Meanwhile, numerical modelling allows a series of various bodies of water configurations to be analysed and compared.

By modifying its basic physical properties, the present study shows evidence of the positive contribution of water ponds to the urban thermal environment. The presence of water ponds inside an urban canyon reduced the air and radiant temperatures throughout the day. The result also shows that, generally, a bigger pond has greater cooling benefits. A bigger pond tends to absorb more heat and has a more evaporation surface. As shown in the measured air temperature, water temperature and globe temperature profile, a larger portion of the radiant energy absorbed within the canyon is dissipated by evaporation rather than converted into sensible heat. This phenomenon shows the critical role of the bodies of water's thermal capacity while also opening the possibility of manipulating these parameters for a better urban thermal environment. When there is a space constraint within urban spaces, introducing chilled water may help further improve the cooling benefits of urban bodies of water bodies.

Chapter 7: The Challenge of Cooling Rapidly Growing Cities: The Case of Densification and Sprawl in Ho Chi Minh City and Adaptation Responses

By: Antje Katzschner, Nguyen Kieu Diem, Thanh Hung Dang, and Nigel K. Downes

Climate change and social-economic development are expected to compound climate changes risks. For southeast Asian cities, the phenomenon of urban heat islands and extreme heat waves are a current and future concern for public health, well-being and household energy consumption due to increased cooling demands of urban residents and limited resources to cope. Urban heat island studies using remotely sensed imagery have already revealed that Vietnam's major cities are characterized by strong temperature differences between urban and rural areas. As a result, implementing adaptation measures based on solid science is critical to mitigating the negative effects of heat on urban residents and adapting infrastructure. While different adaptation measures are currently debated by the political authorities in Vietnam, decision-making is hampered by multiple scientific knowledge gaps and the lack of practical tools to support decision-making. This chapter presents methods to investigate and monitor recent urban development in Ho Chi Minh City, an emerging megacity and economic powerhouse of Vietnam.

Chapter 8: Traditional Dwellings in Four Middle Eastern Cities: Adaptation Strategies to Harsh Climate in Privacy

By: Hirou Karimi, Mohammad Anvar Adibhesami, Maryam Ghasemi, and Borhan Sepehri

Climate change is one of the most serious environmental issues of the twenty-first century, compelling designers to adapt their work to completely new climate-change-adapted settings. The Middle East's dry environment causes issues with rising temperatures and decreasing humidity. Environmental harmony has long been a priority in Middle Eastern architecture. Designers changed nature to accommodate the limited supply and demand for energy. Concerns about privacy and climate change influence home construction in areas with similar religious and climatic conditions. As a result, the purpose of this research is to look into the environmental and privacy-enhancing characteristics of historic and contemporary buildings. To accomplish this goal, observations and reviews of relevant literature were used to collect qualitative data. Analysis from a variety of research and climate-tested data was used in the following: This study's data and analysis include traditional homes, the Koppen climatic classification, and contemporary house design. Furthermore, research methods have been used in areas with well-established internal residential characteristics, such as Baghdad, Riyadh, Mukalla, and Kashan. The climate and isolation of each instance were studied and compared to nearby, modern dwellings. Our data show that these communities' older buildings made good use of natural heating and cooling resources. Summer and winter rooms are available for rent in historic mansions in Kashan and Baghdad. Summers in these regions are scorching, and winters are bitterly cold due to the different positions of the sun. We have not yet investigated any sun-facing locations in modern architecture. Wind turbines are also very important. The wind tower passively cools the structure's air. In modern homes, air conditioning provides ventilation. These items are both expensive and energy-intensive.

Chapter 9: Urban Thermal Environment Under Urban Expansion and Climate Change: A Regional Perspective from Southeast Asian Big Cities

By: Can Trong Nguyen, Amnat Chidthaisong, Rungnapa Kaewthongrach, and Wijitbusaba Marome

Southeast Asia (SEA) is a hotspot of rapid urbanisation and climate change, which is supposed to influence millions of people. They altogether exacerbate urban thermal environments and amplify urban heat islands (UHIs). The chapter provides a comprehensive assessment of urban warming trends in SEA big cities over the past thirty years in a connection with urban expansion and climate changes; of which climate change is represented by temperature extremes as an additional element deteriorating UHIs. It reveals a significant warming trend in nighttime extreme indices across the cities against daytime. Manila and Kula Lumpur have confronted the most prominent temperature variations. There were drastic transformations in urban areas, urbanisation patterns, and landscape characteristics during urbanisation. The fastest-growing cities during this period are Jakarta, Bangkok, and Ho Chi Minh City. The degradation of the urban thermal environment was also confirmed via spatiotemporal escalations of both land surface temperature (LST) and surface UHI (SUHI) over time. The aggravation in urban thermal environments was mainly driven by urbanisation-related elements and temperature extremes as a background climate factor. The changes in surface characteristics are the main driving factors across the cities. Yet, the stimulations of climate on thermal environment degradation are uneven among the cities. Ho Chi Minh City, Jakarta, and Manila are the most vulnerable cities due to combined impacts rather than others. It verifies the integrated impacts of climate change and urbanisation on urban microclimate change, it therefore should have long-term strategies to mitigate the adverse effects of SUHI. The general principle is to reduce horizontal urban expansion, ensure urban spatial planning and urban green spaces, and mainstream climate change into urban planning.

Chapter 10: Climate-Responsive Designs to Enhance Outdoor Thermal Comfort in Urban Residential Areas

By: Tingting Yuan, Hongyun Qu, and Bo Hong

Our study aims to determine relationships among microclimate, outdoor thermal perception, and residents' behavior in a residential area in Xi'an, China. Four typical open spaces in the residential area were investigated using meteorological measurements, questionnaire survey, and behavioral records to determine how individuals' thermal comfort relates to their outdoor activities. Physiological Equivalent Temperature (PET) was applied to quantitatively determine the outdoor thermal benchmarks in Xi'an, and climate-responsive strategies for open spaces were proposed based on thermal benchmarks. Results showed that: (1) spaces differed significantly in air temperature, wind speed, solar radiation, globe temperature, mean radiative temperature, and PET, but not relatively humidity, (2) in summer, residents preferred activities in shaded environments and attendance was inversely linearly related to PET, and (3) optimum design strategies for open spaces were proposed to consider shelterbelts, shaded facilities, plants, water, and underlying surfaces. These results will help urban designers improve their understanding of the relationship between behavior and thermal comfort and provide design advice for open spaces in residential areas in China's cold region.

Chapter 11: Dynamic annual solstice patterns and urban morphology: Bioclimatic lessons for in-situ adaptation measures within the warming city of Ankara, Türkiye

By: Andre Santos Nouri, José Abel Rodriguez-Algecíras, and Andreas Matzarakis

Within the existing literature, there already is a wealthy initiation into how different types of local adaptation measures can help urban fabrics respond to increasing temperatures as a result of climate change. Arguably propelled by the climate change adaptation agenda, different typologies of thermal sensitive measures are becoming continually more organised and solidified to improve the bioclimatic responsiveness of the consolidated urban fabric. Along with this growing body of knowledge, is the recognition that the in-situ efficacy of different measure typologies in counteracting increasing urban heat levels depends on two interrelated factors, these being: (1) how well the dynamic microclimatic conditions are assessed and understood; and (2) how well characteristics such as urban morphology are understood. Following this line of reasoning, in order to be utilised to their full potential, and moreover avoid symptoms of mal-adaptation, thermal sensitive adaptation measures must account for the unremitting and symbiotic cause-and-effect between these factors.

Today, it is widely known that mean radiant temperature (MRT) is one of the most significant factors upon human thermophysiological thresholds. In addition, it is furthermore a particularly dynamic variable as a result of the continuously shifting annual solstice. Accordingly, MRT must be understood as a variable which modifies not just on a diurnal bases, but in addition one which oscillates throughout the different months and seasons of the year. Depending on the time of year, as dictated by the Urban Energy Balance, radiation fluxes interact with the static structures of the urban fabric through different seasonal energy exchange patterns/quantities. Such an understanding calls upon the approach of both yearly and different seasonal analytical scopes to better comprehend the symbiotic relationship of urban morphology and solstice patterns. It permits a finer understanding of the impacts associated to crucial climatic variables that play a significant role in human thermal comfort. Invariably, this consequently includes the fundamental role of in-situ dynamic radiation fluxes that are undeniably dictated by modifying yearly/seasonal solstice patterns. Grippingly, and unlike encircling air temperature, MRT can more easily be manipulated through different measure typologies within the urban fabric, and in addition, presents means to alter the cause-and-effect relationship with other encircling microclimatic variables.

Within this book chapter, a structured reflection will be undertaken for Ankara, Türkiye—and how an innovative methodical case study presents bioclimatic lessons pertinent to the crucial role of in-situ dynamic radiation fluxes within a densifying and warming urban fabric in an era of growing climate change.

Chapter 12: Comparison of Thermal Indices in Urban Environments with SkyHelios Model

By: Marcel Gangwisch, and Andreas Matzarakis

Global climate change and its thermal implications on cities makes it necessary to react with long-term climate-adaptive urban planning. This should be part of heat action plans to be implemented by municipalities, to minimize future risks of overheated city districts on the city dwellers and especially on risk and vulnerable groups. The evaluation of the thermal impact, based on thermal indices (depicting human thermoregulation) is most important in order to allow for a safe and risk-minimized but also human-adapted urban planning.

The assessment of thermal impacts can be achieved using numerical urban microscale models, which are suitable to analyse the human thermal outdoor conditions of future building- and local climate- scenarios. This chapter aims to demonstrate the applicability of the urban microscale model SkyHelios and thermal indices to an urban district in Freiburg, Germany. The findings demonstrate the thermal vulnerabilities, strengths and similarities of the indices and provide additional information for future action.

PART III: Policies

In the third part, we delve into 'policies' relevant to climate change strategies in cities and communities, particularly those with case study examples, framework development, and policy development directions. Divided into four chapters, this part includes studies on urban heat island effect, thermal comfort assessment frameworks and models, climate justice, and urban biometeorology. Below is the summary of the four chapters included in this part.

Chapter 13: Urbanisation and Urban Heat Island in a Mekong Delta City: From Monitoring to Dominant Factors

By: Phan Kieu Diem, Nguyen Kieu Diem, Can Trong Nguyen, and Nguyen Thi Hong Diep

Urbanisation is an indispensable process along with socio-economic development. However, this is also the root of various challenges in urban areas from social to environmental and microclimate changes such as urban heat islands (UHI). This book chapter showcases a case study regarding rapid urbanisation, dynamic of surface urban heat island (SUHI), and controlling factors of UHI in Can Tho city—a regional newly developing city in the Mekong delta since 2005. Using an integrated methodology framework of earth observation analyses and Analytic Hierarchy Process (AHP), we assessed the urbanisation trends based on urban density and annual growth rate (AGR). The deterioration of SUHI was analysed using land surface temperature (LST) retrieved from Landsat thermal infrared band. AHP is a social approach via expert interviews to identify the key elements and their contribution weights to UHI under the local conditions. It revealed that urban areas have continuously expanded outwards since 2005 towards the Western and main roads along the Bassac river. The AGR is about 0.73%/year over the period of 2005–2019. In particular, the city center has experienced a relatively high rate of urbanisation compared to other areas (i.e., 3.98–5.04% versus 0.5%/year). LST increased significantly and the growth of SUHI was more moderate in terms of intensity and spatial patterns. SUHI is frequently observed in industrial zones and densely populated areas. Urban sprawl was found to significantly stimulate the variations of SUHI intensity. Regards to the driving factors of UHI, five (05) main factors including nature, society, infrastructure, policy and environment are found contributing to form of UHI at this specific areas. In which, the natural factors including coverage ratio of vegetation and water surface are the most contributors to UHI. The key analytical factors from AHP are likely to be prioritised elements, which should be mainstreamed into urban planning to mitigate UHI towards a cooling city.

Chapter 14: A Study on Thermal Comfort Assessment Frameworks and Models in Cities

By: Hadi Alizadeh, and Ayyoob Sharifi

Considering the increasing trends of urbanization, climatic change, and air temperature in cities, the issue of urban heat island mitigation for ensuring thermal comfort is of high importance. Enhancing thermal comfort also has implications for human health, well-being, and productivity. In recent decades, several assessment frameworks and models have been proposed to measure and predict thermal comfort in cities. This chapter tries to explore major assessment frameworks and models that explain and measure thermal comfort in cities by considering physical, physiological, psychological, and behavioral dimensions. It shows that thermal comfort models could be divided into two major categories, namely, knowledge-based thermal comfort methods and data-driven thermal comfort models. Each of these two has subset models for thermal comfort testing in cities. The findings indicate that recent trends in measuring thermal comfort are focused on data-driven models based on simulation algorithms.

Chapter 15: Who benefits more from urban cooling strategies? Exploring climate justice in vulnerable groups' Access to Blue-green Infrastructure in Mashhad City, Iran

By: Safoora Mokhtarzadeh, and Mahdi Suleimany

Climate change and consequently global warming have made the decision-makers adopt a set of urban cooling strategies and policies. These policies, the most common of which is the development of blue-green infrastructures, lead to a decrease in the ambient temperature of cities. However, many studies suggest that the uneven development of these infrastructures has led to climate injustice in many cities. In other words, developing blue-green infrastructure to meet predefined standards is one side of the coin in coping with global warming, which indicates the efficiency of urban resiliency measures. While ensuring equitable access to these services and infrastructures is the other side, which shows the effectiveness of adaptation programs. Therefore, in this research, we have analysed climate justice in a case (Mashhad metropolis, Iran) considering vulnerable groups' access to blue-green infrastructure. We have implemented spatial analysis techniques and multi-scale geographic weighted regression (MGWR) model to identify the patterns of the aforementioned climate (in)justice at two scales of city and neighbourhoods. The results have indicated the significant climate injustice in low-income groups' access to blue and green infrastructures on both scales. Besides, the findings have depicted patterns of climate injustice in the access of sensitive age groups, the disabled, and immigrants to blue infrastructure. The most important reason for this injustice is the uneven distribution and development of blue infrastructures and their spatial concentration in the western half of the city which arose from the inequitable decisions of city management and planning. Although these findings are context-specific, the research process is applicable to any other context. We have also provided some recommendations to promote climate justice in the adoption of urban cooling policies.

Chapter 16: Urban Biometeorology of Tropical Climate: Af, Am, Aw, a Propensity of 34 Provincial Cities in Indonesia

By: Beta Paramita, Hanson E. Kusuma, and Andreas Matzarakis

Indonesia lies between 6° North Latitude–11° South Latitude and 95°–141° East Longitude. Located in the eastern hemisphere, this geographical location causes Indonesia to be included in the equatorial zone and has a tropical climate. Indonesia is the largest archipelagic country in the world with 17,000 islands, 416 districts and 98 cities in 34 provinces. In general, there are three city characteristic that are in the coast (+0 masl) have maximum temperatures above 33°°C. In lowland areas (10–20 masl) the maximum air temperature recorded above 30 °C. Meanwhile the cities located in the hills area (above 500 masl) which are not many in number, have the lowest maximum air temperature between 25 and 28°C. Based on Köppen-Geiger, climate of Indonesia is almost entirely tropical. Dominated by the tropical rainforest climate (Af); tropical monsoon (Am); and tropical savannah (Aw) that occurs on every Indonesian island. This article then reveals the perspective of biometeorology of 34 cities of provincial capital in Indonesia. Cities that represent the tropical rainforest climate such as Medan, Balikpapan, Padang, and Pontianak. Meanwhile Jakarta, Semarang, and Yogyakarta represent cities with tropical monsoon climate. Last, Denpasar and Surabaya represent cities with tropical savannah climate. The climate data is generated from 2009 to 2019 that provides a link between the microclimate elements and human activities that affected on human perception in their living space. The biometeorology perspective for each climate characteristic gives an understanding on meteorological vulnerability and physiological aspects in the city inhabitant, such as thermal stress.

4 A Summary

The book concludes with several reflective views, lessons learnt, and pathways for future cooling strategies in cities. The last chapter serves as a summary chapter, concluding with some extracted lessons for cooling cities, now and in the near future.

Part I is of importance to present holistic and emerging concepts, theories, and trends for urban heat mitigation and adaptation. In particular, Part I develops a novel urban thermal environment assessment indicator of UTFVI and applies it to 15 megacities in Pakistan to explain how land surface temperature varied spatiotemporally. Such an indicator and demonstration enhance urban managers' understanding of heat island formation and strengthens policymakers' capability of identifying vulnerable areas and adding proper planning/design interventions. A comprehensive urban heat mitigation framework was developed for urban greening, cool materials, evaporative techniques, and shading strategies. The novelties lie in identifying cooling effectiveness and key planning and design variables, allowing urban planners and designers to make evidence-based decisions on the selection of cooling strategies and techniques. Part I also explores the co-benefits approach, which can cost-effectively address more than challenges synergistically, with the integration of nature-based techniques to achieve the dual goals of biophilic design and urban cooling. Furthermore, Part I conceptualises a new, integrated and holistic framework of heat island assessment and management by identifying heat island drivers into climate and non-climate-related types. Such a framework supports the development of ready-to-use/off-the-shelf tools for enhancing the communication of urban planners, decision-makers, and other associated stakeholders.

Part II broadly showcases and explores the mitigation and adaptation strategies and techniques across urban planning, urban design, and building design scales. The analysis and identification of heat island evolution in Ho Chi Minh City, Vietnam, is of significance to provide Southeast Asian cities which are under rapid urbanization insights into planning interventions for adaptation. A comparison of the heat island development over 30 years in several southeast Asian cities (e.g., Jakarta, Bangkok, Ho Chi Minh City, Manila, and Kula Lumpur) was more intuitive to verify the impact of climate change and urbanisation on the urban thermal environment deterioration, and consolidate the urgency of reducing horizontal urban expansion, ensuring urban spatial planning and urban green spaces, and mainstreaming climate change into urban planning. This part also presents the parametric design of water bodies tailoring to Saitama, Japan, for cooling performance enhancement. It suggests the climate-responsive design of open spaces in Xi'an, China, based on shelterbelts, shaded facilities, plants, and water for outdoor thermal comfort improvement. This part also adds new knowledge of bioclimatic lessons by exploring how urban morphology counters urban heat challenges based on the mean radiant temperature assessment indicator by an empirical study in Ankara, Türkiye. Meanwhile, the relationship of urban morphology with urban heat challenges is more broadly explored based on thermal indices of Physiologically Equivalent Temperature, Perceived Temperature, and Universal Thermal Climate Index in an urban district in Rieselfeld in Freiburg, Germany. Such studies promote the understanding of safe and risk-minimized but also human-adapted urban planning. In addition, an analysis of the built form of traditional dwellings in four middle eastern cities of Baghdad, Riyadh, Mukalla, and Kashan reveals the formula of such buildings adapting to harsh climates. Moreover, the study in Freiburg, Germany, also presents the sensitivity of the SkyHelios Model in predicting different thermal indices, which is conducive to enhancing the methodological understanding of microclimate modelling.

Part III generates wide implications on urban planning policy, governmental regulations, planning practice, and design schemes by identifying dominant factors of heat islands, thermal comfort assessment frameworks and models, climate justice, and urban biometeorology. The adoption of the Analytic Hierarchy Process method to explore the land surface temperature variations in Can The city highlights five key driving factors in aspects of nature, society, infrastructure, policy, and environment. This provides the planning directions for urban heat alleviation in Mekong Delta City. More importantly, this study demonstrates an exemplary method for many other cities to identify key drivers and main priorities for cooling actions accurately. This part also delineates the assessment framework of thermal comfort that is a function of physical, physiological, psychological, and behavioral factors and categorises various methods into knowledge-based methods and data-driven models. Such work is conducive to providing scholars with proper justifications for using either knowledge-based methods or data-driven models for thermal comfort assessment. This work also answers who is the beneficiary of urban cooling strategies from the perspective of heat vulnerability and climate (in)justice, which is beneficial for avoiding the occurrence of process-related injustice relevant to improper decisions. The last study in the context of 34 provincial cities restructures the way to describe urban climate by linking microclimate elements and human activities, enabling urban planners and designers to better understand meteorological vulnerability and physiological responses/feelings.

The specific examples in the following 15 chapters would help us highlight the importance of (1) concepts, theories, and trends (see Chaps. 2–5), (2) mitigation and adaptation strategies (see Chaps. 6–12), and (3) policies (see Chaps. 13–16). The following chapters provide global case study examples beyond the existing and current policies and practices and highlight some of the main concepts, best practices, and policies around the globe. This volume helps considering cooling strategies in cities, communities, and the built environments in combatting climate change and its impacts on the living environments.

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Part I
Concepts, Theories, and Trends

Chapter 2
Urban Heat Mitigation Strategies

Jinda Qi and Bao-Jie He

Abstract Urban heat has been detected in many cities worldwide and has negatively impacted the urban environment and human well-being. Many strategies have been developed to mitigate urban heat, collectively called urban heat mitigation strategies (UHMSs). This study reviewed the four types of passive UHMSs (i.e., greenery, cool materials, evaporation techniques, and shading devices) from an implementation perspective to support urban heat mitigation. The definitions, mitigation performance, planning and design variables, and cost-benefits of these UHMSs are elaborated from three categories, according to the place of application: private realm, public realm, and combinations. The results show that green infrastructures have high performance in cooling and energy saving in private and public realms, and their effectivenesses are affected by many factors, such as vegetation species. For cool materials, reflective materials generally have higher cooling potentials and lower costs than heat storage materials and heat harvesting materials. The predominant planning and design variables for cooling effectiveness are the colour and construction materials, and coating materials. The evaporation techniques can reduce ambient temperature significantly due to the high cooling potential of latent heat. The main variables include water flow rate, water particle size, area and shape of water bodies etc. To achieve optimal cooling performance, it is required to properly define the surface temperature of the evaporative cooling pads for evaporative cooling towers and shading structures and slat angles for shading. Also, UHMS combinations can have higher mitigation performance than a single one. All these findings help decision-makers better understand the implementation of UHMS in

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detail, supporting the proper selection and application of strategies for urban heat mitigation.

Keywords Urban heat · Mitigation strategies · Green infrastructure · Blue infrastructure · Grey infrastructure

1 Introduction

Urban overheating (or Urban heat) has been detected in numerous cities, such as Toronto, Canada (Wang et al., 2016); Sydney, Australia (Ding et al., 2019); and Athens, Greece (Santamouris et al., 2012a). Mounting evidence reveals that the frequency, intensity, and duration of urban heat in these cities have been increasing with global warming and will continually increase globally in the twenty-first century at a global scale with a 90–100% probability (Field et al., 2012; Melillo et al., 2014). The increasing frequency, intensity, and duration of urban heat negatively affect the urban environment, human well-being and health, and the economy in many ways, including extreme heat, air pollution, water pollution, outdoor thermal comfort, heat-related morbidity and mortality (Akbari, 2005; Qi et al., 2020; Stone Jr et al., 2014).

To address the negative impacts of urban heat, numerous strategies have been developed, collectively called urban heat mitigation strategies (UHMSs). UHMSs refer to "any anthropogenic intervention aiming to reduce the sources and enhance the sinks of high-temperature anomalies in cities" (Santamouris et al., 2017). According to the energy balance proposed by Oke (1988), UHMSs are able to lower temperature through four cooling mechanisms: increasing latent heat release, reflecting solar radiation, increasing heat storage and reducing anthropogenic heat release, as shown in Fig. 1. Based on these cooling mechanisms, four types of passive UHMSs have been developed. First, the use of greenery (e.g., green roofs and vertical greening systems) increases latent heat release by transpiration. Second, the use of cool materials (e.g., reflective materials and phase change materials) reflects solar radiation and increases heat storage. Third, the use of evaporation techniques like water bodies and misting systems increases latent heat release by evaporation. Finally, the use of shading devices reflects solar radiation.

To support urban heat mitigation, the definitions, mitigation performance, planning and design variables, and cost-benefits of passive UHMSs (i.e., greenery, cool materials, evaporation techniques, and shading devices) are elaborated from an implementation perspective. The elaboration is divided into three parts according to the place of application: private realm, public realm, and combinations.

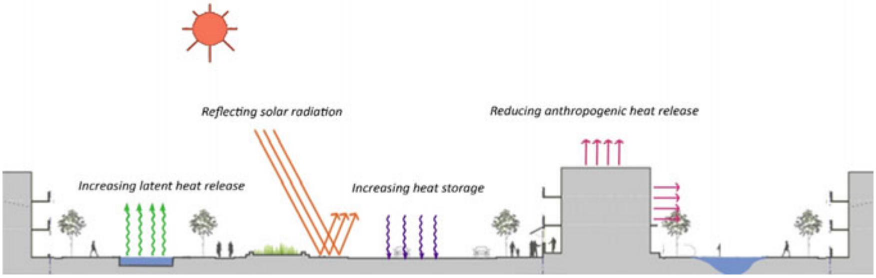

Fig. 1 Cooling mechanisms for urban heat mitigation (Qi et al., 2019)

2 Urban Heat Mitigation Strategies Applied in the Private Realm

The private realm in this study refers to buildings, courtyards, and private hard surfaces. UHMSs applied in the private realm can be classified into four categories: (1) building-integrated green infrastructure or courtyard greenery, (2) cool materials for buildings or hard surfaces, (3) building-integrated evaporative cooling towers, and (4) building-integrated shading.

2.1 Building-Integrated Green Infrastructure or Courtyard Greenery

Green infrastructure can generally be applied to building roofs, walls, and courtyards in the private realm, as shown in Fig. 2. Because of the limited space in cities, applying green infrastructure on roofs and walls is more practical than in courtyards. The following sections, therefore, review studies related to green roofs and vertical greening systems.

2.1.1 Green Roofs

Green roofs are "the roofs and podiums with vegetation growing in a specifically designed substrate" (Williams et al., 2010). They have been widely used in urban areas due to their high potential to promote sustainable cities. In general, there are two types of green roofs: intensive roofs (or roof gardens) and extensive roofs (or eco-roofs). Intensive green roofs are those with "deep soil layers, which support larger plants and bushes and typically require maintenance in the form of weeding, fertilising, and watering" (Berndtsson, 2010). Extensive vegetated roofs are those with "thin soil layers, which are normally planted with smaller plants and expected to provide full coverage of the vegetated roof in the final stage" (Berndtsson, 2010).

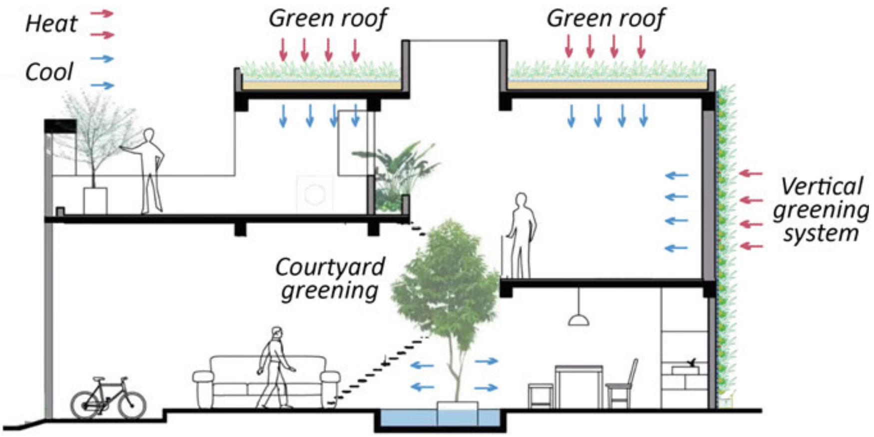

Fig. 2 Schematic view of building-integrated green infrastructure and courtyard greenery

Intensive roofs with deep soil layers are only suitable for buildings with adequate bearing capacity, while extensive roofs with thin soil layers are suitable for buildings with relatively light-weight structures. Both types of green roofs are discussed in this research.

Green roofs have positive effects on microclimate amelioration and energy conservation. Alexandri and Jones (2008) pointed out that employing green roofs in an entire city reduced average air temperature and roof surface temperature by 0.55–1.2 °C and 9.1–12.8 °C, respectively, in nine cities such as London, UK; Moscow, Russia; and Hong Kong, China. However, the cooling impacts of green roofs are negligible if they are applied to high-rise buildings (Ng et al., 2012). Also, large-scale roof gardens can beneficially affect electricity consumption, particularly in summer. Sailor (2008) found that changing the traditional membrane roofs with a solar reflectivity of 0.30 to extensive green roofs reduced annual energy consumption by approximately 2% in Chicago and Houston. Although green roofs have positive impacts on cooling performance and energy saving, there are some barriers to their installation, including leakage and high implementation and maintenance costs (Dunnett, 2006).

The cooling and energy-saving potential of green roofs can be affected by applying design and planning variables. One of the most critical variables is vegetation species, which influence shading levels and the transfer of radiation through the layers of the plants (Santamouris, 2014). Speak et al. (2013) compared green roofs with different vegetation species such as *Juncus* species, *Plantago lanceolata*, and *Senecio jacobaea*. The results showed that the temperature reduction between different species in summer could reach 0.5 °C. The cooling effects are also affected by vegetation coverage rates. Perini and Magliocco (2014) measured green roofs with vegetation cover varying between 30 and 90% in Milan, Italy. The results indicated that the average temperature reduction of green roofs with high coverage rates was 0.2–0.9 °C higher than those with low coverage rates. To sum up, vegetation species and coverage rates can significantly affect the cooling or energy-saving potential of green roofs.

2.1.2 Vertical Greening Systems

Vertical greening systems (or green walls) refer to “all forms of vegetated wall surfaces with plants either attached to the façade or rooted into the ground and the wall itself” (Perini et al., 2013). Vertical greening systems can be classified into green façades and living walls according to their growing methods. Green façades attach “climbers directly to building surfaces or indirectly to cables or trellis” (Perini et al., 2013). Living wall systems are constructed from “modular panels that contain soil or other artificial growing mediums, including foam, felt, perlite, and mineral wool” (Perini et al., 2013).

Vertical greening systems reduce the temperature mainly by transpiration. Existing studies have explored their performance in the reduction of indoor temperature and building surface temperature. Sunakorn and Yimprayoon (2011) pointed out that the average indoor temperature of a room with bio-facades was lower by 0.9 °C than a room without bio-façades in a tropical climate. Alexandri and Jones (2008) concluded that applying a green wall covered with species of ivy reduced the surface temperature by 5.6–14.3 °C in nine cities, including Beijing, China; London, UK; and Brasília, Brazilian. In addition to cooling performance, the use of vertical greening systems also has positive impacts on energy consumption. Perini et al. (2013) found that building façades covered by greenery could reduce energy consumption by 43% in the Mediterranean climate. Despite the positive effects of vertical greening systems on cooling potential and energy saving, their high water demand may be a challenge for implementation in regions with water scarcity. This problem can be alleviated by employing rainwater harvesting technologies or irrigation systems, although the overall cost of installation will be increased for the additional equipment.

Recently, more efforts have been devoted to the planning and design variables that can affect the mitigation performance of vertical greening systems. Sunakorn and Yimprayoon (2011) compared the ambient temperature surrounding the *Blue trumpet vine, Ivy gourd,* and *Mexican creeper* to understand the influence of vegetation species on cooling potential. The results showed that the *Blue trumpet vine,* with its smaller and denser leaves, presented more cooling than the others. Similarly, Wong et al. (2010) measured the cooling potential of eight types of living walls and recommended a high-performance living wall structure with modular panels and inorganic substrates. Although there are other planning and design variables such as substrate type, composition, soil depth, and moisture content, the impacts of those variables on cooling performance are not significant (Wong et al., 2010). In summary, vegetation species and physical structures have significant impacts on the cooling performance of vertical greening systems compared with other variables.

2.2 Cool Materials for Buildings or Hard Surfaces

Cool materials for buildings or hard surfaces in this research refer to the use of specialised materials on building roofs, building walls, or hard surfaces such as pavements in the private realm. Cool materials applied here can generally be divided into reflective materials, heat storage materials, and heat harvesting materials, according to the cooling techniques (Qi et al., 2019). Reflective materials change albedo (e.g., light-coloured or thermochromic roofs), reducing surface and ambient temperature. Heat storage materials, such as phase change materials (PCMs)-based walls, absorb heat in the daytime and discharge heat in the nighttime. Heat harvesting materials like photovoltaic (PV) roofs reduce the temperature by transferring heat to other types of energy, such as electricity.

2.2.1 Reflective Materials

The cooling performance of reflective materials relates to the amount of reflected long- and short-wave radiation. The performance predominantly depends on the albedo of materials, where a higher albedo always means a greater ability of reflecting solar radiation and produce a lower surface temperature (Santamouris et al., 2011). Through summarising studies on the cooling potential of increased albedo, Santamouris (2014) concluded a linear relationship between albedo and surface temperature. The relationship was further explained in the following equation (CSE, 2015):

$$K_S \times (1 - \alpha) = 4\sigma T^4 \tag{1}$$

…where the K_S is solar insolation, α represents albedo, σ is the Stefan-Boltzmann constant, and T is temperature.

Although increasing albedo can reduce the cooling load, it results in a higher heating load in winter due to a decrease in solar absorption. This issue can be addressed by using thermochromic materials that can change surface colour and albedos based on the surrounding environment. The threshold between heat reflection and absorption is defined as the transition temperature. When the surface temperature is higher than the transition temperature, the surface colour of materials changes from a dark colour to a light colour, thereby increasing the albedo. It is well documented that the cooling performance of thermochromic materials remains high. For example, Ye et al. (2012) pointed out that a maximum reflection ratio of 33% and indoor temperature reduction of 6 °C caused by a thermochromic roof with a 32 °C transition temperature.

Currently, a typical way to change albedo is through the coating, which refers to a thin layer attached to the material surface. The albedo of reflective materials usually depends on coating materials and colours. Figure 3 compares widely used coating options, including tiles, shingles, metal panels, membranes, paint, and colours. In

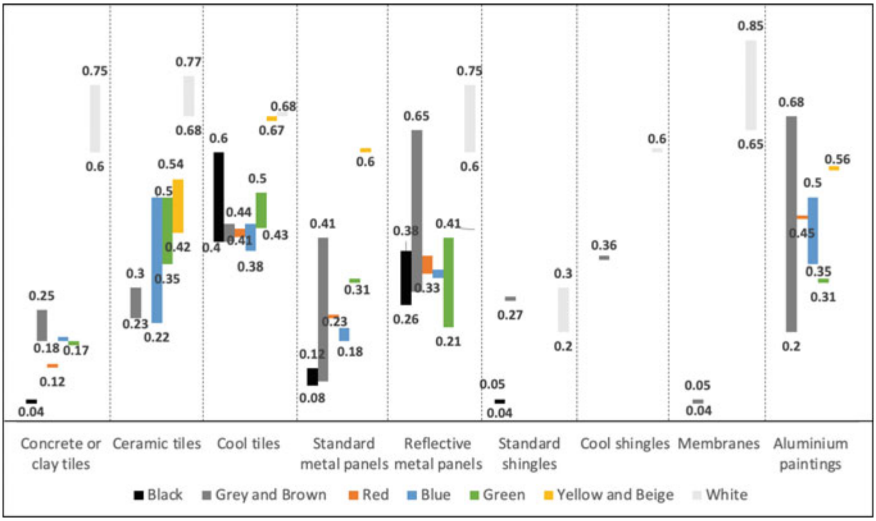

Fig. 3 Albedo characteristics of the coating materials (Qi et al., 2019)

general, the materials with white colour present high albedo that can reach 0.85. The main differences in albedo between those materials are non-white colours. For example, non-white coloured concrete and clay tiles are mostly characterised by low albedos, such as red (0.12), blue (0.18), and green (0.17). Comparatively, the albedos of non-white coloured cool tiles ranges from 0.38 to 0.6.

2.2.2 Heat Storage Materials

The long- and short-wave solar radiation absorbed by materials heightens the surface temperature, subsequently heating the ambient temperature via sensible heat transfer. One effective practice of ambient temperature reduction is to reduce peak heat fluxes and the energy released into the atmosphere by improving the thermal storage capacity of materials. The typical approach to storing thermal energy is using phase change materials (PCMs) that can be characterised into sensible heat, latent heat, and chemical energy (Zhang et al., 2007), as shown in Fig. 4. Solid–liquid PCMs using latent heat are suitable for application in practice own to their volumetric stability and high capacity of heat absorption (Qin, 2015).

The temperature at which phase changes or liquid–solid transitions occurs is defined as melting temperature, which can significantly influence the mitigation performance of PCMs. The optimum melting temperature differs from climate conditions. Figure 5 illustrates the optimum melting temperature and thermal stress reduction of PCMs in 24 cities under different climate zones. The results show the highest melting temperature in semi-arid climates (19.28 °C) and the lowest melting temperature in arid climates (15.60 °C). Likewise, the thermal stress reduction of the PCMs

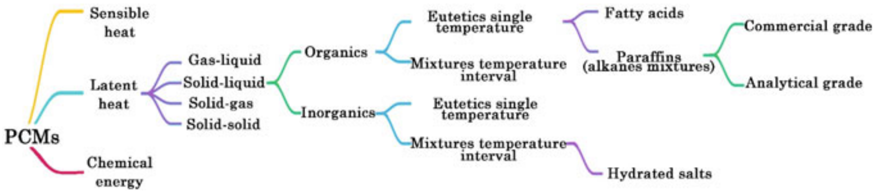

Fig. 4 Classification of phase change materials (Qi et al., 2019)

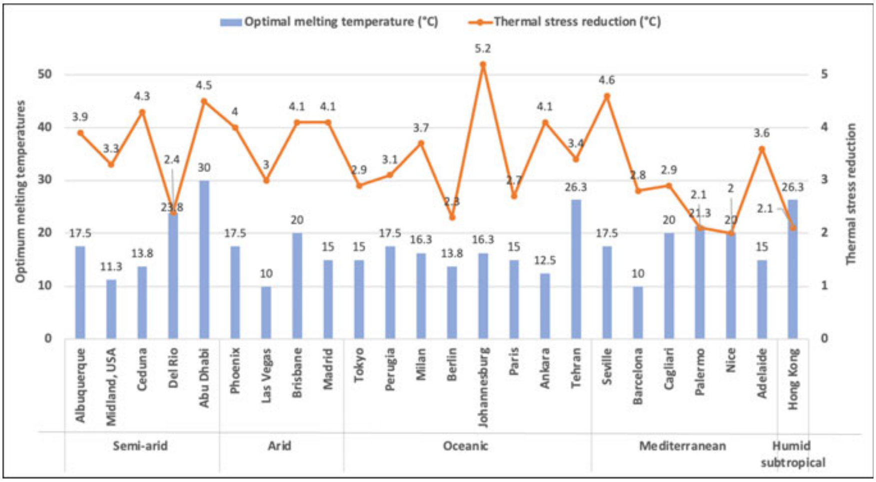

Fig. 5 The optimum melting temperature and thermal stress reduction of PCMs in 24 cities (*Source* Adapted from [Saffari et al., 2018])

with optimum melting temperatures varies significantly across the cities. Compared with other climates, PCMs at the optimum melting temperature in Mediterranean climates underperformed, possibly due to their less exposure to solar radiation (Jayalath et al., 2016).

In addition to thermal stress, existing studies have also explored the performance of PCMs on temperature reduction and energy consumption. Kuznik and Virgone (2009) developed PCM composite wallboards with a 13.6 °C melting temperature, which reduced the indoor temperature by 4.5 °C in comparison with regular wallboards. PCMs also have high performance in relation to energy efficiency since they reduce energy saving for cooling and heating. Song et al. (2018), for example, indicated energy savings for cooling (34.5%) in summer and heating (21%) in winter using a PCM-gypsum plasterboard.

A drawback of PCMSs is the high initial cost despite their low cost for maintenance and high durability (Qi et al., 2019). In addition to the high initial cost, it is argued that the heat absorbed by PCMs in the daytime may be released in the night, aggravating the night-time urban heat effect. Thus, the use of PCMs depends decidedly on the requirement of householders. To sum up, the use of PCMs can be an extremely helpful strategy to lower daytime peak indoor air temperature and reduce energy use if the optimal melting temperature can be defined. However, the disadvantages of high implementation cost and aggregation of night-time urban heat may affect the adoption of PCMs.

2.2.3 Heat Harvesting Materials

Heat harvesting suppresses energy released to the air, which gains a lower ambient temperature and other forms of energy, such as electricity. Some harvesting methods exist, including using photovoltaic (PV) materials and polyethene tubes (Van Bijsterveld et al., 2001). This research narrows its focus down to PV materials. PV materials are generally integrated with a transparent layer in the application, collectively called the PV system. There are two layers in the system. The top layer (e.g., glass) aims to protect the sublayer. The sublayer consists of several solar panels, converting light to other types of energy (Van Bijsterveld et al., 2001).

A PV system generally is installed on roofs; however, it shows lower cooling potentials than reflective roofs (Taha, 2013). Salamanca et al. (2016) concluded a temperature reduction (2 m height above roofs) of PV roofs with 0.2–0.4 °C, which is only half of the reduction (0.4–0.8 °C) provided by reflective roofs. The PV can also be applied on massive walls. Air gaps are commonly added between the PV panels and walls to remove the heat via natural ventilation. Roofs with air gaps present a lower roof surface temperature (7 °C) than roofs without the gaps (Wang et al., 2006).

Additionally, despite the relatively high initial cost of PV, the cost can be offset by energy return and durability. DOE (2016) concluded that PV has a long lifetime of up to 50 years and a low degradation rate ranging from 0.75 to 0.2%/year. In summary, the application of PV systems has low effectiveness on cooling potential. Although the cooling potential can be increased by adding a ventilated gap, the effectiveness is still limited in comparison with cool materials.

2.3 Building-Integrated Evaporative Cooling Towers

Using evaporative cooling in the private realm can be achieved by developing building-integrated evaporative cooling towers. The tower is an infrastructure attached to the building, as shown in Fig. 6. In general, the cold air drops down to the bottom of the building because of buoyancy forces, followed by reducing the air temperature in the lower part of the tower. The cold air subsequently flows into the indoor space for the cooling (Oropeza-Perez & Østergaard, 2018). In order to improve cooling efficiency, a sprayer device is installed at the tower top to cool the air. The average and maximum indoor air temperature reduction using evaporative cooling towers reach 1–4 °C and 3.5–7 °C, respectively (Santamouris et al., 2017). A planning and design variable considered in this research is the surface temperature

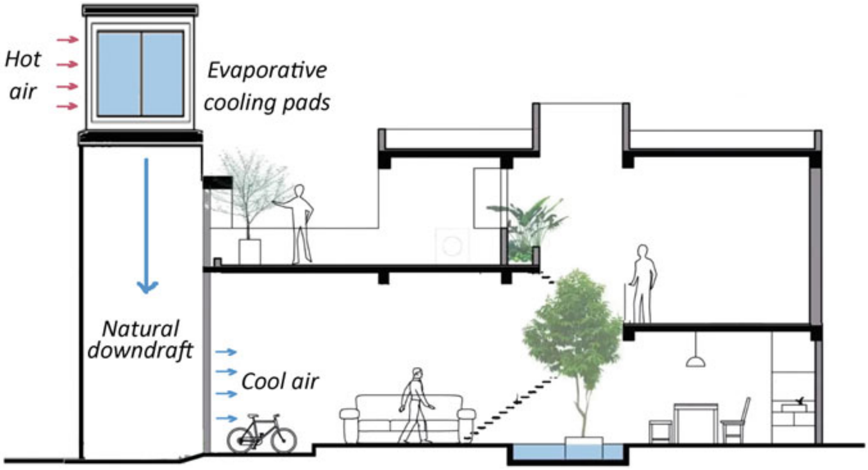

Fig. 6 Schematic view of the building-integrated evaporative cooling tower

of the evaporative cooling pads. The surface temperature can affect the air temperature in the cooling towers by heat convection. In general, lower surface temperatures have a larger amount of energy convection with hot air, leading to a higher cooling potential.

2.4 Building-Integrated Shading

Building-integrated shading can prevent the penetration of direct sunlight and solar radiation into buildings to achieve energy-saving and cooling purposes (Kuhn et al., 2001), as shown in Fig. 7. Cho et al. (2014) installed a horizontal overhang and a vertical panel in a high-rise residential building in Seoul, Korea. The results showed that the two exterior shading devices reduced cooling energy demand by 19.7 and 17.3%, respectively.

The planning and design variables of building-integrated shading in this research mainly focus on the shading structures and slat angle since they have significant impacts on the cooling load. Kim et al. (2012) measured the cooling load and energy efficiency of a three-storied building with three shading devices from March to September in Seoul, Korea. Compared with buildings without shading devices, the cooling loads of buildings with overhang, blind systems, and light-shelf devices were reduced by 19, 10.7, and 14.3%, respectively. Additionally, a low slat angle in blinds can save more energy for cooling purposes than a high slat angle. Kim et al. (2012) found that blinds with a slat angle of 0° reduced the cooling load by 70.2%, which was higher than those with the slat angle of 60° by 12.3%. The conclusion is that buildings with overhang structures and low slat angles may be very effective in achieving cooling potential.

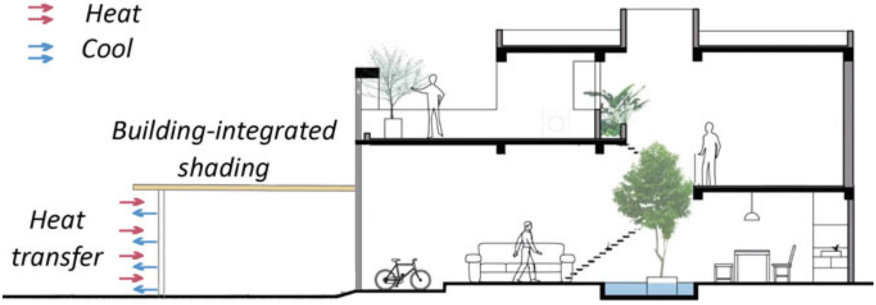

Fig. 7 Schematic view of building-integrated shading

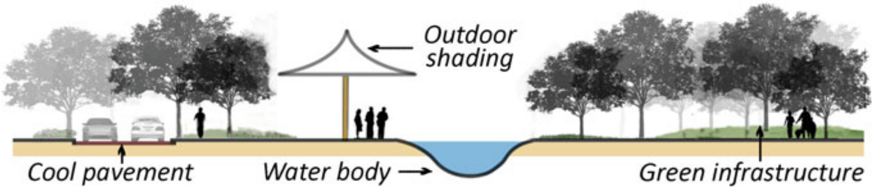

Fig. 8 Schematic view of urban heat mitigation strategies applied in the public realm

3 Urban Heat Mitigation Strategies Applied in the Public Realm

The public realm includes urban elements of streets, plazas, parks, and water bodies. This research focuses on four types of UHMSs applied in the public realm: green infrastructure, cooling pavements, water bodies and misting systems, and outdoor shading, as illustrated in Fig. 8.

3.1 Green Infrastructure Applied in the Public Realm

Green infrastructure applied in the public realm can be classified into green spaces, street trees, and greening parking lots, according to the place of application. The details of green infrastructure, including mitigation performance and planning and design variables, are explained in the following sections.

3.1.1 Green Spaces

The area surrounding green spaces, including protected or conserved land, is cooler than the area without nearby green spaces, which is named the park cool island (PCI)

(Jauregui, 1991). Studies showed that PCI intensity could reach 3.6 °C in Phoenix, USA (Chow et al., 2011); 6.7 °C in Addis Ababa, Ethiopia, (Feyisa et al., 2014); 3.8 °C in Chongqing, China (Lu et al., 2012); and 4.3 °C in Nagoya, Japan (Cao et al., 2010). In addition to their cooling potential, green spaces can also contribute to electricity energy saving. Buildings surrounding parks in Singapore consume 10% less electricity than those without nearby parks (Yu & Hien, 2006). Recently, increasing attention has been paid to exploring the impacts of green spaces on human well-being. Studies revealed that residents of neighbourhoods with abundant green spaces tend to enjoy better general health and lower mortality risk (Takano et al., 2002).

Table 1 summarises the planning and design variables for green spaces used in this research. One of the vital variables is vegetation species. Feyisa et al. (2014) compared the cooling performance of *Eucalyptus, Acacia, Cupressus, Grevillea*, and *Olea* in the 21 parks of Addis Ababa, Ethiopia. The difference between these species in PCI intensity could reach 6.6 °C. Similarly, Chow et al. (2011) measured the cooling potential of 13 tree species (e.g., *Brachychiton populneus, Citrus aurantium,* and *Eucalyptus microtheca*) with heights ranging from 5 to 12 m in Phoenix, USA. Results showed that cooling performance is affected by not only tree species but tree height also. Additionally, PCI intensity has a negative correlation with a park shape index, while it has a positive correlation with green ratio and park area, especially for parks over 14 hectares (ha) (Lu et al., 2012). To conclude, both tree species, tree height, shape index, green ratio, and park size can affect the performance of green spaces on cooling, energy saving, and human well-being.

3.1.2 Street Trees and Greening Parking Lots

Street trees and greening parking lots in this research are defined as the trees planted on the sides of streets and in parking lots, respectively. They can significantly lower ambient temperature and surface temperature through transpiration and shade effects (Loughner et al., 2012). Lin and Lin (2010) concluded that the air temperature under a tree canopy was 2.5 °C lower than the unshaded open space in summer. Ca et al. (1998) pointed out that greening parking lots lowered land surface temperature by 15 °C and air temperature 1.2 m above the ground by 2 °C compared with concrete-covered lots in summer in Tokyo, Japan. The high cooling performance of greening parking lots could further be improved at night in comparison with the daytime because of the reduced sky view factor inhibiting longwave cooling at night (Bowler et al., 2010).

The cooling potential of street trees and greening parking lots considerably depends on tree species, tree height, and green coverage ratio (Table 2). Lin and Lin (2010) compared the cooling effects of 12 different tree species in Taipei. The results showed that the difference between those species in air temperature reduction could reach 1.9 °C. A comparison of 12 different tree species at Campinas, Brazil, revealed that the air temperature reduction ranged between 0.9–2.8 °C in summer and 0.1–2.4 °C in winter. Additionally, tree height related to tree canopy decides the extent of the shading area, thereby influencing the cooling area. By comparing

Table 1 Planning and design variables of green spaces

Variables	Location	Number of green spaces	Attribution	PCI intensity (°C)	References
Tree species	Phoenix	1	13 tree species	0.7–3.6	Chow et al. (2011)
	Addis Ababa	21	5 tree species	0.1–6.7	Feyisa et al. (2014)
Tree height	Phoenix	1	5–12 m	0.7–3.6	Chow et al. (2011)
Shape index	Chongqing	6	1.24–2.49	0.2–3.8	Lu et al. (2012)
	Nagoya	92	1.01–5.76	0.1–4.3	Cao et al. (2010)
Green ratio	Chongqing	6	64–99%	0.2–3.8	Lu et al. (2012)
	Addis Ababa	21	>60%	0.1–6.7	Feyisa et al. (2014)
Park area or size	Chongqing	6	1.2–45 ha	0.2–3.8	Lu et al. (2012)
	Nagoya	92	0.1–41.9 ha	0.1–4.3	Cao et al. (2010)
	Addis Ababa	21	0.8–22.3 ha	0.1–6.7	Feyisa et al. (2014)

the trees with heights ranging from 2 to 11 m, Huang and Li (2017) concluded that the air temperature difference between varying tree heights could be 0.1 °C in the summertime in Taipei. Other studies have also explored the relationship between temperature reduction and green coverage ratio. Takebayashi and Moriyama (2009) pointed out that greening parking lots with green coverage ratios of 6%, 10%, 20%, and 30% lowered air temperature by 0.1, 0.2, 0.3, and 0.5 °C, respectively compared with those without grass at 1 pm in Kobe, Japan. To summarise, tree species, tree height, and green coverage ratio highly impact cooling performance.

3.2 Cool Pavements

Cool pavements are "the paving materials that reflect more solar energy, enhance water evaporation, or have been otherwise modified to remain cooler than conventional pavements" (Qin, 2015). There are several types of cool pavements, such as reflective pavements, PV pavements, and permeable pavements. One of the widely used types is the reflective pavement due to its low cost and easy application (Qi et al., 2019). Existing studies have evaluated the performance of reflective pavements by measuring surface temperature reduction. For example, Santamouris et al. (2012a)

Table 2 Planning and design variables of street trees and green parking lots

Variables	Technical details	Average air temperature reduction (°C)	References
Tree species	Trees representing 12 species (e.g., *Alstonia scholaris, Ficus elastica, and Bambusa vulgaris*) in Taipei, China	0.6–2.5	Lin and Lin (2010)
	Trees representing 12 species (e.g., *Pinus palustres, Lafoensia, and Spathodea*) in Campinas, Brazil	0.1–2.8	De abreu-harbich et al. (2015)
Tree height	Street trees of 2–11 m height at Taipei, China	0.1	Huang and Li (2017)
Green coverage ratio	Parking lots with green coverage of 6%, 10%, 20%, and 30% in Kobe, Japan	0.1–0.5	Takebayashi and Moriyama (2009)

found that replacing conventional concrete and asphalt with white reflective materials on pavements reduced the land surface temperature by 12 °C in Athens, Greece. In comparison, few efforts have been devoted to evaluating the effects of reflective pavements on air temperature (Qin, 2015). The limited studies revealed that reflective pavements could reduce the average ambient temperature of up to 01 °C (Georgakis et al., 2014).

The cooling performance of reflective pavements mainly depends on the material's albedo, which is determined by several variables, including surface colour and construction materials. Colour is one of the most high-impact variables of material albedo. Light-coloured surfaces generally have a higher albedo than dark-coloured surfaces. Taking asphalt as an example, changing surface colour from black to white increases the albedo of 0.24, reducing a diurnal surface temperature reduction of 7.7 °C in Athens (Synnefa et al., 2011). However, it is noted that some black materials (e.g., Near-infrared materials) can have a high albedo because of their high reflectance in near-infrared light with more energy than the visible spectrum (Kinouchi et al., 2003). For example, Kinouchi et al. (2003) developed a dark-coloured asphalt for pavement coating with a high albedo (0.7).

The surface texture, thickness, and construction materials also affect albedos. Changing surface roughness presents slight impacts on albedo and limited temperature reduction. Taking concrete albedos as an example, replacing a rough surface with a smooth one increases the albedo by 0.13 (Alchapar et al., 2013) and a surface temperature of less than 1 °C. Likewise, modifying surface pattern with rustic yellow concrete from 'straight diagonal surface' and the 'flat start surface' shows negligible impacts on albedo variation of only 0.03 (Alchapar et al., 2013). The impact of thickness on albedo variation is dependent on the number of layers changed. Just modifying the thickness of the single layer is not enough to increase the albedo (Li et al., 2013a), while changing both the thicknesses of the paver and sublayer increases the albedo. Li et al. (2013b) changed a paver from 6 to 8 cm and a bedding layer from 4 to 2 cm to obtain an increase in the albedo of 0.03 and a decrease in surface temperature (2 °C). For construction materials, concretes and natural stones consistently show higher albedos than asphalt. For example, white concrete tiles and natural stone presented a higher albedo of almost 0.55 and 0.43, respectively, than the white asphalt shingles (Santamouris et al., 2011).

To sum up, surface colour and construction material can significantly affect albedo, while increasing albedo through the change of surface texture and thickness is quite limited. Additionally, the initial implementation cost of reflective materials is relatively cheap, ranging from $0.2 and $6.0 per square foot (Foster et al., 2011). The low lifecycle cost of reflective materials can also arouse the stakeholders' interest. For instance, new reflective pavements can be used for up to 10 years without resurfacing, saving $0.07/m^2 per year (Akbari, 2005).

3.3 Water Bodies and Misting Systems

This section explains how to apply evaporative techniques to gain urban heat mitigation in the public domain. It focuses on the use of water bodies (e.g., ponds) and misting systems (e.g., sprayers).

3.3.1 Water Bodies

Water bodies lower the ambient temperature by heat convection between the ambient temperature and the water surface. Specifically, intense solar radiation during overheating is capable of increasing the water surface temperature. With the increase in water surface temperature, water evaporation accelerates and then absorbs a vast amount of latent heat. Studies have shown that the cooling potential of latent heat derived from the surrounding water is almost 600 times higher than that of sensible heat (Santamouris & Kolokotsa, 2016). The considerable heat absorption in evaporation allows the ambient temperature to be significantly reduced. Al-obaidi et al. (2014) pointed out that evaporating 1 kg of water could decrease the temperature of 2000 m^3 of water by 1 °C.

The ambient temperature reduction of water bodies can be affected by many factors, such as the surrounding environment and the area of water bodies, as described in Table 3. The cooling effects primarily depend on the area of the water body. Larger water areas have more opportunities to absorb heat and reduce the amount of energy reflecting the building surface, leading to high cooling effects. For example, Theeuwes et al. (2013) pointed out that cities covered with 5, 10, and 15% of water areas, presented 15.9, 22.9, and 26.2% impacted areas, respectively. Despite the high cooling potential of large water bodies, they are not suitable in cities due to the high cost and limited availability of space in urban area. Increasing the number of small water bodies such as ponds and pools in street landscaping and gardens can be an appropriate strategy for cities because of their low space demand. However, the cooling effects of small water bodies are quite limited. Cao et al. (2010) found that the cooling potential was negligible if the water body was less than 2 hectares in area.

Regularly shaped water bodies have a higher cooling performance than those with irregular geometries. Sun and Chen (2012) calculated the landscape shape index of 197 water bodies using ASTER images. The study pointed out that the water bodies with square and round shapes were more effective because the regular shape generates a large gradient of humidity and temperature between water bodies and the surrounding areas. Additionally, the surrounding environment is also important for cooling performance. Hathway and Sharples (2012) found that the water bodies surrounding vegetation presented higher cooling potentials than those without vegetation since the photosynthesis and evaporation of vegetation absorb a great amount of heat energy. However, the role of buildings surrounding water bodies in the thermal environment is quite controversial. On the one hand, water bodies near high-density buildings have high cooling intensity. The dense buildings generate a significant volume of heat, thereby increasing the surrounding ambient temperature, while the temperature of the water is relatively stable. The large gradient of water bodies and the surrounding temperature leads to high cooling intensity (Sun & Chen, 2012). On the other hand, water bodies surrounding areas of low building density have extensive impacted areas (Murakawa et al., 1991). Compared with high-density areas, low-density areas with more open space have better ventilation, which increases the propagation of cooling (Hathway & Sharples, 2012).

Table 3 Planning and design variables of water bodies

Variables	Technical details	Findings	References
Area of water bodies	• Assessing the impacted area in cities with 5, 10 and 15% water area • Assessing the cooling effects of the park with water and those without water	• Cities with 5, 10 and 15% of water areas have 15.9, 22.9 and 26.2% impacted areas respectively	Theeuwes et al. (2013), Cao et al. (2010)
The shape of water bodies	• Assessing the cooling potential of 197 water bodies with different landscape shape indexes in Beijing	• Regular geometries of water bodies have higher cooling potential than irregular ones	Sun and Chen (2012)
Surrounding environment	• Assessing the cooling potential of the water bodies distributed near CBD • Monitoring the air temperature of four regions near a river	• The cooling effect is stronger near the CBD; • A river with vegetative banks gains more cooling	Sun and Chen (2012), Murakawa et al. (1991), Hathway and Sharples (2012)

3.3.2 Misting Systems

Misting is a way in which water can be sprayed directly into the air or onto a land surface. Hendel et al. (2016) compared the ambient temperature above pavements of those spayed with water and those not sprayed at two sites in Paris, France. The results showed that spaying pavement reduced the average ambient temperature by 0.22 °C on a typical summertime day. The cooling potential can be enhanced by combining a spraying device with water bodies. Nishimura et al. (1998) found that combing a waterfall and spray fountain dropped average air temperature by up to 2 °C. A combination of fountains and sprayers used by Chatzidimitriou et al. (2013) achieved maximum and average air temperature reduction of 7.1 and 1.9 °C, respectively, in summer at Thessaloniki, Greece.

Table 4 shows the planning and design variables for misting systems that are covered in this research. The predominant variable is the water flow rate. Montazeri et al. (2017) compared the cooling performance of the misting systems with the flow rate by 2.25, 4.50, and 9.0 L/min. The result showed that when the water flow rate was 9.0 L/min, mist spray systems gained the maximum cooling with temperature reduction of 7 °C in Rotterdam, Netherlands. Thus, an increase in water flow rate leads to high cooling potential.

Additionally, water particle size affects the impacted areas of misting systems. Yamada et al. (2008) investigated the cooling performance of sprayers with 16.9, 20.8, and 23.6 μm Sauter at the same height. The results showed that although the temperature reductions of these sprayers were similar in the study, the minimum height of mist particles varies significantly. This means that a larger spray water particle size corresponds to a lower minimum height of mist particles and extensive impacted areas (Yamada et al., 2008).

Table 4 Planning and design variables of misting systems

Variables	Technical details	Performance	References
Water flow rate	Measuring the cooling effects of mist spray systems with flow rate by 2.25, 4.50, and 9.0 L/min	• A high water flow rate presents more cooling	Montazeri et al. (2017)
Water particle size	Comparing the temperature reduction and the minimum height of mist particles on spaying with 16.9, 20.8 and 32.6 μm Sauter mean diameter	• The average air temperature reduction is similar • The larger diameter has a lower minimum height of mist particles	Yamada et al. (2008)

3.4 Outdoor Shading

Outdoor shading can block solar radiation and reduce surface temperature, which further lowers the ambient temperature and improves thermal comfort in the public realm. In general, shading may be provided by natural (trees) or artificial structures. Based on the shading structure, it can be divided into the tree canopy and light-coloured shading (Osmond & Sharifi, 2017). Since the shading effects of tree canopies have been discussed in Sect. 3.1, this section mainly focuses on the mitigation performance of light-coloured shading.

Light-coloured shading provides cooling by reflecting solar radiation and reducing the incident radiation. It has significant impacts on surface temperature reduction. Osmond and Sharifi (2017) have pointed out that the maximum surface temperature reduction by light-coloured shading could reach 15 °C. However, the specific performance varies across the coating materials (Osmond & Sharifi, 2017), which is defined as the planning and design variable for outdoor shading in this research. The details of coating materials have been provided in Sect. 2.2. Additionally, the impacts of light-coloured shading on outdoor thermal comfort varies according to the time of day. Vartholomaios and Kalogirou (2020) concluded that the influence of shading on outdoor thermal comfort was minimal during sunrise and sunset due to the low solar radiation intensity. However, the impact was significant during the afternoon since the enormous amount of solar radiation in this period could effectively be intercepted by shading surfaces. Unfortunately, due to the limited studies on outdoor shading, the nature of the impacts, for example, economic ones, are still unclear (Vartholomaios & Kalogirou, 2020).

4 Combination of Urban Heat Mitigation Strategies

Recent studies indicated that the combined use of UHMSs could present a higher temperature drop than the use of individual UHMSs (Santamouris et al., 2017). Table 5 illustrates some of the possible UHMS combinations and their reported performance in the existing literature. Reported performance data show that water-based UHMS combinations present high cooling potential. Chatzidimitriou et al. (2013) indicated that combining green spaces, cool pavements, water bodies, and misting systems reduced the average air temperature by 1.9 °C in the summer of Thessaloniki, Greece. Zoras et al. (2015) simultaneously employed cool pavements, cool roofs, and misting systems to gain an air temperature decrease by 0.6 °C. Similar results have been documented by Amor et al. (2015) and Martins et al. (2016) and show that a combination of water bodies and misting systems could reduce air temperature by 0.9–2 °C.

UHMS combinations related to cool pavements also contribute strongly to urban heat mitigation. The average air temperature reduced by a combination of green roofs and cool pavements was higher than 0.1 °C and could reach 0.9 °C in some cases

Table 5 Characteristics and reported performance of combinations of urban heat mitigation strategies

No.	Strategy combinations	Average air temperature reduction (°C)	References
1	Green roofs and cool pavements	0.1–0.9	Sailor (1995), Santamouris et al. (2012), Zhou and Shepherd (2010)
2	Green spaces and cool pavements	0.6	Chatzidimitriou et al. (2013)
3	Green spaces, water bodies, misting systems, and cool pavements	1.9	Chatzidimitriou et al. (2013)
4	Cool roofs, street trees, and cool pavements	0.2–0.4	Stone Jr et al. (2014)
5	Water bodies and misting systems	0.9–2	Amor et al. (2015), Chatzidimitriou et al. (2013), Martins et al. (2016)
6	Cool roofs and cool pavements	0.1–0.9	Millstein and Menon (2011), Wang et al. (2016)
7	Cool roofs, cool pavements, and misting systems	0.6	Zoras et al. (2015)

(Sailor, 1995; Santamouris et al., 2012; Zhou & Shepherd, 2010). Similar cooling performance can be achieved by combing cool roofs and cool pavements (Millstein & Menon, 2011; Wang et al., 2016).

In addition to cooling performance, existing studies have also explored the impacts of UHMS combinations on energy efficiency and human health. Shahidan et al. (2012) combined green spaces with a leaf area index of 9.7 and cool pavements with an albedo of 0.8 in Putrajaya, Malaysia, and showed that this combination produced a building cooling load reduction of up to 29%. Additionally, Stone Jr et al. (2014) concluded that combining cool roofs and pavements reduced heat-related mortality by 40% in Atlanta and Philadelphia, USA. Therefore, UHMSs combinations can be an extremely useful weapon to counterbalance urban heat problems if the high-performance combination can be identified.

5 Conclusions

This study reviewed four types of passive UHMSs (i.e., greenery, cool materials, evaporation techniques, and shading devices) and discussed their definitions, mitigation performance, planning and design variables, and cost benefits based on the place of application, including private realm, public realm, and combinations.

In the private realm, building-integrated green infrastructure or courtyard greenery (i.e., green roofs and vertical greening systems) have high performance in microclimate amelioration and energy conservation up to an air temperature reduction of 1.2 °C, roof surface temperature reduction of 12.8 °C, and energy saving of 43%. The performance can be affected by the variables of vegetation species, coverage rates, and physical structures. Cool materials for buildings or hard surfaces, consisting of reflective materials, heat storage materials and heat harvesting materials, also show high cooling potential. Reflective materials generally have higher cooling effectiveness and lower initial cost than heat storage materials and heat harvesting materials. The cooling potential of reflective materials predominantly depends on the albedo of materials, which varies significantly across the coating materials and colours. The main impacts of building-integrated evaporative cooling towers are indoor air temperature reduction. If the surface temperature of the evaporative cooling pads is cooling enough, the average and maximum reduction can be up to 4 and 7 °C, respectively. Building-integrated shading can reduce 70.2% the cooling load if the shading structures and slat angles can be defined properly, such as buildings with overhangs and blinds (a slat angle of 0°).

In the public realm, green infrastructures, such as green spaces, street trees and green parking lots, present positive effects on cooling, energy saving, and human well-being. The green infrastructures can reach PCI intensity of 6.7 °C and a 10% reduction in electricity use. Their performance relates to tree species, tree height, shape index, green ratio, and park size. The cool pavements, surface colour and construction material have been widely applied due to high cooling performance and low initial and maintenance costs. Surface colour and construction material can significantly affect albedo, while increasing albedo through the change of surface texture and thickness is quite limited. The water bodies and misting systems have high cooling performance in ambient temperature reduction because of the high cooling potential of latent heat. The main variables for cooling include many factors, such as water flow rate, water particle size, the area and shape of water bodies, and the surrounding environment. Outdoor shading is provided by natural (trees) or artificial structures and can be classified into the tree canopy and light-coloured shading. However, due to the limited studies on outdoor shading, the nature of some impacts is still unclear.

A combination of UHMSs may have a better performance than the single one. For example, a joint application of green spaces, water bodies, misting systems, and cool pavements reduce the average air temperature of 1.9 °C. Cool pavements have been widely used in combinations, which also contribute strongly to cooling load reduction and heat-related mortality. Due to the limited studies on UHMS combinations, this study only discussed the seven types of combinations. Considering the high cooling potential provided by combinations, future studies should devote more effects to exploring the optimal combinations for urban heat mitigation.

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Chapter 3
Biophilic Design: Pinpointing Nature-Based Techniques in Urban Areas to Combat Global Warming

Abdollah Baghaei Daemei, Masoumeh Mazandarani, and Mahshid Motamed

Abstract The rate of global warming has increased rapidly in recent decades, and experts agree that climate change is exacerbating dangerously high temperatures around the world, which will ultimately lead to an increase in urban heat islands (UHI), longer warm seasons, and severe health-related issues. This study aims to provide strategies, exemplars, and approaches to tackle the mentioned problems. Hence, this research proposed biophilic design elements as a promising technique to mitigate UHI resulting from global warming, to examine the importance of vegetation and plants in urban areas. The Rhino software, and Grasshopper and Ladybug plug-ins have been deployed to simulate UHI; referred to as Urban Weather Generator (UWG). The humid climate of Rasht was selected as an example of the study area in this research. Thus, findings showed that adequate vegetation could help drop the average monthly temperature by approximately 2 °C, and this mean temperature could vary between 9 and 19 °C annually.

Keywords Biophilic design · Nature-based strategies · Urban areas · Global warming · Cooling cities · Urban Heat Island

1 Introduction

Global warming and climate change have caused severe disruptions in the built environment worldwide (Rantanen et al., 2022). Numerous studies proclaim that, by increasing public awareness, optimal consumption of fuel and energy, preventing the

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destruction of forests and increasing the extent of green spaces, recycling materials, and using alternative energies instead of fossil fuels, global warming and its adverse effects on human life may be controllable (Abbasi & Abbasi, 2011; Zhang & Zhai, 2022).

Tackling this long-term phenomenon, which is considered to be a robust fact and severe problem, requires continuous research and in-depth studies. Thus, employing approaches such as various international attempts to stop global warming in order to protect human civilization from possible future crises remains vital. To address these all-pervasive, a vast range of scientific reports have already been implemented as part of the long-term vision. Sustainable development goals (SDGs) and indicators consist of a set of seventeen global goals for 169 specific areas, which require an urgent call for action by all countries (Stafford-Smith et al., 2017; UN, 2022).

Consequently, it is necessary to develop a sustainable framework by evaluating extensive architectural techniques as comprehensive guidelines to make better decisions in terms of urban planning. Several approaches work together to bring about the expected consequences in terms of architectural design and configuration (Díaz-López et al., 2022). Biophilic design patterns can potentially reposition the environmental quality conservation to satisfy occupants' needs in equal consideration, in addition to conventional parameters for enhancing building performance (Ghaziani et al., 2021).

Hence, in architectural and urban design, biophilic design strategies (BDS) are sustainable design approaches that incorporate reconnecting people with the natural environment. Hereafter, the question arises as to how individuals and urban areas can benefit from the results of this study to improve the overall performance of cities through the role of biophilic design? Therefore, the primary aims of this chapter are divided into four phases: (a) Formulating the key elements of biophilic design and its current theories; (b) Scrutinizing a number of successful exemplars regarding biophilic design worldwide as case studies; (c) Providing a framework to promote a health-based population, and cities based on the concept of biophilic design; and (d) Analyzing the impact of plants and vegetation on reducing outdoor temperatures and mitigating UHI.

2 Global Warming: Concepts and Elements

The exhaustion of freshwater resources around the world ringed warning bells of the deglaciation era. In this context, biophilic design is considered as a new paradigm attempt to present a new solution. There are four main environmental factors to assess the environment's thermal comfort including: *dry bulb temperature*, *humidity*, *airflow*, and *radiant exchange*; and two personal aspects, namely *clothing* and *metabolism*. However, other criteria must also be taken into account regarding outdoor thermal comfort. Table 1 explains the parameters which affect biophilic design, namely Outdoor Thermal Comfort (OTC), Urban Heat Island (UHI), and Heat Stress Effect (HSE).

Table 1 Explanation of OTC, UHI, and HSE

	OTC	UHI	HSE
Aspects	Physical, Physiological, Psychological, and Social Parameters	Urban atmospheres Urban anthropogenic heat Impacts of global warming Latitude and regional climate	Extreme cold/ heat Indoor conditions Shaded outdoor conditions Metabolic heat production Heat exchange with the environment
Caused by	Microclimate Design Guidelines, and Urban Planning Regulations	Urban structures High thermal mass emitted by concrete and asphalt roads Low ventilation capacity Vehicle and air conditioner exhausts Heatwaves during extreme heat event days in the summer Changing the thermal environment in the city Exposing people to heat stress	Materials characteristics of buildings Energetic performances of buildings Vacuum insulation systems Reflective materials
Results	Outdoor Ambiance, City’s Liveability, Sustainability, and Outdoor Ambiance	Higher degree in downtown Absorbing and reradiating solar radiation	Thermal sensation

As indicated above, urban thermal comfort is heavily influenced by UHI, and biophilic design seeks to decrease UHI to the minimum extent possible. Studying urban heating, especially UHI, has been conducted in detail to determine the major role that heat re-radiated by urban structures plays. There is a wide range of factors contributing to UHI, and numerous approaches to control it, and this paper has focused on VGS as one of the significant biophilic design elements.

One of the essential issues in future urban design that designers and policymakers should consider is comprehending the key role of climate change (CC), and its impact on the functioning and formation of patterns in nature. The harms of the abovementioned issues on human health have already been proven. Environmental health-related diseases such as heat-related illnesses (Graczyk et al., 2022; He et al., 2022), expanding allergens (Agache et al., 2022; Dawson et al., 2022), drinkable water quality-related diseases (Khurana & Sen, 2021; Miyoshi et al., 2022), environmental degradation (Kaushal et al., 2021), or vector-borne diseases (Tourapi & Tsioutis, 2022), are part of the health challenges associated with CC.

Accordingly, the adverse effects associated with CC, its role on the health and well-being of various societies, as well as vital goals such as SDG3 (Good Health and Wellbeing) and SDG13 (Climate Actions) must be taken into consideration. These are some of the aims that sustainable development is trying to attain as much as possible around the world (Leal Filho et al., 2021).

Research shows that the mentioned factors related to CC threaten the quality of life of millions, especially low-income people, worldwide (Akhtar, 2020; Herring et al., 2018; Javadinejad et al., 2020; van Woezik et al., 2016). Figure 1 shows the probable relationship between the risk factors related to the issue of CC throughout the world, and sustainable development measures against these critical changes.

According to Fig. 1, *part a* of the chart signifies the risks and effects caused by CC, sequentially and simultaneously on human societies and ecosystems. In *chart b*, beneficial practices and opportunities for the future of CC are presented, which can be described as follows:

> Diagram (a): CC causes changes in human societies, and subsequently causes ecosystem destruction and loss of biodiversity all over the world. Also, ecosystem destruction threatens human societies in the same way. CC, through the creation of potential and actual risks, causes various communities to become exposed and vulnerable, regardless of race, wealth, etc., which can exceed controllable and adaptive limits and lead to a severe loss of life. Human societies can adapt, become incompatible, or even reduced to a significant extent through adopting different approaches to face CC. Also, ecosystems, as responsive collections, can adapt to limitations and be effective in reducing them. Ecosystems and their biodiversity have many effects on the presence and growth of communities.
>
> Diagram (b): Beneficial procedures and opportunities for the future of CC are presented, and by implementing these approaches, the seventeen goals of sustainable development, especially the support of human health, ecosystems, and the well-being of human societies will be provided. This approach requires flexible climate policies along with the diagnosis of climate risk factors to consolidate adaptation and mitigation of climate risks. Most of these measures should be

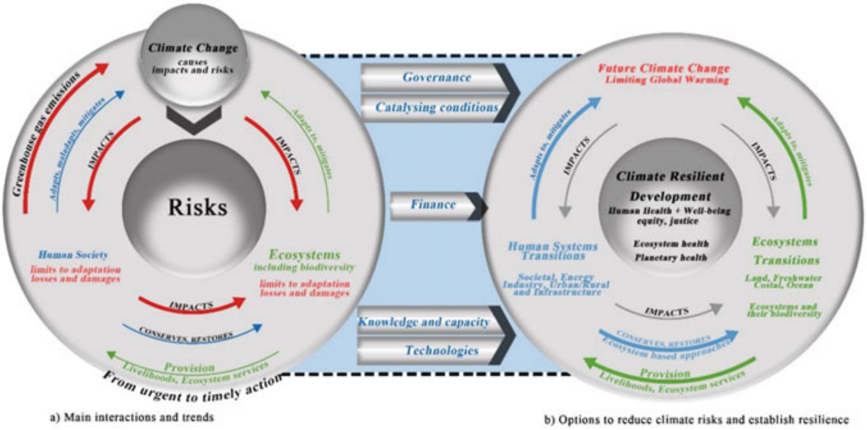


Fig. 1 interactions among the system factors of climate, and other related issues (Pörtner et al., 2022); developed by the authors

> taken by governments, and it is possible for them to do so according to financial categories, knowledge and capacity building, technology, and examination of conditions. Transformation requires shifting the system from inflexible to flexible.

Intergovernmental Panel on Climate Change (IPCC) has expanded a whole nomination to characterize the certain assurance of their intuitions. Achievements are estimated most probably using witnessing, modeling results, or expert adjudication. They are given a rule on a scale continuum ranging from *exceptionally unlikely* to *virtually certain.* IPCC measures certainty using the likelihood criterion in 10 categories (Change, 2007). Some theories presented in the field of classification of CC risks have divided them into three categories of *short-term risks* (2040–2021), *medium-term risks* (2060–2041), and *long-term risks* (2081–2100) (Pörtner et al., 2022). Some other theories in the field of CC divide them into the three categories of *high-intensity effects*, *long-terms effects*, and *changes with uncertain impacts.* This classification shows the priority of the parameters that should be considered for practical actions in the schedules made by countries, and public and private institutions. Therefore, this view is in favor of a short-term and long-term policy approach toward dealing with CC. Figure 2 depicts the global warming process depending on a set of factors.

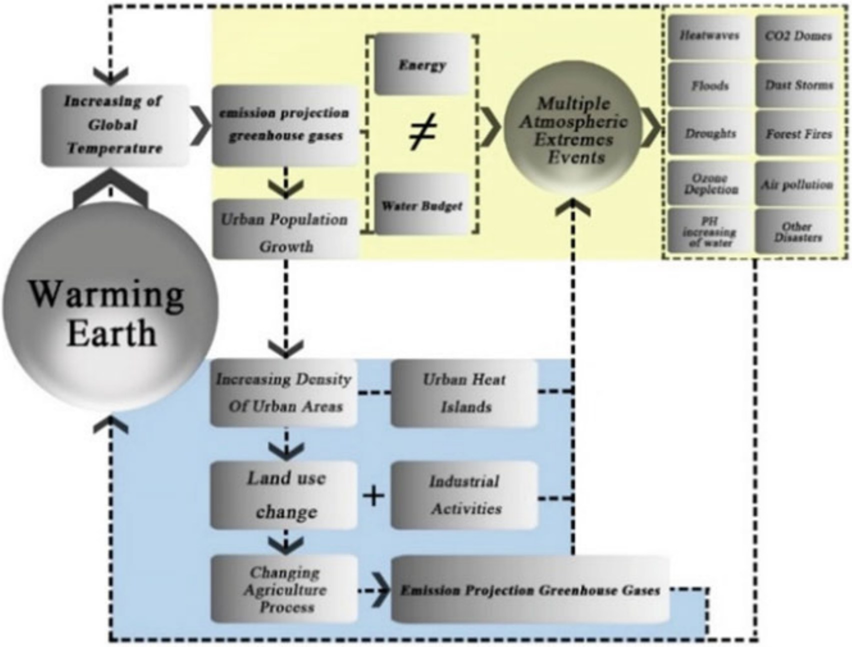


Fig. 2 The general structure between global warming and human activities (Al-Ghussain, 2019; Kang et al., 2022; Zhou, 2022); developed by the authors

Fig. 3 Variables related to CC Vulnerability (Ho et al., 2022; Jamwal et al., 2022; Nájera-González & Carrillo-González, 2022; Nandintsetseg et al., 2021); developed by the authors

In the following, the main variables of CC that have a great impact on urban design mechanisms and conditions are *dry and wet temperatures*, *relative humidity*, *amount of precipitation*, *wind speed and direction*, *type of wind*, *number of waves*, and *amount of tide* (Fig. 3).

3 Biophilic Design Performance to Mitigate UHI

Spatial relationships enhance well-being through the experience of space and place. For this reason, design disciplines use biophilia in order to enhance user experiences. Zhong et al. (2022) declared that due to growing environmental concerns, biophilic design has received widespread attention in architecture over the past decade. As Kellert et al. (2011) defined, the new design paradigm is referred to here as "restorative environmental design", which emphasizes both minimizing and mitigating adverse environmental effects, as well as fostering a beneficial contact between people and nature in modern buildings and landscapes through implementing a positive environmental impact or biophilic design approach.

Wilson developed the concept of biophilia and popularized it in his publication; he explained biophilia as "the innate tendency to focus on life and lifelike processes" (Wilson, 1984). Although the very first published paper on biophilia was concerned with its social aspects (Desouza & Flanery, 2013; Kellert & Calabrese, 2015), more recent investigations progressed on to scrutinize the realm. Meanwhile, Kellert (2018) declared that biophilic design is about addressing the deficiencies of contemporary building and landscape practices by establishing a new framework for enhancing the presence of nature in the built environment. In the contemporary built environment, biophilic design aims to create a decent habitat for people to promote their health, fitness, and well-being. As Mollazadeh and Zhu (2021) explained, rapid urbanization has had a significant impact on human health, and has affected the lives of many people. By 2050, the current population growth rate is projected to add 2.5 billion people to the world's population.

3.1 Concepts and Strategies

According to the mentioned issues, the five rules for how urban areas following the NBS approach are adjusted and propounded, and based on the five particular urban challenges have been outlined. These rules have been approved based on the multilateral interaction between several disciplines related to the city, such as *urban ecology*, *urban design*, *urban planning and governance*, and *urban sociology*. Although these five rules are suggestions, they should be considered as a complete and interactive group, and it is not possible to employ any of them separately. They are closely interrelated and sometimes overlapping. The path toward achieving a number of them is common, but at the same time, they have subtle differences regarding some basic aspects. This fact indicates that NBS planning in cities should be carried out carefully (Frantzeskaki, 2019; Tzoulas et al., 2021; van der Jagt et al., 2020). The next figure illustrates the function of the five rules for urban NBS.

In the mentioned Fig. 4, rule 1, as a commander rule entitled "systemic understanding", underlies all other conditions and rules. Rule 2 shows that "benefiting people and biodiversity" should aim to provide an equilibrium supply of various benefits to both humans and non-humans. The realization of rule 2 is based on the realization of the local context and concept (rule 4: context consideration), and is not possible without it. Rule 3 is presented as a long-term solution to make NBS sustainable over time. Rule 5 refers to the very serious issue of "communication and learning", which depends on the compromise, agreement, and support of a wide range of people in society; therefore, it is related to rule 3 "self-inclusive solutions for the long-term." The formerly mentioned rule 4 "context consideration" and rule 5 "communication and learning" are interactively and adaptively related to one another (Dorst et al., 2019) (see Fig. 4).

The concept of providing comfort with an energy approach, or in other words thermal comfort, is quite essential in the urban climate, but in most situations, the concept faces many limitations that challenge researchers. OTC and UHI are the two essential areas for research in city and urban design. The UHI effect is a known weather phenomenon that creates warmer temperatures in urban areas than in nearby rural areas. Generically, it is crucial to fundamentally changing the type of questions in this field, and for researchers to try to find answers using a new perspective. Therefore, not only are the issues of energy and thermal comfort in the urban environments (or UTC) and UHI important, but it seems necessary to take immediate

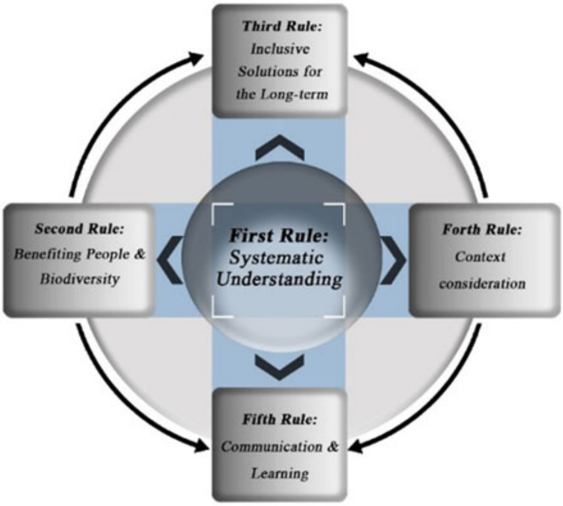


Fig. 4 Five rules for nature -based urban solutions of planning (Dorst et al., 2019)

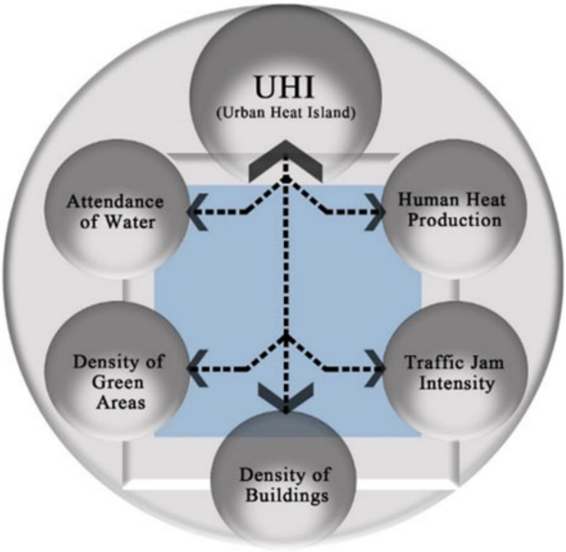


Fig. 5 Five main indexes are introduced in the field of UHI (Mahdavi et al., 2016); developed by the authors

action. Figure 5 illustrates five primary indexes which are introduced in this field, namely *density of buildings*, *human heat production*, *traffic jam intensity*, *the density of green areas*, and *the attendance of water in places* (Mahdavi et al., 2016).

4 Case Study Examples

The effects of destruction of nature along with the population and information congestion of the present age have caused many physical, psychological and social consequences and with exorbitant costs of human life and have caused many countries to gradually develop programs for the revision of nature.

Attention has been paid to the view of the presence of nature in urban contexts, even in recent decades and perhaps centuries. The following description (Table 2) identifies several buildings which had been built and designed by the six biophilic design elements namely environmental features, natural shapes and forms, natural patterns and processes, light and space, place-based relationships, and evolved human-nature relationships (Kellert et al., 2013, p. 5).

Design based on biophilic principles is not limited to architecture. But now the world is witnessing the instruction and development of biophilic policies in the field of cities and urban design. The following table shows examples of urban design based on biophilic principles, which have provided solutions in this field on a large scale (see Table 3).

The parameters mentioned in the table below do not directly refer to the parameters of the previous table that described the principles of biophilic design in architecture, but are considered a subset of them. The methods of achieving the concept of biophilic in cities can be wider and more diverse than those in the table below and can be changed under the influence of factors such as economy, culture, population and people’s needs.

The concept of biophilic can go beyond the city and urban design and can be examined on a regional and national scale. Also, by considering it in the theoretical foundations of urban and regional planning for short and long-term periods, it can provide the goals of sustainable development of countries according to their prospects.

Biophilic urbanism shows its power as an approach to create views and a common understanding of the many benefits of nature in cities and thus strengthens the place of planning for urban green spaces in policy makings. In general, it is necessary for urban policymakers to correctly understand the integrated potentials related to the green space of each city and to use the biophilic concept as a practical tool to strengthen the green place positions. At the same time, consider the challenges related to laws, future natural and human hazards, and future development.

5 Numerical Simulations to Measure UHI

The study area in this research is a city with a humid climate (Köppen climate classification: Cfa) and latitude and longitude of 37° 16′ 51.0024‴ N and 49° 34′ 59.0052″ E, respectively, and is located in the north of Iran. The average annual rainfall in this city is 1,359 mm. The average annual temperature is 15.9 °C, the average annual

Table 2 Case studies which illustrate the six biophilic design elements

Environmental Features	Natural Shapes and Forms	Natural Patterns and Processes
 Kashan Fin garden in Iran (Incorporates water as a positive experiential and eco-element to create evaporative cooling effects)	 Hotel Tassel in Belgium (Tendrils twisting and growing is a metaphorical representation of nature)	 Sagrada Família in Barcelona (This building mimics some organic features)
 The Museé du Quai Branly in Paris (Integrating vegetation as a green wall into the building facade)	 Milwaukee Art Museum in the USA (This is an iconic building which is dramatically designed as a wing-like structure)	 Lavirotte Building in Paris (The facade is decorated with a woman's head and vegetal designs, and the door is decorated with wrought iron lizards)
Light and Space	Place-Based Relationships	Evolved Human-Nature Relationships
 Shanghai Natural History Museum in China (An outdoor exhibit garden, welcomes visitors with an abundance of natural light)	 Napo Wildlife Centre in Ecuador (By hiking through the rain forest in search of wildlife and medicinal plants, you can enjoy forest lodges along the way)	 Fallingwater in Pennsylvania (The harmony of architectural design with nature is in accordance with what humans show a desire for)

(continued)

Table 2 (continued)

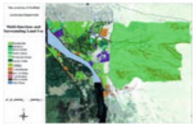
Environmental Features	Natural Shapes and Forms	Natural Patterns and Processes
 Ortega Mora House in Colombia (The combination of indoor and outdoor spaces with natural light and vegetation seems to increase the comfort of the residents)	 Shazdeh Garden in Iran (The presence of the water path along with trees throughout the entire perspective has increased the dynamism and vitality of the space)	 Lapa Rios Eco Resort in Costa Rica (In this incredible setting, guests can look forward to rainforest adventures, wildlife encounters and ocean activities)

Table 3 Case studies which illustrate the six biophilic design elements in urban design

Urban Water Management	Urban Natural Shapes and Forms	Street Natural Perspectives
 Flood management, design and construction of concrete water channels and integrating water bodies and canals with parks and green spaces in The Singapore Green Plan 2012 (Newman, 2014)	 Meymand Troglodyte Village in the Central District of Iran is an example of the use of natural shapes and forms in accordance with the environment and climate (Moradinasab & Khaksar, 2021)	 In Detroit, Michigan, street perspectives were improved by adding natural elements such as trees, by sharing tree species selection and maintenance responsibilities with the residents of each neighborhood (Carmichael & McDonough, 2018)
 Integrated Urban Water Management in Jamshedpur, Jharkhand india by improving efficiency and developing the piped water coverage, thus decreasing the load on groundwater sources and The water sources were augmented by utilising the surface runoff (Indiawaterpartnership, 2022)	 Kandavan village is located in the mountainous region of northwestern Iran. The houses in this village are similar to the ancient stone caves inside the mountain, which greatly reduces heat loss in the very cold winter (Khodaverdizadeh et al., 2008)	 Tree density in the Eastern Cape, South Africa shows more affluent suburbs in these towns had larger mean street tree densities. Paying attention to the importance of the street perspective in the city based on urban ecosystem services can be an important step for human health and well-being such as “climate regulation”, “air quality regulation” and “aesthetic and cultural services” (Salmond et al., 2016)

(continued)

Table 3 (continued)

Urban Water Management	Urban Natural Shapes and Forms	Street Natural Perspectives
Green urban neighborhood connectors	Horticulture Parks, gardening as a lifestyle hub	Marginal Gardens or parks
 The creation of the natural infrastructure (NI) network in the master plan of Cairo, Egypt naturally creates a connection along the Nile River, where three large islands are connected to each other and different urban communities are formed (Mahmoud & Selman, 2011)	 Woodland Park Rose Garden in Seattle is a large-scale park that provides opportunities to interact with nature for people in the urban space (WoodlandParkRoseGarden, 2022)	 Marginal da Areia Preta Park in Macao It is located in a narrow coastal strip, which, in addition to increasing the level of vegetation in the city, provides a suitable space for people's social interaction and walking and cycling (nature.iam.gov, 2022)
 The green network of Maadi and Wadi Degla preserve area in district south of Cairo, Egypt is a green lattice and ecological passage designed to conjoin the innate preserved area with the urban district. with this approach Maadi urban district has a green network and is connected with the River Nile with different ecological and inherent elements (Mahmoud & Selman, 2011)	 Montreal's Botanical Garden has great potential as a site for studying the complexity and versatility of human relations with non-humans in urban areas and it can make different kinds of ecological learning for children (Neves, 2009)	 Danny Woo Community Garden is a good example of the participation of park gardeners in the regeneration of unused marginal green spaces. Gardeners working in this park contribute to its maintenance by contributing to the income earned from it (Hou et al., 2009)

maximum air temperature is 20.6 °C, and the average annual minimum temperature is 11.3 °C. The maximum and the minimum annual temperature difference was reported to be 9.3 °C. The average relative humidity in Rasht (recorded from 2004 to 2014) is approximately 80.9%. Wind speed decreases in the summer, and increases again in autumn. The average annual wind speed in Rasht is 1.7 m/s.

5.1 Study Area: Shahrdari (Municipality) Square

Several studies have examined issues related to UHI in the humid climate of Rasht, where temperature differences of 5–6.4 °C between the central part of the city and the surrounding areas during the cold season, and 3–5.6 °C in the warm season (Karimi Zarchi & Shahhoseini, 2019) were recorded. In a study reported by Ramezani and Dokhat Mohamma (2010), they assessed UHI in Rasht through field measurement by implementing nine environmental sensors to identify the possible effects of UHI. The results showed that temperature differences of 5 to 6.4 °C occurred at *Sabzeh-Meydan Square* and *Shahrdari stations*. Besides, Oji et al. (2021) presented the change process of green space in Rasht city from 1964 to 2013. The results revealed that the total green space has decreased from 7,255 hectares to 5,990 hectares (17%), and dense green space has decreased from 2,855 hectares to 788 hectares (72%). Also, the majority of these reductions can be observed in the central area of Rasht (see Fig. 6).

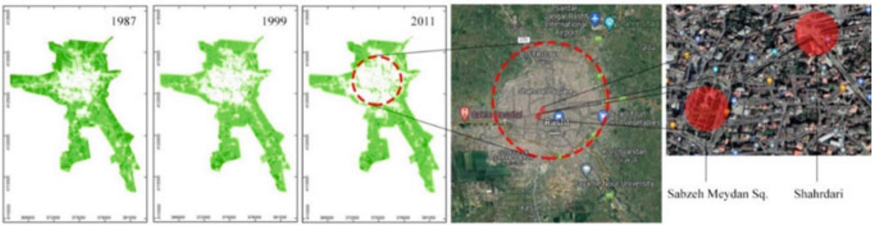


Fig. 6 The trend of changes in total green space in Rasht city (Oji et al., 2021); developed by the authors

Fig. 7 From left to right, study area 3D and top views, current picture, and the distance to Sardar Jangal Rasht International Airport (SJRIA), as a comparison of the rural area

Based on the aforementioned studies, *Shahrdari (Municipality) Square* was selected as the study area by the research team. The Cultural Walkway in Rasht is located near Shahrdari Square and the traditional Bazar of Rasht (with an area of over 26 thousand square meters). It is paved so that vehicles are not permitted to enter it. The Shahrdari complex includes the Municipal Palace, Post Museum, and the historical building of Iran Hotel. Generally, the buildings around this complex are used for retail purposes (Fig. 7).

5.2 Outline of the Simulation Analysis

According to the design of the Shahrdari Sq., it can be stated that during the warm months of the year, almost no protective measures have been considered for this area, which is equipped with a number of immovable urban furniture. A vast area of this space features limited vegetation covers and plants with no shadow protection. In addition, limited vegetation covers were implemented. However, it must be noted that these plant and tree species are not capable of protecting citizens. Thus, they can be considered as almost negligible in terms of creating shade. For the next step, the simulation was done in using the Rhino software and the Grasshopper and Ladybug plug-ins. Heat islands, referred to as Urban Weather Generators (UWGs), were calculated using Dragonfly. Dragonfly enables users to create district-scale models for urban heat island modeling using the Urban Weather Generator (UWG). This simulation is carried out based on the definition of UHI, the temperature difference of an urban area (in this case, Shahrdari Square) compared to the suburbs or rural areas (in this case, SJRIA); whose EPW (EnergyPlus Weather) data file is the criterion for climate calculations.

The distance from the study area to SJRIA is approximately 8 km. Regarding the simulation parameters, concrete, as the pavement material, is composed of ordinary Portland cement, fine aggregate from crushed limestone, and light-colored slag cement in a way that the albedo, thickness, and Conductivity are 0.64, 0.15, and 0.9 cm, respectively (FHA, 2021; Sanjuán et al., 2021). Due to the commute of motorcycles and bicycles in the study area, and the limited number of daily car traffic, the number of traffic watts per area was considered 1 (Sailor, 2011). Besides, the volume heat capacity reported in this work was 1.8e8 j/m^3-k (Tarasov et al., 2010). Based on the calculation of the vegetation cover area (trees and grass) from the existing map, tree cover and grass cover values of 0.2 and 0.3 have been applied, respectively. Figure 8 presents the simulation parameters and input data that can be defined through components composing the interface of the tool. The results of the simulation are provided below (Figs. 9 and 10).

According to Fig. 10a, the blue color shows the dry bulb temperature in the measurement conditions of the meteorological station of SJRIA, which is located in a rural area with a lower density than the main study area. In this figure, the red color illustrates the dry bulb temperature according to the effect of the factors affecting the UHI, such as the buildings in the urban environment (number, density, height, ratio of

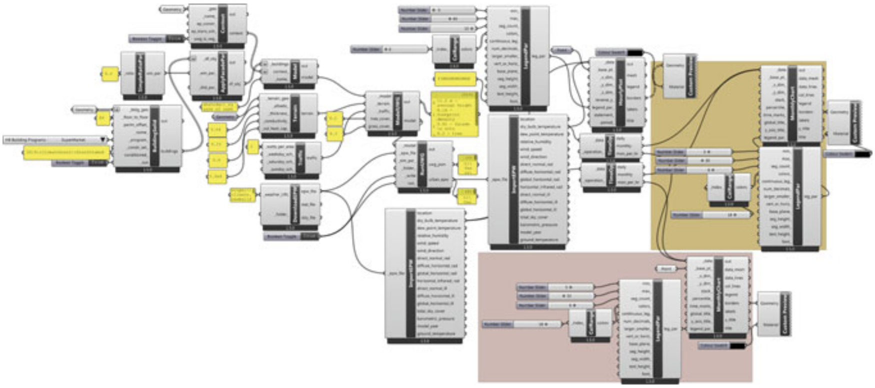


Fig. 8 The interface of the tool on the Grasshopper canvas

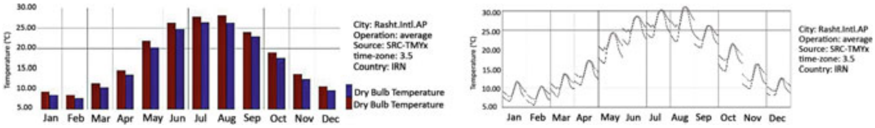


Fig. 9 Monthly temperature differences within the study areas

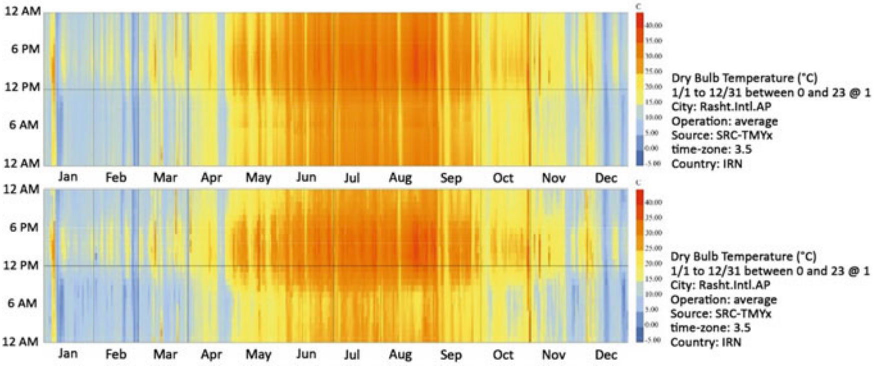


Fig. 10 Dry bulb temperature differences: **a** study area, and **b** SJRIA

opening to façade—window to wall ratio, floor height and function), pavement (type of material, albedo, conductivity, thickness, volume heat capacity), the amount of tree cover, the amount of grass cover, and the amount of traffic have been looked into. This graph depicts that, on a monthly average, the dry bulb temperature is 2–4 °C higher than the temperature measured simultaneously in the study area. In this regard, the blue color in diagram b presents the dry bulb temperature under the measurement conditions of the meteorological station of SJRIA, which is significantly different from the red line, i.e., the dry bulb temperature under the measurement conditions of the study area. During the hot months of the year, this difference reaches 4–5 °C.

Figure 10b indicates that the dry bulb temperature in SJRIA, and the accumulation of heat intensity during the hot seasons of the year is between 9 and 19 °C. In contrast, diagram b depicts the dry bulb temperature in urban conditions. Regarding the effects of the mentioned indicators, the amount of heat accumulation has continued during more hours of the day.

6 Discussion and Conclusion

The risks of future disasters caused by excessive construction, the indiscriminate use of inefficient and non-renewable materials, and overusing energy in the construction sector indicate severe and hazardous consequences for human societies; irreparable dangers that will not only lead to the destruction of the Earth, but also increase the risk of creature extinction. This 4-phase study investigates and attempts to identify strategies, exemplars, and tools to combat global warming through implementing a biophilic design concept. First of all, several studies have been examined as the literature review to highlight the importance of the research topic and its key elements. In the following, to provide a concrete theoretical framework, current theories and strategies are provided, in which successful exemplars of biophilic design worldwide have been discussed as case studies; of which six biophilic design elements including *environmental features*, *natural shapes and forms*, *natural patterns and processes*, *light and space*, *place-based relationships*, and *evolved human-nature relationships* can be employed in urban design to ensure having a healthy population.

A review of the biophilic design was carried out before the assessment of UHI in the case study. The new design paradigm is hereby referred to as “restorative environmental design,” which emphasizes both adapting and mitigating adverse environmental effects, as well as fostering a beneficial contact between people and nature in modern buildings and landscapes by means of practicing a positive environmental impact or biophilic design approach. Thus, one of the abovementioned elements is *vegetation and plants.* At its final phase, this research focused on VGS thermal performance as the proposed technique to mitigate UHI in the urban area of Rasht with its humid climate. To conduct this phase, Shahrdari (Municipality) Square is selected as the case study in an urban scale, and to compare the existence of plants with SJRIA, which is located in a rural area.

By comparing results regarding the age and differentials of vegetation in Shahrdari Sq., a model to assess the dry bulb temperature was developed. The findings demonstrated that UHI heavily relies on the coverage of trees, grass, traffic, pavement, material, and the urban environment, and fluctuates averagely between 2–4 and 4–5 °C during hot months. However, the studies carried out on coupling among different UHI parameters are inadequate. Consequently, findings revealed that vegetation was able to lower the average monthly temperature by about 2 °C, and that this amount could vary between 9 and 19 °C annually.

In addition, by examining the findings, there seems to be a significant temperature difference between the numbers recorded in the study areas, which is due to the presence of UHI in these areas. In the simulation, the traffic category has been considered due to the prohibition of vehicles entering this area, and the presence of a minimal density of motorcycles with a slight difference compared to the car-free zone. It seems that if driving vehicles freely was permitted in this area like other areas, the aforementioned recorded heat temperatures would be much higher. Therefore, increasing tree and grass cover, which is one of the urban design items based on the biophilic approach, helps reduce the temperature difference between the two mentioned areas, and makes the environmental conditions more comfortable for citizens. Given the value and significance of this approach, appropriate access of vegetation to water resources (according to the global water crisis), and their endurance during climate change is another critical issue that may be the background of future studies.

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Chapter 4
Warming Cities in Pakistan: Evaluating Spatial–Temporal Dynamics of Urban Thermal Field Variance Index Under Rapid Urbanization

Mirza Waleed and Muhammad Sajjad

Abstract With ~57% of the world population living in cities, the global urban population is increasing at an alarming rate, which further stimulates the urbanization process. Consequently, the increasing impervious surfaces in cities and associated variabilities in local/regional climatic characteristics pose several challenges to citizens (i.e., heat-related health issues, higher energy demands, and flooding among many others). Currently, cities contribute 75% of Green House Gases emissions, which is further worsening climate change impacts through global warming. Pakistan, the 6th most populated country globally, with ~220 million people, is among the top 10 most-affected nations vulnerable to climate change. Hence, studies addressing climate variability in local geographical regions have important implications to address the adverse urbanization-associated challenges, such as sustainability of the land resource and mitigating urban heat island (UHI) impacts in the context of climate change mitigation/adaptation. Due to temperature differences between urban, suburban, and rural areas, mapping city zones prone to the UHI effect is essential to provide actionable references. In connection with this, the present study analyses 15 megacities in Pakistan regarding their temperature variability in response to built-up area increment and highlights heat stress zones using the Urban Thermal Field Variance Index (UTFVI). The cloud-computing-based Google Earth Engine platform is employed to explore spatial–temporal variation in Land Surface Temperature (LST), which further leads to the identification of top-15 cities in terms of LST increase and the further evaluation of UTFVI for each city. The findings of this study suggest that the strongest UTFVI zones are concentrated around city-core areas, which are pure impervious surfaces with little or no green space. Moreover, in the last three decades (1990–2020), most of the weak and strong-strength UTFVI areas have been converted into the strongest strength primarily because of a rapid increase in the

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built-up areas. The findings of this study can help urban policymakers to identify priority intervention areas and design/implement strategies to counter the UTFVI and associated challenges. With proper land-use planning and on-time policy implementation, people residing in higher UTFVI zone areas can be safeguarded from noxious heatstroke-like health consequences along with mitigating and adapting to changing environmental conditions in cities.

Keywords Urbanization · Climate change · Urban heat island · Spatial analysis · LULC · LST

1 Introduction

In the last few decades, changing climatic conditions have predominantly affected the living conditions of human beings. Recent studies suggest that those living in metropolitan cities are more prone to the adversities brought by climate change and associated extreme events, such as heat waves and intensifying natural hazards (IPCC, 2021). The changes in land use land cover (LULC) have a direct linkage with changes in climatic conditions of an area, particularly in cities (Faisal et al., 2021). The global population in 2050 is expected to increase by 68% (Nations, 2019). Cities are responsible for three-half (75%) of the world Green House Gases (GHSs) emissions (Masson-Delmotte et al., 2021). According to the IPCC (2021) report, the surface temperature of the earth has increased by ~1.09 °C since 1861, which is primarily due to the increase in impervious surfaces in cities and the reduction of green cover.

Recently, urban sprawl has resulted in several challenges for cities around the world (Alqasemi et al., 2021). According to the European Environmental Agency (EEA), urban sprawl is the low-density conversion of other land-use types, especially nearby vegetative and barren land into urban/built-up (Kafy et al., 2022a). This expansion is a primary consequence of a rapid increase in the population of that particular area due to growth and influx. As a result, cities witness an increase in resource demand (Faisal et al., 2021). Similarly, being a major factor behind the land cover change (Corner et al., 2014), urbanization induces changes in ecology, biodiversity, landscape, and natural habitats as well. The rapid alteration of LULC, especially in developing countries, causes the degradation of essential resources such as water, soil, and vegetation—compromising long-term sustainability (Hassan et al., 2016). Similarly, LULC-induced reduction in green spaces in cities is likely to facilitate the urban heat island effect, which has several consequences in terms of health challenges and higher energy consumption among many other issues (Kafy et al., 2022b). Therefore, supervising LULC alterations is fundamental to proper planning, management, and achieving sustainable development goals through informed decision-making and science-backed policy development (Hua et al., 2021).

Urbanization-led decrease in vegetation and increase in impervious surface results in larger heat retention, and consequently, the urban heat island (UHI) effect takes place. UHI is a phenomenon when the observed surface temperature of core urban regions is higher than the surrounding sub-urban/rural areas (Alqasemi et al., 2021). Though there is no prominent boundary differentiating urban from nearby rural areas, a temperature difference is observed and well-documented around the world (Rahman et al., 2022). Impervious surfaces including roads, tall buildings, and non-vegetative regions (e.g., sandy or barren) within cities are primarily responsible for the UHI effect. The primary contributors to urban warming are a rise in short-wave radiation captivation, heat storage, human-induced heat generation, and reduced evaporation rate (Rajasekar & Weng, 2009). Earth observation data (EOD) is proven to be useful in understanding the urbanization process and associated environmental effects. The use of EOD to evaluate UHI and its effects on spatial distribution, urban vulnerabilities, and health-related risks are widely published globally (Kafy et al., 2022b; Kaplan et al., 2018; Zhou et al., 2018). To evaluate the influence of UHI, the urban thermal field variance index (UTFVI) is usually employed (Tomlinson et al., 2011). Hence, exploring spatial–temporal heterogeneities in UTFVI could provide progressive opportunities to advance our understanding of UHI effects in cities.

The urbanization rate in Pakistan is the highest among all south Asian countries with ~ 37% of people living in cities (UNDP, 2022) In the last five decades, Pakistan has faced rapid urbanization in its metropolitan cities (Waleed & Sajjad, 2022). Punjab, the largest province in Pakistan with respect to population and agricultural productivity, has undergone some noticeable changes in its urban areas. While many researchers (e.g., Dilawar et al., 2021; Hussain et al., 2021; Safder, 2019; Saleem et al., 2020; Tariq et al., 2021; Waleed & Sajjad, 2022) have studied urban LULC patterns in Pakistan, there is still a lack of a systematic investigation of urban regions in terms of LST change and the spatial–temporal evaluation of UTFVI. Furthermore, while such assessments are rare to find in Pakistan, those that are available mostly focus exclusively on the top metropolitan cities (i.e., Lahore, Karachi, and Faisalabad) despite their smaller city area and already highly urbanized nature (Baqa et al., 2021; Imran et al., 2021; Tariq et al., 2021). As a result, the current research focuses on highly populated cities in Punjab and neglects other regions which might have experienced comparable urbanization and associated changes in terms of urban thermal characteristics. This situation represents a significant information gap for other rapidly urbanizing regions and thus hinders informed planning and policy production. In connection with this, the present study evaluates the LST in Punjab province and selects the top 15 cities based on LST change during the past three decades (1990–2020). Based on LST, this study further investigates the spatial–temporal dynamics of UTFVI in these cities. Furthermore, the built-up area increase in these 15 cities is evaluated to discuss urbanization trends along with the increase in the intensity of UTFVI. To do so, the Google Earth Engine (GEE) platform and spatial modelling techniques in ArcGIS Pro. are employed. The results from this study will provide important insights into UTFVI and built-up area dynamics in Pakistan's cities along with providing references for decision-making and designing appropriate action plans in the context of climate change mitigation/adaptation.

2 Data Acquisition and Preparation

The overall work is conducted in various steps, such as data acquisition, built-up area classification, change assessment, LST computation and evaluation, and mapping UTFVI for spatial–temporal inconsistencies evaluation. The data preparation stage starts with filtering the Landsat-5 Thematic Mapper (TM) tier-1 Surface Reflectance (SR), Landsat-8 Operational Land Imager (OLI), and the Thermal Infrared Sensor (TIRS) tier-1 SR data from the GEE data catalogue in the form of image collection. The overall analysis is divided into four periods (i.e., years 1990, 2000, 2010, and 2020) as the LULC change is a slow process. For the years 1990, 2000, and 2010, we use data from the Landsat-5 TM tier-1 collection. For the year 2020, Landsat-8 OLI tier-1 SR data are used. It is noted that we avoid using Landsat-7 data despite its availability for 2000 and 2010 due to scan-line errors since 2007 (Alexandridis et al., 2013). These satellite images for each year are then used to determine urban areas for each period. For this purpose, the machine learning-based random forest (RF) algorithm is utilized due to its robustness and improved LULC classification accuracy compared with other approaches (Waleed & Sajjad, 2022). The obtained classification of built-up area is validated using accuracy assessment indices, such as the Kappa coefficient and Overall Accuracy (Waleed et al., 2022).

3 LST Retrieval Through Earth Observations

As the next step, the Landsat data are used to compute Land Surface Temperature (LST). For this purpose, LST is taken from summer month's satellite images individually for each year. For LST estimation, the Landsat TM and ETM + (Band 6) and Landsat OLI/TIRS (Band 10) thermal bands are used. Landsat 8 (OLI/TIRS) imagery has two thermal bands (10 and 11), but only band 10 is used for the LST estimation because of its more accurate results (Zhou et al., 2018). Equations (3–5) are used to convert digital numbers (DN) into LST as previously used in many studies (Tariq et al., 2021; Waleed & Sajjad, 2022). Firstly, the DN values of each pixel are converted into radiance values (L_λ) using the following equation.

$$L_\lambda = \left(\frac{L_{max\lambda} - L_{min\lambda}}{QCAL_{max} - LQCAL_{min}}\right) + L_{min\lambda} \tag{1}$$

where $L_{max\lambda}$ is the highest radiance value, $L_{min\lambda}$ is the lowest radiance value, $QCAL_{max}$ is the highest quantized adjusted pixel value (consistent to $L_{max\lambda}$ in DN (255)), and $QCAL_{min}$ is the lowest quantized adjusted pixel value (consistent to L_{min} in DN (01)).

All the values used in the above equation are taken from the metadata files that come along with the Landsat images. The radiance values are then converted to surface brightness temperature given as:

$$T_B = \left(\frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \right) - 273.15 \tag{2}$$

in which, K_1 and K_2 are the constants, and for reference, their values are available on the United States Geological Survey (USGS) website (https://www.usgs.gov/).

After estimating the at-surface brightness temperature T_B, we compute the pixel-based land surface emissivity (ε). In order to calculate the value of emissivity, we use the pre-defined calibrated values for different Landsat missions along with a particular region's Normalized Difference Vegetation Index (NDVI) as used in recent research (Imran et al., 2021). The LST is computed using Eq. 3, in which T_B is applied with an emissivity correction (ε).

$$T_S = \frac{T_B}{\left[1 + \left[\frac{\lambda T_B}{p}\right] \ln\varepsilon\right]} \tag{3}$$

where T_S is the per-pixel LST value, λ is the wavelength of emitted radiance (value = 11.5 μm), and p is equal to 1.438×10^{-2mk}.

The above procedure is followed to evaluate LST in Punjab province in Pakistan. The derived LST is then used to evaluate the spatial–temporal patterns and trends, if any, in several cities in the study area over the last three decades (1990–2020). In addition, LST is further used to assess UTFVI, which is utilized to map heat stress-affected areas in the top 15 cities in terms of LST change during 1990–2020. It is noted that for simplification, we used a 10-km buffer zone around the central business districts of the cities and quantified changes in the LST, which is then used to select the top 15 cities for further evaluation.

4 UTFVI Estimation and Its Spatial–temporal Heterogeneities

Previously, many researchers have used different techniques to calculate the intensity of UHI specifically in urban and near urban areas (Kaplan et al., 2018; Rahman et al., 2022; Tomlinson et al., 2011). Remote Sensing (RS) techniques have been proven to analyze data in a continuous and cost-effective manner. Using RS techniques, UHI can continuously be monitored with the help of infrared satellite data. Instead of just point readings, the RS-based UHI could show the intensity of heat stress over large geographical areas. According to the literature (i.e., Zhou et al., 2018), the UHI is directly linked to different LULC classes and also to the geographical distribution of vegetation cover. By using RS techniques, the UHI is calculated independently in urban and rural areas following Faisal et al. (2021).

A normalization method is adopted to compare UHI due to observed variations in LST of different seasons within a year. This is given in Eq. 4.

$$UHI_N = \frac{T_s - T_m}{T_{Std}} \tag{4}$$

where UHI_N is the normalized UHI, T_s is the LST, T_m is the mean LST of the study area, and T_{std} is the standard deviation in the LST of the study area.

After computing the UHI, we use the UTFVI to describe its effect. The UTFVI is a quantitative measure to explain UHI in terms of thermal comfort level in a city and is among the most widely used thermal comfort indices (Guha et al., 2017). The index value is quantitatively calculated using the formula given below.

$$UTFVI = \frac{T_s - T_m}{T_s} \tag{5}$$

where the variables are similar to Eq. 4.

The UTFVI is computed for every city for each time period (1990, 2000, 2010, and 2020), and maps are produced to provide spatial references on geographical disparities. This approach is particularly helpful in understanding the distribution of urban thermal comfort across space and time, allowing relevant authorities to take appropriate measures via informed decision-making.

5 Changes in LST, UTFVI, and Built-Up Areas

Figure 1 shows temperature change (LST change) in the top 15 cities of Punjab during 1990–2020. Among 58 cities of Punjab, 15 showed up to 7 °C of temperature change. Among these, Kasur, Chiniot, Sheikhupura, Sahiwal, and Lahore are the ones with surface temperature change greater than 4 °C. Besides, Rawalpindi and Rahim Yar Khan are the ones that experienced the least temperature change (i.e., < 1 °C change). This temperature change (based on LST) provided a base for highlighting cities that underwent noticeable temperature changes in the last thirty years and are investigated further to analyze UTFVI and built-up area variations during 1990–2020.

Once the cities are ranked according to the estimated LST change during the past three decades, the top 15 cities with the largest temperature change are shortlisted to further study the abrupt temperature rise by computing the UTFVI for each city and its dynamics in space and time. For each city, the evaluated UTFVI and its spatial distribution under different periods (1990, 2000, 2010, and 2020) are presented in Fig. 2. To further facilitate the analysis, the cities are grouped based on three regions, including (A) the Central region, (B) the North region, and (C) the South region (Fig. 2). Interestingly, it is observed that most of the cities experiencing increment in LST belong to the central regions of Punjab province in Pakistan, with two cities each from the north and south regions. The location of many large cities in the central areas of Punjab province could be the potential reason behind the rapid urbanization-led change in the LST of these cities. For UTFVI, 11 cities belong to the Central region while 2 to each North and South region.

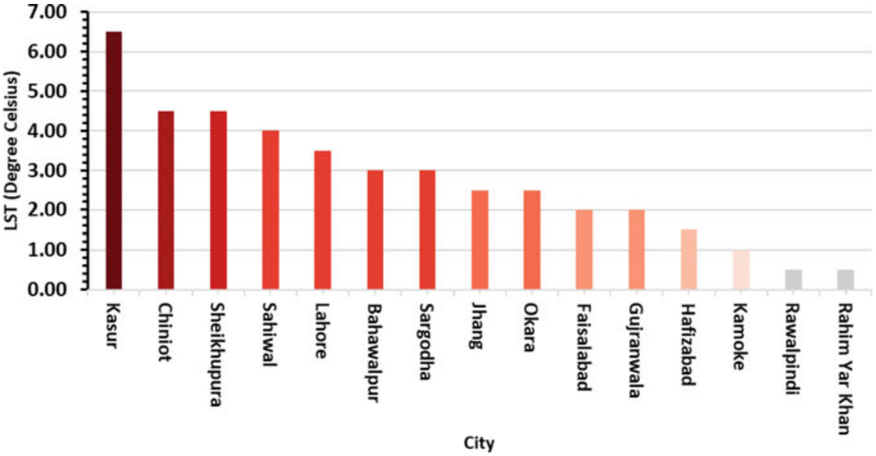

Fig. 1 Ranking of cities of Punjab based on highest temperature change (LST Change in °C)

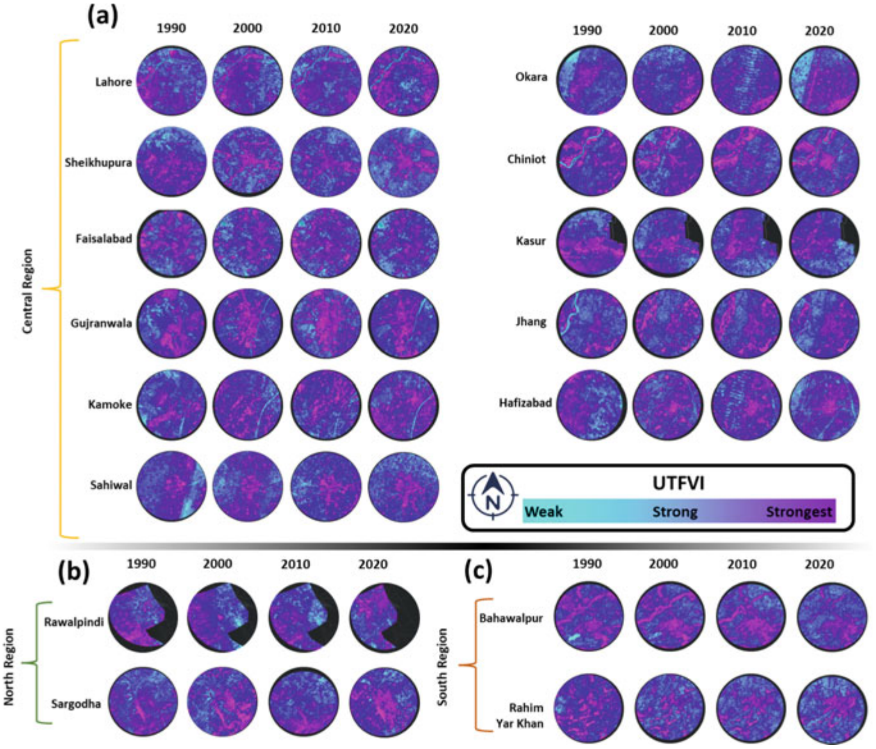

Fig. 2 UTFVI for 15 selected cities based on the change in LST during 1990–2020. The results are visualized using one standard deviation representing how much the value of each 30 m pixel varies from the mean across the overall city

Nearly in all cities, two prominent trends are observed. Some cities, such as Sahiwal, show the strongest UTFVI located in the city core, with UTFVI strength increasing during the past three decades (1990–2020). On the other hand, some cities, such as Hafizabad, show dispersed strongest UTFVI in the surroundings of the city's core area. These dispersed strongest UTFVI areas then experienced a shift toward the city's centre with each passing time period. Besides the strongest UTFVI, weak and strong UTFVI areas are also visible in surrounding regions, and their concentration is reduced by each decade. For example, in Rawalpindi and Sargodha, weak and strong UTFVI areas were prominent in the 1990–2010 duration around the city's centre. Whereas, in the last decade (2010–2020), these weak and strong UTFVI zones are converted into the strongest UTFVI zones. Additionally, it is worth mentioning that although many cities have shown a significant increasing trend of the strongest concentration of UTFVI, there are some cities, such as Lahore, with a minimal increasing trend over the years in the strongest UTFVI. This may be attributed to the fact that metropolitan cities, such as Lahore, are already densely populated and well-urbanized, leaving far lesser space for any new development. In Fig. 2, among the Central region cities, Gujranwala, Faisalabad, Sahiwal, Lahore, and Chiniot showed the highest UTFVI, among which Kasur stands first. For the North and South regions, Sargodha and Bahawalpur are the highest UTFVI concentrated regions, respectively.

To further check the association of the core strongest UTFVI areas of cities with urban development, we evaluated LULC classification for each city, and the results on the sprawl of built-up areas are presented in Fig. 3. In general, Lahore city, which is among the largest cities in Pakistan and accommodates a huge proportion of Pakistan's population, has the highest urban area whereas Bahawalpur has the least urban area. In terms of area change per year, Lahore showed the minimum urban expansion than others between 1990–2020. Also, in Lahore, most of the urban development occurred in the city's core areas, thus, increasing the city's density instead of expanding outwards. This may be due to the fact that the city is already urbanized and can only increase its density in future, which gives minimal space for further expansion unless it is merged with the surrounding smaller cities, such as Sheikhupura and Kasur, or vertical development takes place for future development instead of current horizontal sprawl. Furthermore, an increase in urban development patterns is observed in nearly all the cities (i.e., Faisalabad, Gujranwala, and Kamoke doubled their urban expansion between 1990–2020). It is also evident that nearly all the cities followed a gradual urban expansion process. For instance, Gujranwala followed a city-centric point, in which the urban area expanded with each passing decade in the surrounding core area. Among all the cities, Okara did not show much urban development. On the other hand, among several regional groups of Punjab, Gujranwala in the Central region (Fig. 3a), Rawalpindi in the North region (Fig. 3b), and Rahim Yar Khan in the South region (Fig. 3c) show the highest urbanization during the past three decades (1990–2020).

The statistical evaluation of area changes for each decade and each city's urban area is given in Fig. 4 with percent change (1990–2020) illustrated in Fig. 4a and actual areal change for each city for different time intervals (1990, 2000,

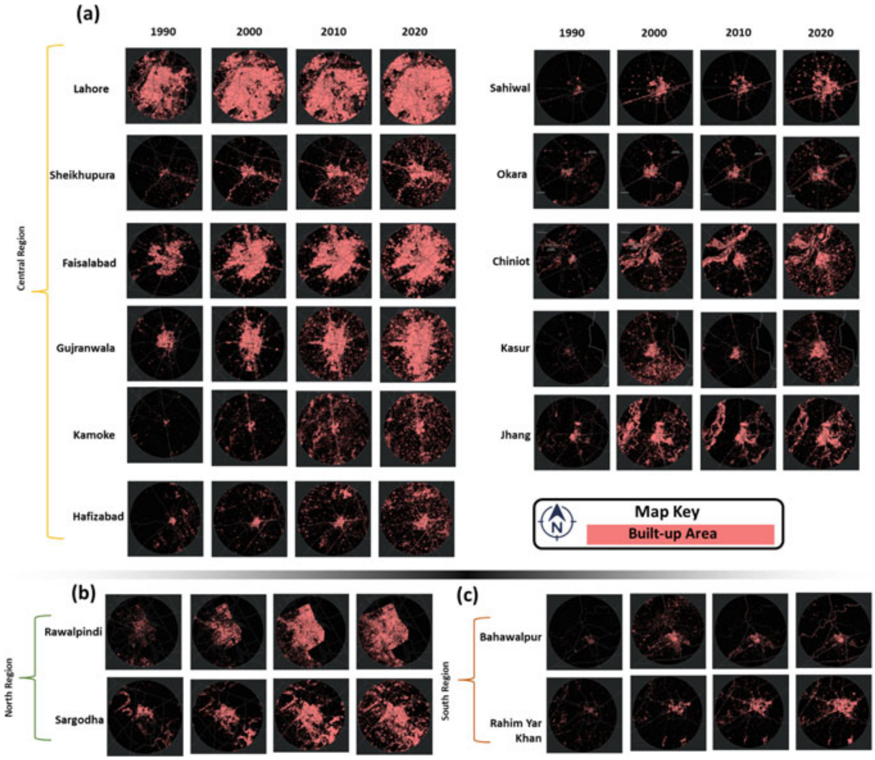

Fig. 3 Urban sprawl for cities between 1990–2020 as estimated using the Landsat Satellite-based earth observation data in Google Earth Engine

2010, and 2020) in Fig. 4b. Notably, area statistics support previous deductions from Fig. 3 that Gujranwala showed the highest urbanization with a 600% change (increase) between 1990–2020. Following Gujranwala, Chiniot, Sargodha, Sahiwal, and Kamoke showed similar urban development trends with percent changes of 405%, 403%, and 333% increase, respectively. Lahore, on the other hand, showed a minor urban increase, with only a change of 47% between 1990–2020. From the perspective of overall percent change, Gujranwala, Chiniot, Sargodha, Sahiwal, and Kamoke are the top five cities in Punjab that show more than 300% change in the last thirty years.

6 Discussions and Implications

While land-use change monitoring is crucial for environmental sustainability, especially addressing development in core urban areas, it is equally important to analyze comfort level by evaluating the thermal conditions within that region. Cities, which

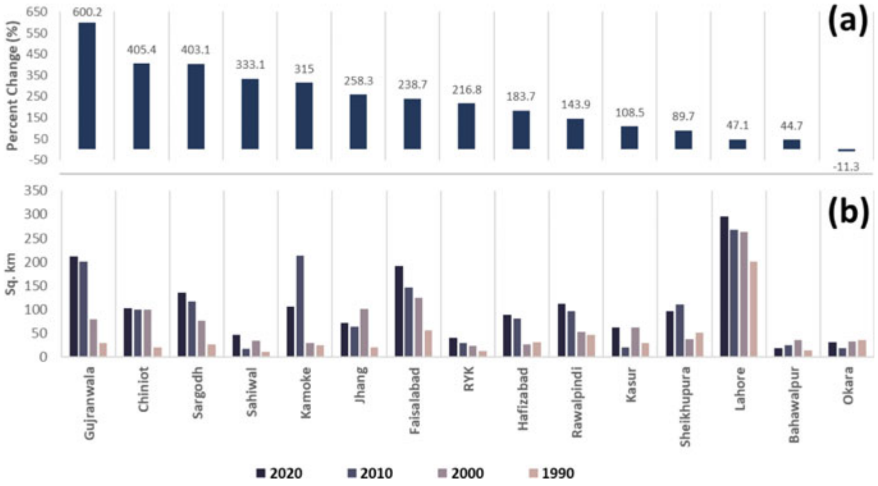

Fig. 4 Urbanization phenomena in top 15 cities. (a) percent change in urban built-up areas (b) actual areal change per decade under the urbanization process during 1990–2020

are the hotspots of global warming, are the most affected regions because of climate change effects. Despite their less than 2% of the earth's surface coverage, they are responsible for more than 70% of GHGs emissions, which is the most significant climate change driver (UN, 2019). Given this situation, the increase in impervious surface, as observed in this study at the cost of natural terrain, reduced the capabilities of cities in terms of carbon sink. As per the available reports, during 1990–2019, the GHGs-based warming induced by anthropogenic activities increased to 45% (IPCC, 2021). Besides GHGs, due to changing landscapes in cities (i.e., the replacement of natural landscapes with the concentration of impermeable pavements, buildings, and other surfaces that influence air and water flows), cities are getting warmer (Dilawar et al., 2021). A similar warming phenomenon is evident in the evaluated cities in Pakistan. This heat that is trapped (also known as the urban heat island effect) results in increased severity of daily weather (i.e., high daytime temperature, low night-time temperature, and high pollution levels), ultimately affecting residents' health, including heat-related mortality and illnesses, such as general discomfort, respiratory difficulties, heat cramps, heat exhaustion, and non-fatal heat stroke (Tomlinson et al., 2011). Hence, managing rising heat in cities with appropriate measures is imperative for healthy and liveable cities, and evaluations, such as this study, provide important insights to direct efforts in the right direction. For instance, the identified top 15 cities (Fig. 1) in terms of LST change during the past three decades should be prioritized for adaptation actions.

As the UHI effect is dependent on land-use surface type, vegetation cover is proved to be effective in UHI mitigation (Kafy et al., 2022b). Therefore, evaluations addressing continuous land-use change and urban comfort analysis are important for improved policy production and smart decision-making to keep a check on the green cover in cities. Ultimately, such efforts ensure higher comfortability in urban areas for the residents. The UHI-based UTFVI disparities in all the studied cities pinpoint zones where the green cover should be prioritized. Although urbanization is directly associated with economic progress and innovation, unsustainable and unplanned growth can cause serious complications for residents. This situation can be worsened with the addition of climatic change-induced uncertainties, which may have long-term effects on human livability.

The United Nations projections show that global urban land will increase by 1.2 million km^2 by 2030 (Vinayak et al., 2021). It is obvious that the urbanization rate of developing countries is much higher than that of developed countries. Hence, the ill-informed urban sprawl resulting in urbanization-induced spatial–temporal changes in their landscapes coupled with unsustainable utilization of land resources put cities at higher risks of looming uncertainties under environmental and climatic changes. Hence, while science-baked development plans should be adopted for the future expansion of cities, other smaller urban areas should not be overshadowed due to the focus of the planners and governments on major cities. Similarly, while the surveillance of smaller urban regions should also be on the agenda of urban planning in Pakistan, the densification of metropolitan cities (i.e., Lahore and Faisalabad) should be monitored and approved under strict policies considering the effects of climate change. For instance, It is also clear from Lahore's percent change (47%) that the city has had minimal urban expansion since 1990, despite being the second largest city in Pakistan after Karachi, as it is already a developed city, and therefore can only increase its core city density as depicted in Fig. 3a. Under this condition, managing green cover in Lahore in the face of future development should be a matter of utmost concern for the relevant authorities. Pakistan being a developing country has faced disastrous climate change consequences over the previous decades. According to the Global Climate Risk Index (2021), Pakistan is among the 10 most affected countries due to global warming. Hence, informed planning and development processes assuring sustainable urbanization (i.e., without compromising the green cover in cities to tackle UHI) are imparative to reduce the impacts of climate change.

The findings of this study ranked 15 cities in Punjab based on LST changes between 1990–2020, in which Kasur, Chiniot, Sheikhupura, Sahiwal, and Lahore are the top five with LST change (i.e., > 4 °C change; Fig. 1). Based on this ranking, UTFVI (Fig. 2) shows increasing trends for all cities with either the strongest UTFVI hotspots localized around the city's centre or dispersed in the surrounding. Either way, UTFVI concentration shows a gradual increment consistent with LST changes (Fig. 1). This increased UTFVI localization can be attributed to landscape changes, including the concentration of impervious surfaces and loss of green cover, as witnessed and documented by recent studies as well (Waleed & Sajjad, 2022). In Pakistan, it is evident from previous studies (Dilawar et al., 2021; Waleed & Sajjad, 2022) that higher resource demand and unsustainable policy management have resulted in negative consequences for the natural landscape. According to Waleed and Sajjad (2022), in the last 30 years in Punjab, the natural landscape has been aggressively used to meet demand resulting in a 250% increase in built-up land, a 10% increase in agricultural land, a 36% reduction in rangeland (vegetative land), and 30% reduction in water bodies (wetlands).

One of the key effects of rising urban heat in the aforementioned cities will be on the energy sector. As per recent studies and governmental reports (Raza et al., 2022), Pakistan has been facing an energy crisis for the last two decades, where the country's demand exceeds 30% of its current production. Thus, the temperature-energy relationship continues to increase, which poses further complications and needs to be addressed through proper investigations. First, the need for air conditioning in summer will put a further burden on the energy sector as well as contribute to additional emissions of hydrofluorocarbons responsible for trapping heat. Second, due to the lack of green energy sources, the energy consumption burden will continue to grow, resulting in contributions toward global warming due to fossil fuel burning (Sajjad, 2020). Hence, it is recommended to prioritize regions in cities for green-cover promotion through different initiatives, such as the recent 10-billion Tree Tsunami (Sabir et al., 2020). The identified cities with increasing LST should be considered under such initiatives to bring back the lost vegetation cover and preserve the remaining through strict no-net-loss policies in future urban planning schemes. For each city, such restoration should be prioritized in the strongest UTFVI zones.

In the context of urban heat mitigation and adaption, this study provides a reference for the top 15 cities in Punjab, Pakistan, for effective planning and design-based policy implementation. In this regard, many existing policy frameworks provided by leading world bodies should be adopted, wherever applicable. For example, the recent report by the Global Alliance for Buildings and Construction (supported by the United Nations Environment Programme) discusses key strategies for mitigating urban heat in cities (Yenneti, 2017). Conclusively, urban greenery, green roofs, water-based cooling technologies, cool roofs, and cool pavements are among the most effective means to reduce urban heat stress. Future policy directions should focus on documenting national benchmarks on heat mitigation measures, emphasize the participation of local municipal governments in the implementation of UHI mitigation strategies, incentives for industry and the public, and encourage community participation for handling localized UHI mitigation projects. Another report by the Energy Sector Management Assistance Program (ESMAP) funded by the World Bank divides urban mitigation solutions into two groups (Energy Sector Management Assistance Program 2020). Firstly, the local authorities should focus on promoting the utilization of reflective surfaces, including solar-reflective green roofs, green walls, and permeable pavements. Secondly, the focus should be towards heat-resistant planning through water infrastructures, urban design (green parks), and reducing human-generated heat.

The findings of this study can act as place-based references to prioritize areas for immediate or gradual actions to take measures for adaptation and mitigation via public participation and enhanced community awareness regarding green spaces. Through informed urban planning, such as initiatives of green roofs, utilization of solar panels for green energy, the introduction of green parking lots, and implementation and sensitization of heat reduction policies, urban comfort can progressively be enhanced in the face of warming cities in Pakistan. In terms of future prospects, it is recommended to simulate future expected urban patterns using cutting-edge approaches (i.e., machine learning) and provide insights into land use land cover dynamics and its association with thermal characteristics in cities. Such important information would further be useful to formulate action plans and guided strategies to cope with the climate change-induced heat stress in cities.

7 Concluding Remarks

Evaluating spatial–temporal inconsistencies in the thermal characteristics of cities provide useful references for urban planning and design in the face of climate change. In this context, this study evaluates the urban thermal field variance index (UTFVI)—also an indicator of urban comfort—in 15 cities in Pakistan, a south Asian country with approximately 220 million people and is often ranked among the ten most vulnerable nations to the impacts of climate change globally. These cities are shortlisted based on the changes in their LST during the past three decades (1990–2020). The results show that most of the cities with increasing trends in LST are from the central regions of Punjab province in Pakistan with two cities each from northern and southern Punjab. While the spatial inconsistencies in the UTFVI in each city are evident, there is a clear increase in the higher UTFVI coverage in all the cities during 1990–2020. Connectedly, there has been a significant increase in the built-up areas of all the evaluated cities in response to the ongoing rapid urbanization in Pakistan over the past three decades. Interestingly, it is found that the increase in LST, UTFVI, and built-up area due to urbanization is much higher in mediocre cities rather than in large urban agglomerations, such as Lahore and Faisalabad, which are the second and third largest cities in Pakistan. This could be the potential consequence of higher saturation in terms of built-up areas in larger cities, and now the smaller urban areas in the vicinity are facing a larger increase in urbanization and its impacts on the urban thermal characteristics (i.e., UTFVI). Given the impacts of rising heat in cities on health, as well as energy consumption, there is an immediate need for adaptation measures. For UHI mitigation, policies should emphasize reflective surfaces (green roofs and green walls) in the strongest UTFVI zones. Besides, localized projects should be introduced and handled by local municipal governments, which should ensure public participation by providing them incentives in sustainable conservative initiatives for combating urban heat stress. Since green cover directly influence UHI concentration, policies should be established for a no-net-loss green cover particularly in the strongest UTFVI areas and all the cities in Pakistan in general. Lastly, though Pakistan is among the countries with a minimal proportion of global emissions, heat stress can further be reduced by achieving net zero GHGs emission. The results from this study, such as the areas with higher UTFVI values, can guide pinpointing priority intervention areas for immediate and/or gradual actions to avoid the potential consequences due to the warming of these cities—resulting in enhanced comfort in urban regions.

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Chapter 5
Urban Heat Island (UHI) Implications and a Holistic Management Framework

Hafiza Saba Islam, Talib Elahi Butt, Shaker Mahmood Mayo, Siddiqa Amin, and Maria Ali

Abstract The Urban Heat Island (UHI) effect is one of the most debated phenomena among the urban researchers and city planners. In addition to fast urbanization, climate change actors are rendering major cites thermal hubs of the modern global civilization. Climate models consistently predict that the frequency, severity, and duration of extreme weather conditions which also include heat wave are on the increase and would be significantly by the end of the twenty-first century. Therefore, there is an emergent and urgent need to rethink the assessment and management of the UHI phenomenon. This study aims to establish the existing knowledge regarding UHI implications by categorically identifying and systematically grouping the factors and sub-factors that contribute UHI phenomenon. The aforesaid aim is based on the literature review, investigation of models, and the thematic analysis. Some new insights are produced by categorizing UHI implications into two main groups climate change and non-climate change related. This leads to a more comprehensive conceptualization of UHI at different tiers which is discussed and presented schematically. Founding on this conceptualization a new, integrated and holistic framework of the assessment and management of UHI is developed. The UHI framework is also schematically delineated. This UHI framework can be used as a basis for further research and development in the form of a ready-to-use/off-the-shelf tool for urban planners, decision-makers, and other associated stakeholders. The framework can also be communal platform of effective communication between diverse stakeholders with varying background and interests.

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Keywords Urban Heat Island (UHI) · Heat Waves (HWs) · Climate change · Urbanization

1 Introduction

The term Urban heat island (UHI) is used behind the warm urban regions in comparison to surround rural ones. Urban heat island (UHI) profile is raised if the surface energy balance and surface temperature changes (Adinna et al., 2009; Synnefa et al., 2008). The unplanned and haphazard urbanization is another factor contributing to the change in the energy budget. Urbanization is causing more problems such as environmental issues and the effects of climate change on both the built and natural surroundings. The sixth assessment report of Intergovernmental Panel on Climate Change warns that a key temperature limit will be exceeded in less than ten years and highlights how human activities are escalating the situation toward unanticipated and occasionally irreversible changes because of climate change.

Risk associated with the warm urban climate in form of frequent extreme weather events, such as heat waves, would increase if the expansion of urban areas proceeds under the same conditions (Perkins-Kirkpatrick & Lewis, 2020). Over 2500 people died as a result of the 2019 European heatwave (CRED, 2019). These local climate warming patterns also predicted the warming trend in and around cities, particularly in terms of increases in mean and extreme precipitation and annual mean temperature over and downwind of cities.

Despite being the deadly impacts of heatwaves are still not receiving due attention in many countries (Harrington & Otto, 2020). The increasing Global warming trend is the rising intensity and frequency of heat waves with an exponentially e.g., a study in Madrid found a shift by +1.5 °C in the mean air temperature during the period 1980–2017 compared to the previous period 1948–1979 accompanied by a noticeable increase in intensity and frequency of HWs after the 1980s. This is due to the possible synergistic interactions between UHIs and HWs with exacerbation of the nocturnal rather than daytime UHI intensity (Rasilla et al., 2019).

Numerous studies using various approaches have been conducted to map UHI in relation to development patterns, including those in the USA, China, Bangladesh, and Pakistan (Ayman et al., 2021) studies that have approximated the positive correlation between raised land surface temperature and unplanned change in land use/land cover (LULC). This needs to be addressed more holistically by considering all-encompassing factors of UHI, and HW to formulate more effective UHI mitigation measures which enable urban planners and policymakers to get more accurate and explicit guidance (Kong et al., 2021).

The dynamism along with heterogeneity of the inner-city heat depends upon various climate change-related and urbanization-induced factors. The heterogeneous characteristic of UHI concerning urban heat is due to the fact all contributing factors of UHI are not categorized separately to gauge the impacts of each phenomenon.

Studying all contributing factors of UHI would assist in the theoretical understanding of the external thermal stress of megacities.

Myriad studies have been conducted and concluded with some contradictions when examined from a more abstract point of view. This leads to "environmental miscommunication" which compromises the effectiveness of coordination, collaboration, and eventually interventions regarding Climate change mitigation and adaptations at local regional national, and global levels. There has not been found evidence of the existence of this holistic and integrated framework that cognitively and categorically divides the constituents of UHI and relates them with each other. Therefore, decision-makers and other stakeholders grapple with the decision-making process regarding urban design and development specifically keeping given UHI.

This implies that UHI needs redefining in terms of its remit and implications in the face of escalating developments regarding concepts, theories, technologies, and techniques, in association with climate change mitigation and adaptation. Which provide a single platform where a wildly diverse range of stakeholders coming from technical through non-technical backgrounds and interests could effectively communicate to design an integrated solution and then implement it. In view of the problematisation, the purpose of chapter is to carry out a theoretical review of UHI insinuations leading to categorization, synthesis, and analysis of UHI components. In addition, create a theoretical framework of UHI assessment and management, which clearly maps out the relationship between UHI components regarding both urbanization and climate change that are accelerating the duration, frequency and intensity of UHI.

2 Material and Methods

Initially, we reviewed documents containing the term "Urban Heat Islands" "causes of Heat waves" "UHI contributing factors" etc. then divides the literature into group and categories. Firstly, the documents and research have been studied by a simple review method to extract definitions and different factors of UHI and heat waves and have been categorized through the thematic color-coding method. Coding, as a method of data reduction, means operations in which data are analyzed, conceptualized, and put together in a new way (Table 1).

A thorough content analysis is done in accordance with five important themes. (i) "*climate change*" (ii) "*factors contributing to urban heat island effect*" (iii) "*factors contributing to heat waves*" (iv) *the variability in UHI and heat wave interactions*, and (v) "*Primary and secondary effects of the urban heat island*". Then factor categorization is done using a focused sample of documents of the most relevant and recent studies on the subject. Thematic analysis has been used to analyze the documents' content. Thematic analysis is a form of analysis technique that combines data classification and categorization to glean several fundamental ideas and trends in the research topic. Therefore, data management is the first step (including setting and organizing the data, separating existing data types, placing data in a Specific conceptual and semantic order, and organizing by title and listing). The second step is data

Table1 Framing the review (Carnwell & Daly, 2001)

Method	Approach	Definition
Simple literature Review	Categorizing or dividing the writing into themes	What are the different UHI contributing factors are addressed in the literature
Simple literature Review	Looking into the relevant theoretical and methodological literature	Discussion of the relevant literature is followed by an examination of the methodological literature to help explain why a specific research design might be suitable for pursuing the topic

engagement, which entails steps for open/axial and theme color coding to examine and synchronize data. Drawing the data is the third stage (in this step, the sub-categories, for example, change in urban climatic conditions; change in the duration of sunshine, change in patterns of wind direction & speed; land use-land cover change, urban infrastructure, built material and air quality, etc.) are interwoven in thematic patterns and conceptual diagrams are depicted. The fourth stage is the creation of analysis (at this stage, analysis based on categories and themes begins and develops, which itself includes two steps: modeling and comparing cases and feedback to refine or change emerging categories). Analyzing the fifth phase of the typology is the final stage (Categorizing patterns according to their similarities and differences to highlight the research gap). "UHI-induced anthropogenically" and "UHI-induced naturally" thermal stressors have been assigned as urbanization induced heat and climate change induced heat. The factors have been listed by using sources both primary and secondary. The authors oversee planning, gathering, evaluating, and reporting the data; hence they are the ones who produce the primary sources. The writers' documents and studies are secondary sources, which are specific data that has already been gathered by another individual or group (Fig. 1).

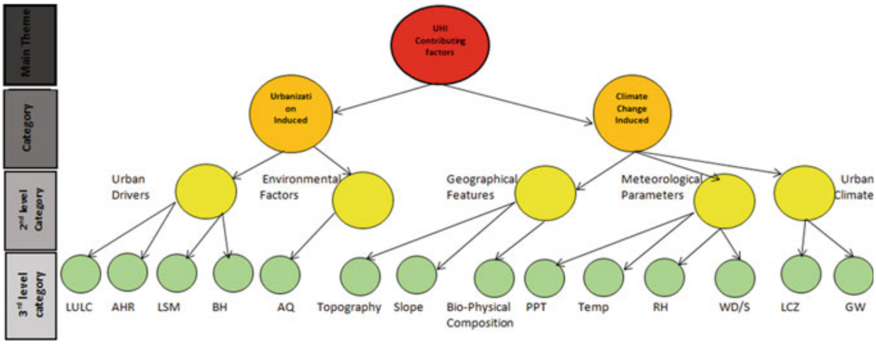

Fig. 1 Mapping literature review (Fundamental themes & Categorization) (*Source* Authors)

3 Urbanization Induced Factors of UHI

Haphazard and unplanned urbanization gave rise to the UHI effect which results in an intensified heat wave. Areas with rapid urbanization have seen an increase in the UHI impact including high-level and exceptionally high-level UHI which intensifies the negative effects of climate change. However, if urbanization is done with climate-friendly urban designs or city layouts may reduce the impacts of the UHI effect. That is only feasible if all the factors that contributed to the rise in UHI in urban cities are properly identified and addressed.

Main urban-induced factors such as surface and air temperature; urban morphology have association with assessment of thermal conditions of any urban settings and use to assess urban heat island (Ayman & Irfan 2022; Li et al., 2017; Peng et al., 2012). Beside those myriad other The urbanization-induced factors that contribute to Urban Heat Island and enhanced land surface temperature of core and dense center of cities as compared to their surrounding are extracted from the literature have been discussed below:

3.1 Urban Drivers

3.1.1 Land Surface Material

Urban surface materials have different capacity to absorb solar radiation that increases UHI (Bowler et al., 2010; William et al., 2005). Urban construction materials like asphalt and concrete store solar heat during the day and discharge it at night. Due to the high heat capacity of urban materials, heat can be trapped in a dense layer.

3.1.2 Site Location and Building's Configuration

The location of tall buildings with continuous slab structures windows and doors placement should be given special consideration because they can obstruct the flow of fresh air and wind and provide different surfaces for levels to reflect and absorb sunlight that warms up metropolitan areas. Urban land cover fraction was found to be extremely consistent with the spatial distribution pattern of urban heat islands. According to one estimate the annual average UHI intensity varies from 1.2 to 0.8 °C, depending on density; ventilation variation due to building heights of urban areas (Elnabawi & Hamza, 2020). Likewise, the capacity to store heat, wind, and evapotranspiration as well as the absorption and reflection of solar radiation are all factors that are influenced by the buildings and structures in metropolitan areas (U.S. EPA, 2013).

3.1.3 Land Use and Land Cover Change

Urbanization leads to rapid and large-scale alteration of the LU/LC pattern, thereby affecting the characteristic radiative, thermal, and moisture properties of urban surfaces and controlling the land surface temperature. This thus creates a Surface Urban heat island (SUHI). As the expansion of the impervious surface greatly affects the thermodynamic properties of the underlying surface and urban green spaces are the best sources to alleviate the impacts of the heatwave (Saleem et al., 2020). Many studies indicate green spaces have a negative correlation with air temperature.

It was estimated that larger parks and areas surrounding parks are 1–2 °C cooler than built-up areas (Oke, 1989), where this temperature difference can vary as much as 5 °C (Upmanis et al., 1998). A reduction in green spaces in the urban area decreases evapotranspiration, shade, and cooling effects of plants that make the city warmer (Shafaghat et al., 2014, United States. NASA) and helps to build a stronger UHI profile.

3.2 Environmental Factors

3.2.1 Anthropogenic Heat Release

Human activities like air conditioning in dwellings, driving, and industrial output all emit anthropogenic heat, which has a negative impact on the climate. (Mirzaei & Haghighat, 2010; Petralli et al., 2014). Directly or indirectly, they contributed to air pollution in addition to the heat emission, which has an impact on both incoming and outgoing radiation (Chen et al., 2011; Li & Zhao, 2012; Sailor, 2011). These tapped radiations along with physical features of an urban area for example high density and forms augment the climate change-induced extreme events. This Change in climate impacts urban air and urban heat island (UHI) (Mika et al., 2018). Whereas urban air quality is sometimes also referred to as urban pollution island (UPI) have correlative interaction with UHI in urban climatology (Giulia Ulpiani, 2021). As urban heat islands impacted air pollution distribution greatly if coupled with wind patterns (Chandler, 1968; Santamouris & Feng, 2018). Yet, the kinds of interactions are relatively underexplored (Czarnecka & Nidzgorska-Lencewicz, 2010). Because interactions between UHIs and poor air quality (Jun Li et al., 2007), sometimes exist in a complicated and intimate pattern of feedback both at regional and local scales be it vertically or horizontally (Oke, 1982).

4 Climate Change Induced Factors

4.1 Geographical Features Based Factors of UHI

4.1.1 Urban Biophysical Composition

In an urban setting, all kinds of land cover (aside from water) can be viewed as a combination of three fundamental biophysical elements: soil, vegetation, and impervious surfaces. Biophysical composition plays a key role in the evapotranspiration process which assists in cooling down the surfaces and air temperature. Because there are more impermeable surfaces in urban areas than in rural ones, evapotranspiration is lower there. As a result, urban green space, including agricultural and forest land, has had a significant negative impact on the UHI effect. Biophysical factorization shows considerable sensitivity of the interaction between UHI and Heat waves to local climate and warming scenarios. As they also contribute to determine evapotranspiration hence UHI Profile (Lei Zhao et al., 2018).

4.1.2 Topography & Slope

At the local level, topography and slope are important factors in the emergence and development of UHI because they influence wind patterns and flow directions (Nitis et al., 2005). Effects of the urban heat island can be broken down into three groups: surface, urban canopy, and border layer. Since topography allows for the existence of the canopy layer of UHI, the majority of studies have focused on the surface and boundary layer effects (Eni et al., 2014).

4.2 Urban Climate

Any set of climatic conditions that are prevalent in a large metro area and are distinct from those of its rural surroundings are referred to as urban climate. Urban climate is also classified on the bases of local climatic zones which have different attributes based on built type and non-built types. Besides that, Global warming is the gradual warming of the Earth’s surface and is attributed to human actions, particularly the burning of fossil fuels, which raises the levels of heat-trapping greenhouse gases in the atmosphere. Cities trapped these gases in different manner. The effect of the said factors has been discussed below:

4.2.1 Local Climate Zone

The built-up density or urban layout of a city determines its LCZ; as urbanization progresses, temperature differentials between the city and the countryside widen the urban heat island, escalating thermal stress. The subject of LCZ study is the UHI phenomenon in Szeged, Hungar, Fuzhou, China, Bogor, Indonesia, and 50 other cities around the world. The thermal conditions of cities are vital considerations for future planning and development. In this regard, Local climate zone maps are most used to steer urban development in the context of surface temperatures (heat waves) (Aymen et al., 2022).

4.2.2 Global Warming

The phenomenon of urban heat island (UHI) has been significantly exacerbated because of global warming and rapid urbanization (Guodong Li et al., 2018). Myriad studies mentioned that the rise in urban heat island (UHI) in urban climate is due to global warming. But very few addressed the outright nexus between Global warming and UHI or the existing ones are not clear. Furthermore, the impact of Global warming upon urban Heat islands (UHI) is also not well and is frequently the target of many overly simplistic and incorrect notions (Alcoforado et al., 2008). The study calculated the amplification in UHIs and its impact on global warming trends. The findings suggest that the UHI effect could account for between 3 and 36% of the observed global warming (Alec Feinberg, 2020). The likelihood of extreme heat events and record-breaking temperatures can rise significantly with even a small increase in average temperature.

4.3 Meteorological Parameters

4.3.1 Wind Direction/Wind Speed

Typically, the vertical profile of the urban heat island is influenced by wind, especially during nights. Wind speed in an urban context is heavily influenced by urban morphology. Many authors have attributed the wind speed decrease to the increase in urbanization. At street level, buildings slow the breeze down by trapping air between them. In the street canyons, buildings also collect long-wave radiation, some of which is reflected to the street level by the sides of the buildings. Growing urban areas, rising temperatures, and air pollution all contribute to a rise in heat island effect intensity, which has an immediate negative impact on human health. More anticyclonic patterns, or a rise in sea level pressure, and fewer cyclonic patterns, because of circulation changes, support UHI (Mika et al., 2018).

4.3.2 Relative Humidity (RH)

Chen et al. (2019) used Humidex (HD) and a single-level Urban Canopy Model (UCM), using high-resolution spatial distribution of air temperature to establish the relationship between humidity, heat index, and UHI intensity within urban environment is necessary to capture urban climate analysis to study complete UHI profile microclimate to macro climatic level.

5 UHI Conceptualization

The conceptualization has been developed by keeping in view the interaction between UHI and Heat waves threefold. At the first level, meteorological conditions e.g., calm air raised temperature and temperature inversions which favor the Heat waves. At the secondary level, human-induced activities in form of land use/land cover change and the Release of anthropogenic heat add to trap the heat up to the boundary layer of the UHI phenomenon. at the third level, the climatic induced factors such as global warming and local climatic situation add in further enhance the boundary layer in form the canopy layer which raised and more intensified form of UHI effect the overall phenomena is the primary reason for shifting the average temperatures; That particular situation mostly developed due to some factors favors by Urban Heat Island effect. On the other side the episodes of heatwaves due to other factors also amplifying the UHI, this could raise the local phenomena of UHI on a Regional and global scale. This needs also be addressed as a 1.5 K increase in global temperature increase likely to intensify the UHI phenomenon, yet the UHI effect is very complex, and its behavior is strongly influenced by macroclimatic factors, it must be researched on multiple levels (Mika et al., 2018). Furthermore, the impact of Global warming upon urban Heat islands (UHI) is also not well understood and is often the object of many overly simplistic and erroneous ideas. The compiled approaches in different studies are finally harmonized to conceptualize the relationship between UHI and heat waves (Figs. 2 and 3).

6 Concluding Remarks

The comprehensive approach to address the phenomenon of UHI catering to all relevant factors has not been explored, according to a review of the literature, no similar study has been carried out and the existing ones are not clear about the all-encompassing factors of UHI. To date, no framework exists for appropriate UHI planning in urban areas. Hence, this study focuses on two strands, firstly reclassification of factors contributes to the Urban Heat Island in the context of urbanization and climate change. The synthesis of the literature review revealed that most of the

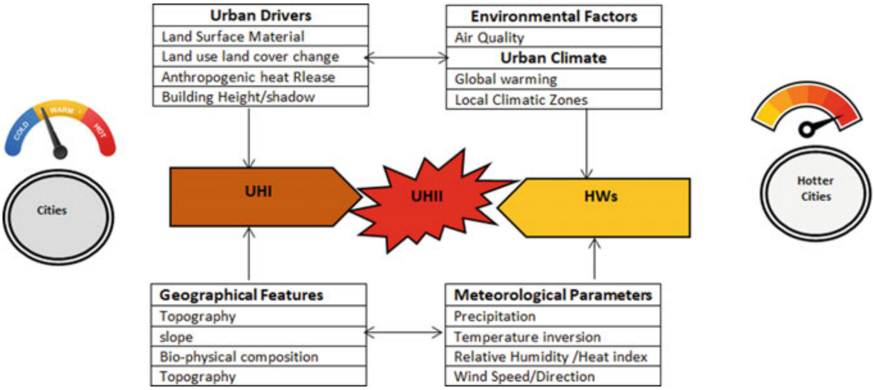

Fig. 2 Inter-relationship of UHI and Heatwave Factors (*Source* Authors)

studies have utilized the urban heat island phenomenon and land surface temperature interchangeably. Moreover, in many studies, UHI considers factors that roam around urbanization and development patterns. This leads to confusion and miscommunication among different stakeholders. The confusion arises due to differences in temporal and spatial scales, research methods, and data sets, as well as the lack of a comprehensive theoretical framework.

Cites are predicted to face more thermal stressors over time if not planned well. Investigating and considering all causes that raised UHI profile is important. It can assist to make more informed decision making by pinpointing measures against the major factors that could exacerbate urban overheating and, in turn, aid in the creation of effective mitigation strategies. Therefore, the current study offers a thorough summary of research on UHI profiling. Even though many research topics have been covered in the open literature, it is discovered that several research gaps still exist and should receive more attention. Examples include *failing to consider different UHI types* and their connections and *failing to consider the long-term effects of heatwave events.*

Furthermore, it highlighted twofold interaction between Urban Heat Island and the heatwave at first. Heat waves are weather phenomena that require different metrological conditions to form (e.g., calm air, raised temperature, and temperature inversions). That situation mostly developed due to some factors favors by the Urban Heat Island effect (Which has been discussed in every literature). On the other the episodes of heatwaves (due to climatic and non-climatic factors) also amplify the UHI, this could raise the local phenomena of UHI on a Regional and global scale (This needs also be addressed). Considering the above discussion, it is recommended for future research.

1. While urbanizing the existing city or even producing another city thermal stressors needed to be cautiously and effectively considered to mitigate urban heat islands (UHI).

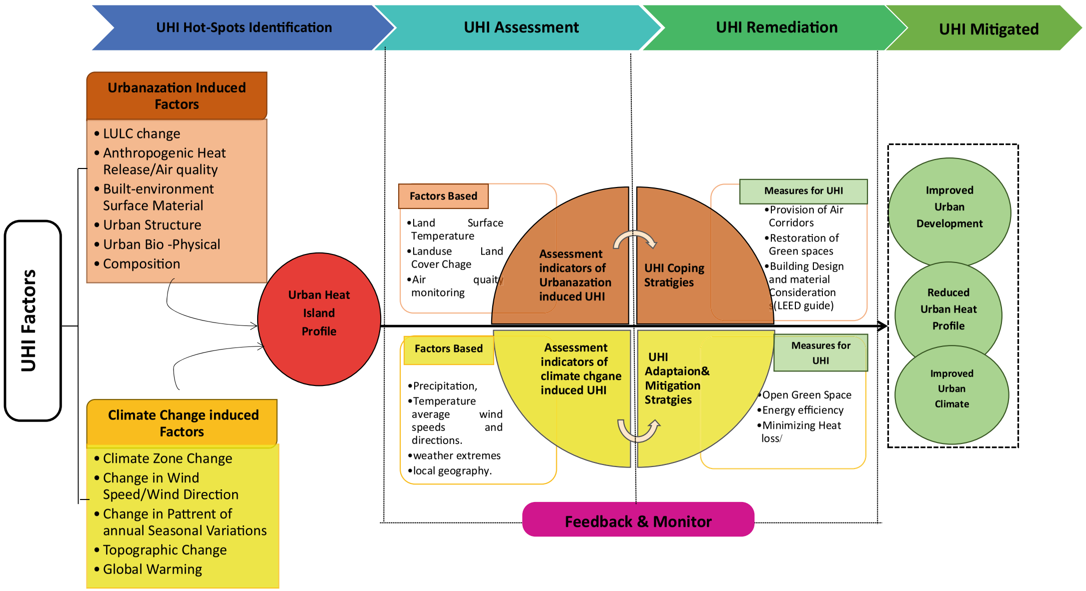

Fig. 3 Anti-UHI management framework (*Source* Authors)

2. There is a dire need to Outline the holistic Policy Framework to Reduce Urban Heat Island Effects which would cater to all contributing factors comprehensively.
3. Urban heat from multiple sources turns Cities into hotspots that need to be addressed by an integrated approach; a whole-system baseline study system is required for a more holistic understanding of heatwave and Urban Heat Island (UHI).

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Part II
Mitigation and Adaptation Strategies

Chapter 6
Contribution of Bodies of Water to the Mitigation of UHI Effect in Urban Canyon: A Parametric Study Approach

Nedyomukti Imam Syafii and Masayuki Ichinose

Abstract To find effective design solutions for bodies of water for better urban thermal environment, a series of comprehensive studies have been conducted utilising an outdoor scale model canopy in Saitama, Japan, and coupled numerical model. The simple form of the outdoor scale model has the advantages of enabling the observation of various physical phenomena under actual climate conditions and conducting comprehensive measurements of a relatively uniform area, thus providing results that are easy to interpret. Meanwhile, numerical modelling allows a series of various bodies of water configurations to be analysed and compared. By modifying its basic physical properties, the present study shows evidence of the positive contribution of water ponds to the urban thermal environment. The presence of water ponds inside an urban canyon reduced the air and radiant temperatures throughout the day. The result also shows that, generally, a bigger pond has greater cooling benefits. A bigger pond tends to absorb more heat and has a more evaporation surface. As shown in the measured air temperature, water temperature and globe temperature profile, a larger portion of the radiant energy absorbed within the canyon is dissipated by evaporation rather than converted into sensible heat. This phenomenon shows the critical role of the bodies of water's thermal capacity while also opening the possibility of manipulating these parameters for a better urban thermal environment. When there is a space constraint within urban spaces, introducing chilled water may help further improve the cooling benefits of urban bodies of water bodies.

Keywords Bodies of water · Cooling effect · Outdoor scale model · CFD · Urban thermal environment

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1 Introduction

The arrangement and orientation of urban elements and landscaping are important considerations regarding mitigating the adverse effects of UHIs and providing better urban pedestrian comfort. Urban bodies of water, which are usually defined as a collection of water in the form of stationary water or pond, are considered potential thermal environment amelioration. Yet, there is still a lack of interest in research and design recommendations. Researchers have done a large number of studies on the ability of the water body to improve the microclimate of the urban environment, despite the fact that their findings are still limited. In general, the results of these investigations showed that the air temperature was 1–3 °C lower near bodies of water (such as rivers, lakes, or water ponds) than those found nearby built-up areas, especially during the day (Chen et al., 2006; Hathway & Sharples, 2012; Ishii et al., 1991; Nishimura et al., 1998; Saaroni & Ziv, 2003).

Thus, the present study aims to evaluate the mitigating capacity of bodies of water to their immediate surrounding while finding the influential factors and the effective design solution to compromise space limitations within an urban setting. Given the context, the current study aims to understand the relationship between microclimate and bodies of water for a better urban thermal environment. The study attempts to elaborate on finding effective water pond configuration through parametric study with a scale model and numerical modelling. Several climate parameters, including air temperature, humidity, radiant temperature, and water temperature, were measured, analysed, and monitored to understand the changes in the thermal environment due to the presence of bodies of water. The scale model more accurately represents the actual urban environment, which is set outdoors and features less complexity. Changes in the thermal environment can be detected inside of a scale model in a somewhat homogeneous area and under real climate conditions. Meanwhile, numerical modelling allows a series of water pond configurations to be analysed and compared. With both, the results are easy to interpret while yielding comprehensive results. After that, other scenarios are being built with different pond configurations, one of which is a no-pond condition that serves as a point of reference and is unaffected by any of the surrounding bodies of water. Ultimately, this study demonstrates that understanding these configuration changes is as important as understanding the cooling effect to have effective bodies of water as mitigation strategies.

2 Assessment Method

The study proposes field measurements and parametric study with numerical simulation as the main research methodologies to achieve the objectives. The first method employs on-site field measurements and a model to estimate the cooling effect of bodies of water on a smaller scale and their variability. This methodology aims to gain a deeper understanding of the thermal benefits that bodies of water provide to urban areas. The second method involved performing numerical analysis in order to provide more comparison and analysis. The following is a synopsis of each of the methods mentioned.

2.1 Field Measurement at COSMO

Two separate experiments were carried out inside COSMO over the summers of 2015 (July–August) and 2016 (August–September), as shown in Fig. 1. The Comprehensive Outdoor Scale Model, known as COSMO, is a 512-cube cubical layout that was built in the Japanese prefecture of Saitama. The painted dark grey cubes were formed from concrete, had a hollow interior, were 1.5 m on each side, and were 1.5 m away from one another. In order to accurately represent a cityscape characterised by low-rise buildings, the model was intended to have a scale of 1:5 (Kanda, 2006; Kanda et al., 2007; Katayama et al., 1990; Kawai & Kanda, 2010a, 2010b).

During this field study, various pond configurations were developed inside the COSMO canyon, including a no-pond condition that served as a point of reference (Fig. 2). A big pond was built for the experimental study conducted over the summer of 2015 (Fig. 2—top) in order to monitor the micro climate fluctuations along a line parallel to the COSMO's long axis. The pond measured 1.5 m × 6 m and had a depth of 0.15 m. In addition, a series of control measurement points were installed in a nearby canyon to reference the no-pond case for comparison purposes. Meanwhile, over the summer of 2016, five distinguish pond configurations were installed for the experimental study. Smaller ponds (1.5 m × 0.5 m, 0.15 m depth) were utilised to test the effect of different pond orientations and water surface area (Fig. 2—mid). The smaller ponds used in this second experiment enable a more focused study. The following is a list of the several configurations of the pond: In Case 1, there are three ponds; in Cases 2 and 3, there are two ponds located around the canyon's edge; and in Cases 4 and 5, there is one small pond located in the middle of the canyon.

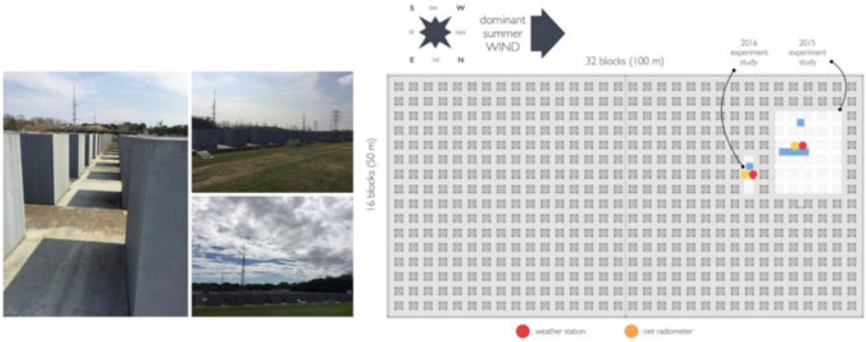


Fig. 1 Footage and plan view of the overall experimental study at the COSMO (Syafii et al., 2017a)

Each case was installed and measured independently within the same canyon to limit the variation due to different canyon physical conditions. Concurrently, an additional experimental investigation, including chilled water, was carried out inside the COSMO canyon to better understand water temperature variations' influence on the surrounding area's thermal environment (Fig. 2—bottom).

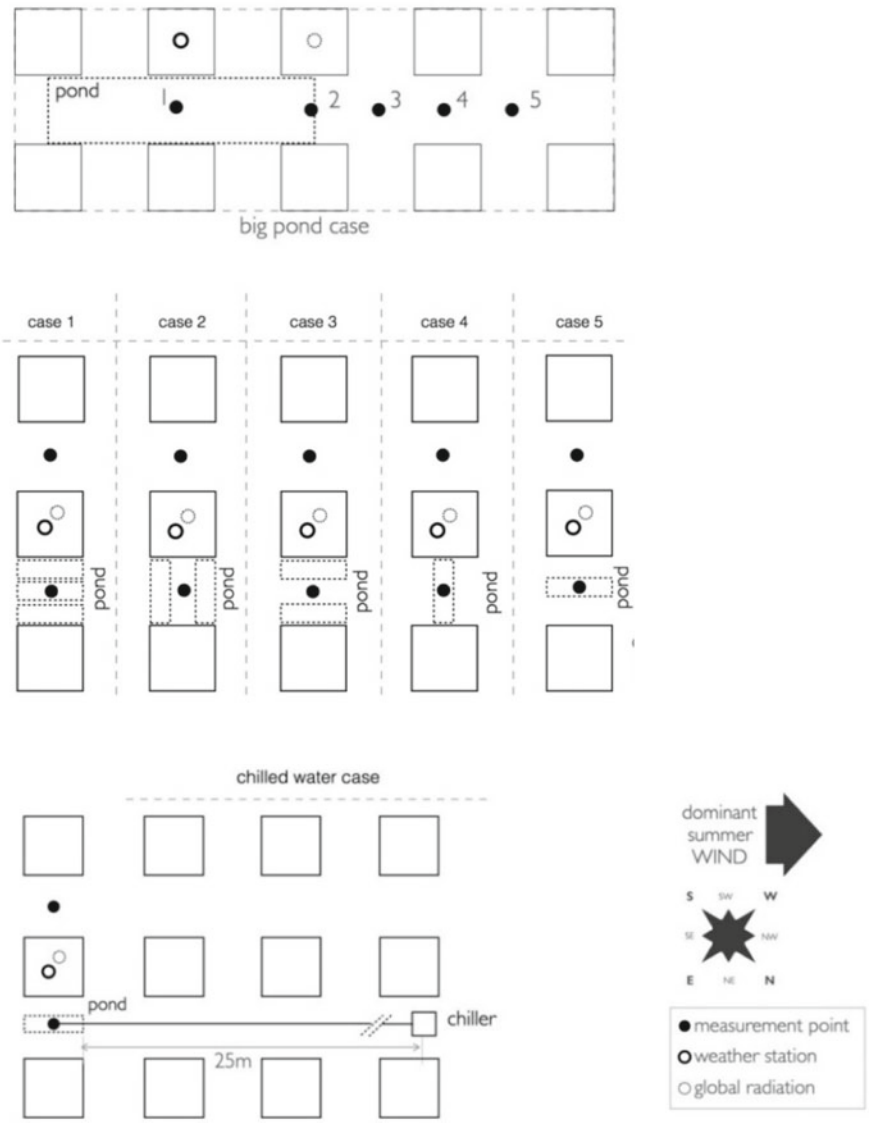


Fig. 2 COSMO experimental studies plan view (Syafii et al., 2017a, 2017b)

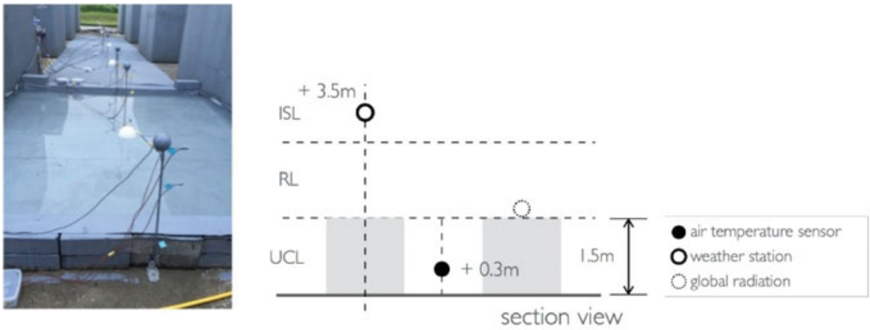


Fig. 3 Detail positioning of the field measurement equipments for the COSMO—experimental study (where UCL: Urban Canopy Layer, RL: Roughness Layer, ISL: Inertial Sub layer) (Syafii et al., 2017a)

The experiments with chilled water utilised a chiller to keep the water temperature at 15 °C. The chiller was located far from the measuring site, so the heat it generated did not affect the measurement outcome. In addition to advancing our understanding of the effect of water temperature, the experimental study with chilled water opened the possibility to utilise urban bodies of water more efficiently.

Thermocouples (*TCs*) wires—type-T are utilised on the outdoor scale model at each measurement point to obtain accurate air temperature readings. The measurements were taken at the height of 30 cm above the ground, which corresponds to a scaled-down version of the typical height of a human being (Fig. 3). In order to measure the reference climate, one weather station was placed three meters above the COSMO canopy, and one pyranometer (EKO ML-01) was positioned directly above the COSMO blocks.

2.2 Parametric Study with Coupled Numerical Modelling

The numerical study combines Computational Fluid Dynamics (*CFD*) and Surface Temperature (*ST*) computation. It’s a steady-state simulation that uses the Reynold averaged Navier–Stokes (RANS) model that examines time-averaged wind and temperature over a neighbourhood-scale area. *ST* computed unstable 3D temperature distributions utilising building thermal structure, building model and surface material. On the other hand, the fluid computation determined the distributions of temperature and wind by taking the mean of the 3D surface temperature distribution obtained from *ST* computation. Table 1 displays the equations that are relevant to the *CFD* analysis. The present investigation does not cover the detailed *CFD* algorithm that was applied in this instance. For further information, Ashie Kono (2011) and Ashie (2016) provide additional knowledge regarding the calculation of surface temperature and CFD.

Table 1 Summary of simulation code for CFD calculation (Syafii et al., 2021)

Item	Description
Flow field	Compressible compound flow under a low Mach number condition
Governing equation	• Continuity equation • Momentum equations (Effects of buoyancy, Coriolis force, and drag forces of plants are taken into account.) • Energy equation (Formulated using potential temperature. Release of sensible heat from artificial sources, walls, etc. is taken into account.) • Transport equation for water vapour (Formulated using specific humidity. Release of latent heat from artificial sources, wall, etc. is taken into account.) • Transport equation for turbulent kinetic energy, k (Production of turbulent energy by buoyancy, humidity, and plants is taken into account.) • Transport equation for dissipation rate of k, ε (Dissipation of turbulent kinetic energy by buoyancy, humidity, and plants is taken into account.) **All equations are formulated based on FAVOR
Turbulence model	Standard k-ε model
Coordinate system	3-dimensional Cartesian coordinate system
Computational grid	Staggered grid
Discretisation method	Finite difference method
Spatial discretisation	1st order upwind differencing scheme (For advection term.), 2nd order central differencing scheme (Except for advection term.)

In order to conduct the parametric analysis, 11 examples were developed, each of which represented the condition of an urban canyon after it had been subjected to a different configuration of urban water bodies. Figures 4 and 5 present the numerical model domain as well as an overview of the models used in the parametric analysis, respectively.

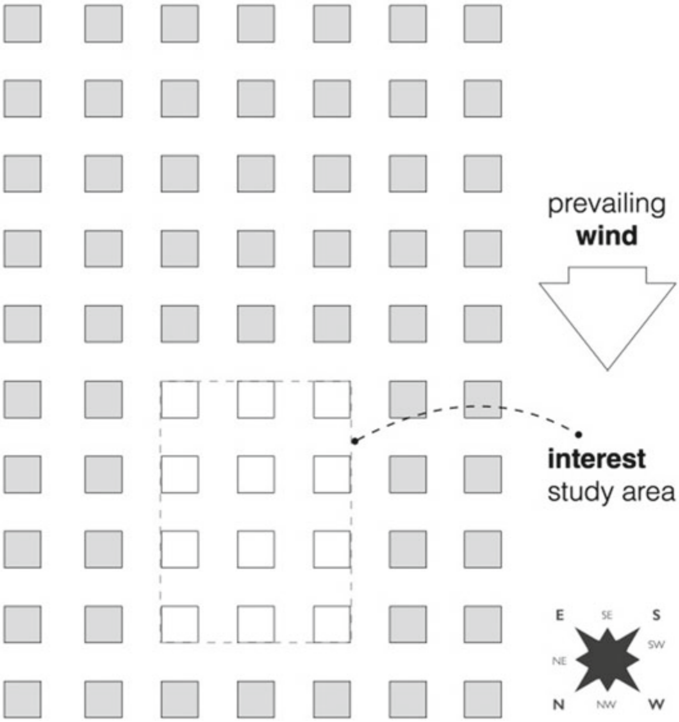


Fig. 4 Numerical domain for parametric (Syafii et al., 2021)

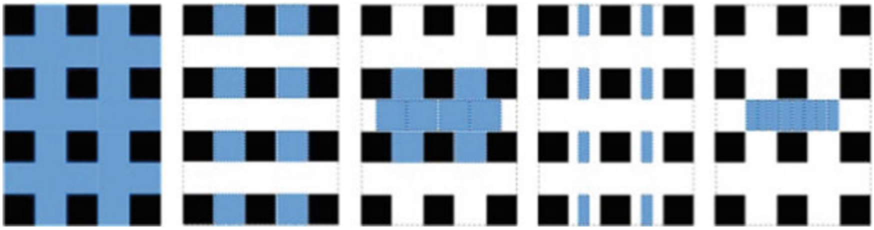


Fig. 5 Model plan for parametric study (left to right): all pond; big pond equally distributed; small pond equally distributed; big pond centred; small pond centred (Syafii et al., 2021)

3 Results and Discussion

Based on the research objectives presented, an attempt is made to highlight the cooling benefits associated with bodies of water by using the methods stated above (scale-model experimental study and parametric study with numerical modelling). In the following section of the chapter, a summary of the key findings will be presented.

3.1 Spatial Cooling Benefits of Bodies of Water

The experimental study conducted at COSMO demonstrated the thermal influence of water ponds as well as the potential advantages of these features for enhancing the urban microclimate and mitigating the effects of the UHI. According to the findings, the existence of water ponds had the ability to bring the average air temperature down throughout the course of the day. This influence was felt beyond the area of the water ponds, and it was felt most strongly in the area that was downwind, as illustrated in Fig. 6. The figure illustrates the difference in air temperature between each measurement point in relation to the reference (*Ta*). The information was provided as an average of over one minute and was shown using trend lines derived from moving averages. It was typical for *ΔTa* to have a negative trend most of the time throughout the day. This would imply that the mitigating effect of urban bodies of water could occur not only during the day but also during the night, albeit to a lesser extent.

Interesting patterns can also be seen on the graph, which illustrates the influence of various other parameters on *ΔTa* diurnal profile. At the start of the day, there were

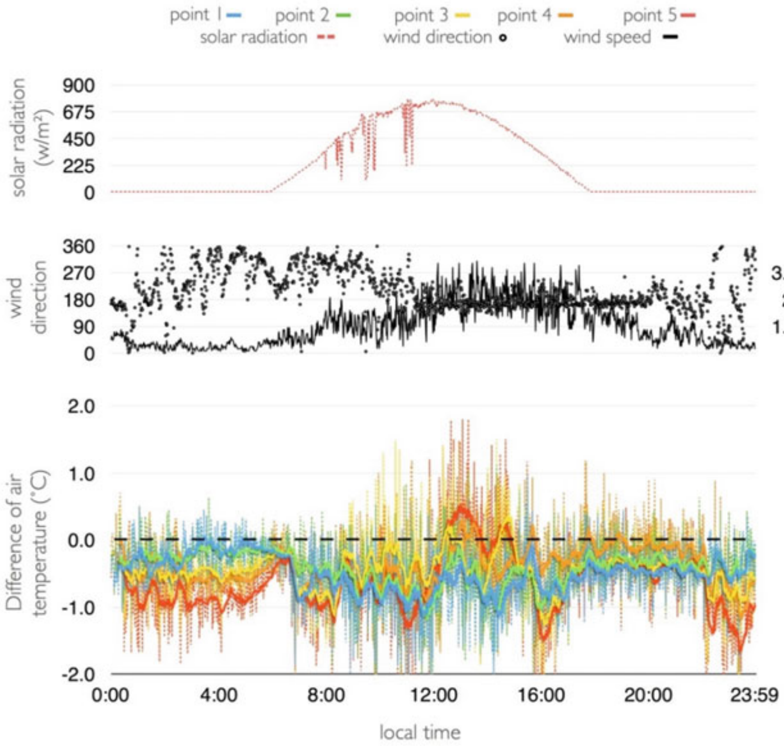


Fig. 6 Diurnal air temperature difference (*ΔTa*) profile of points near the water bodies respectively from the points at the reference case

sudden temperature changes due to the availability of solar radiation. All the points appear to experience an increase in air temperature at varying warming rates. Later in the morning, evaporation induced by solar radiation caused the air temperature to decrease. Throughout the day, the temperature of the air decreased. At the time when the solar radiation is at its highest, the wind speed is more than one meter per second, and the wind direction is relatively stable, the *Ta* at points near the pond (Points 1–2) tends to show lower values as compared to the *Ta* at points away from ponds.

The following noticeable pattern emerged over the night. Even when there was no solar radiation and the wind was still blowing from the southeast direction upwind of the pond, practically all of the points that were close to the water ponds were still cooler than the reference. The points closest to the water pond had the lowest air temperatures in this pattern, which is similar to the pattern seen during the day but with less temperature variation. On the other hand, an interesting pattern appeared when the wind speed was very low (less than 1 m per second). During this time period, the profile of the air temperature had a significantly more pronounced decreasing profile, which followed a reversed pattern. The fact that point no. 5 was the coldest and points 1 and 2 were the warmest led researchers to conclude that the pond cooled off more slowly than the concrete surface did throughout the night. Regardless, there is also the possibility of unexpected effects coming from the surrounding cooler grass area close to the COSMO as a result of changes in the wind direction.

3.2 Influence of Pond Size and Orientation on the Thermal Environment

During the summer of 2016, a further experimental study was conducted. The experimental study results provide evidence of bodies of water's effectiveness as early-stage design and planning solutions to improve urban thermal environments. In accordance with prior research, this experimental study demonstrated that the presence of water ponds was capable of regulating the local thermal environment, despite the fact that varied pond layouts and changes appeared to produce different daily temperature profiles (Fig. 7).

In general, larger ponds provided more benefits in terms of temperature reduction. Nevertheless, the lack of available space in urban canyons could necessitate additional design adaptations. When the ponds were oriented parallel to the prevailing winds, temperatures were reduced by up to 2.1 °C compared to the reference condition. These findings demonstrated that certain configurations of ponds tend to have a better ability to maintain low radiant temperatures than others. Because of this, it was more likely that certain designs would achieve improved pedestrian comfort.

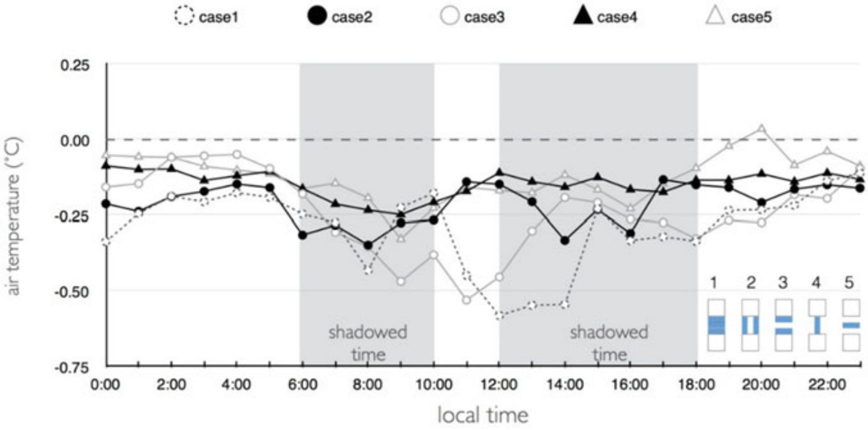


Fig. 7 Hourly average profile of air temperature difference (*ΔTa*) of summer 2016 experiment study (Syafii et al., 2017a)

3.3 Enhancing the Mitigating Capacity of Water Bodies

During the experimental study in the summer of 2016, a different experiment with cold water was carried out. In theory, a larger part of the radiant energy absorbed within the canyon is lost due to evaporation rather than being transformed into sensible heat. This is because evaporation is less efficient than the conversion process. In light of the evidence presented, which demonstrates that the thermal capacity of the water bodies plays an essential role, cold water was added to the water bodies. As can be seen in Fig. 8, the results indicate that the use of chilled water leads to an increase in the cooling benefit.

The *Ta* improvements were observed to increase by as much as 0.3 °C when compared to the natural water conditions. By keeping the temperature of the water at a low level, it was possible to eliminate the heat that the water pond had absorbed, following the previous findings (Syafii et al., 2017b). These conditions limit the release of sensible heat, hence decreasing the air's temperature. Although adding chilled water can greatly improve and further boost the cooling benefits, maintaining the water's temperature low may need additional energy. As a result, it is necessary to manage the trade-off between the demand for cooling and the actual cooling of the water, which can be done by using cool groundwater.

3.4 A Numerical Modelling for Parametric Studies

In order to evaluate the differential impact of different urban water pond layouts and thermal capacity (water temperature) on the urban thermal environment, a simulation

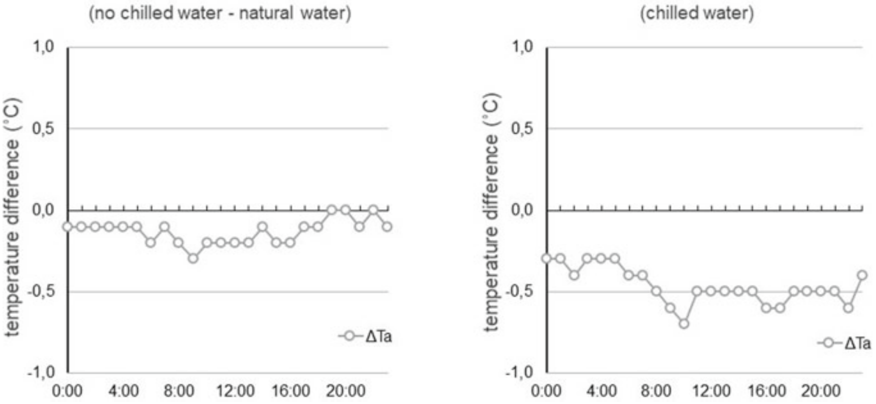


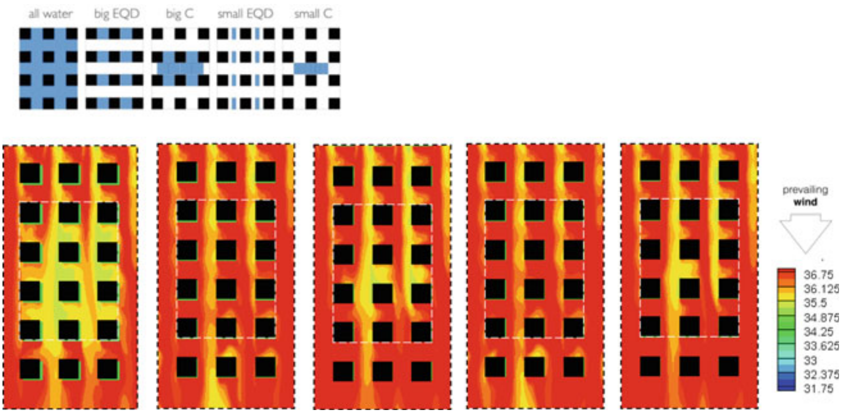
Fig. 8 Summer 2016 experiment studies averaged hourly profile of air temperature difference relative to a reference point (*ΔTa*) for a pond with natural water condition (left) and chilled water condition (right)

of 11 unique cases was conducted and evaluated. Generally, the findings of the numerical study shed even more light on how critical it is to properly arrange and position different types of bodies of water. Relative to the wind that blows most frequently, water ponds with a larger surface area and a more dispersed distribution have a greater potential to exert their impact across a broader area.

Figure 9 illustrates how the different configurations of the water ponds affected the temperature gradients throughout the surrounding air. It was established that the temperatures found around the big pond with the centred design had the lowest air temperature when compared to the temperatures found around the pond with the other configurations. On the other hand, the cooling effect seemed to be most noticeable in the centre of the area of interest, where the water pond was situated. In contrast, the large water pond that was distributed uniformly had a tendency to have a cooling impact that was more widespread. It was discovered that the cooler air temperature almost completely covered the area of interest. Although the cooler air is not as noticeable, the same trend was seen in the configuration of the smaller ponds.

The findings from the field measurements indicate, in addition, that the addition of a water pond containing cooled water may be able to reduce the air temperature further. In order to improve the efficiency of the design of the chilled water pond, it was necessary to conduct tests on three distinct water pond layouts, each of which included the addition of chilled water. Figure 10 illustrates the air temperature distribution of both the large and small pond configurations, with one having a measured water temperature of 37 °C and the other having a predetermined water temperature of 15 °C.

In general, the addition of a water pond containing chilled water was, in fact, successful in further reducing the ambient temperature. It was determined that the cooling effect would grow pretty dramatically if the size of the pond was increased.



All water Big equally distributed Big centered Small equally distributed Small centered

Fig. 9 Distribution of air temperature of different water pond configurations (Syafii et al., 2021)

The magnitude of the cooling improvement could also be noticed extending beyond the area of concern. The cooling improvement that was achieved using chilled water in the small pond design appeared to be superior to that achieved in the large pond arrangement where chilled water was absent. Suppose there is a shortage of space in the urban area; this finding may suggest a novel approach to finding a solution for enhancing the effectiveness of existing bodies of water cooling benefits.

For further investigation, the occurrence of lower air temperature in each scenario was assessed and compared to determine the relationship between the possible benefits of the water body and the design configurations regarding the cool area ratio or CAR. The occurrence of cooler air temperature was derived using a simple mathematical calculation from the difference in air temperature in each case relative to those found in no water condition as the reference, ΔT_c:

$$\Delta T_c = T_c - T_r \tag{1}$$

where T_c is the air temperature calculated from cases with water ponds, and T_r is calculated from cases with no water ponds. This attribute can provide a basic overview of the cooling intensity and the factors that influence it. While the cool area ratio (CAR) is defined as the ratio of the total area where the cooling effect occurs (A_{Cool}) relative to the total unbuilt area inside the area of interest (A_{Total}):

$$\mathrm{CAR} = \frac{A_{Cool}}{A_{Total}} \tag{2}$$

Figure 11 illustrates the CAR between the cases in addition to the maximum and average air temperature differences. According to the result, the cooling benefits of the centralised configuration exceeded those of the evenly distributed configuration.

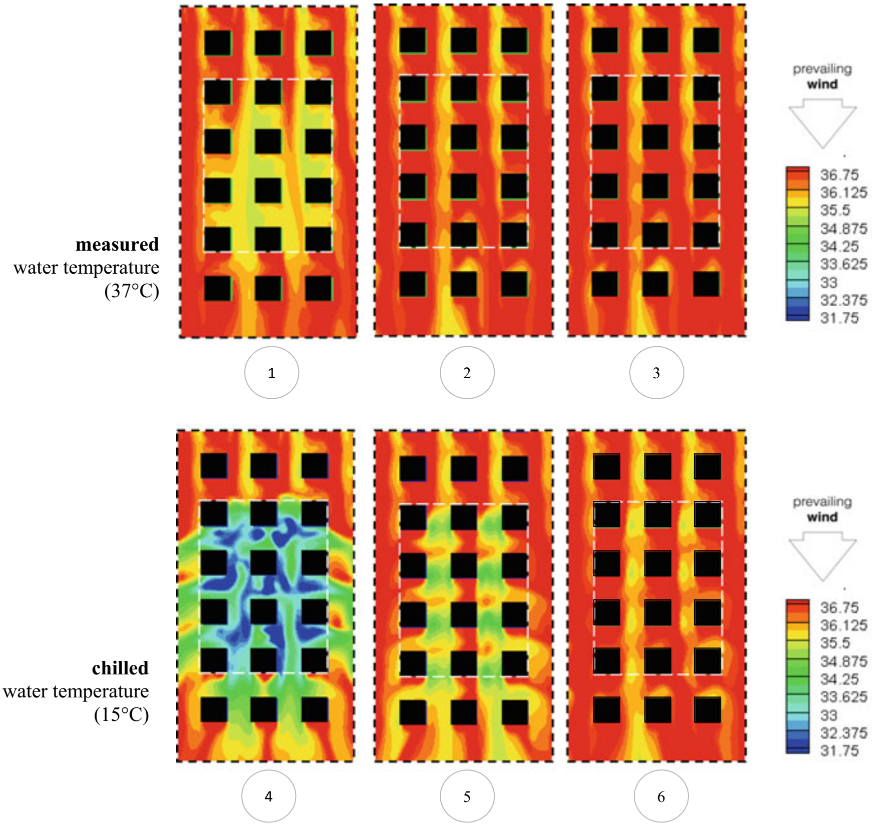


Fig. 10 Horizontal distribution of air temperature of different water pond configurations with different water temperatures: (1 & 3) all water configurations (2 & 4) big pond equally distributed, (3 & 6) small pond equally distributed (Syafii et al., 2021)

The colder air region was more pronounced and had a lower maximum air temperature in the central configuration. However, when considering the average value and air temperature distribution, configurations with uniform distribution have a greater impact over a bigger area. Additionally, the numbers indicate the significance of having a bigger water surface area. On the other side, introducing chilled water may further enhance the cooling benefits, but it will also intensify the cooling effect.

4 Conclusions

Due to the urban environment being comprised of a wide variety of complex surface features that influence its thermal environment, it is essential to design comfortable urban spaces. This indicates that the interaction between the urban canyon and the

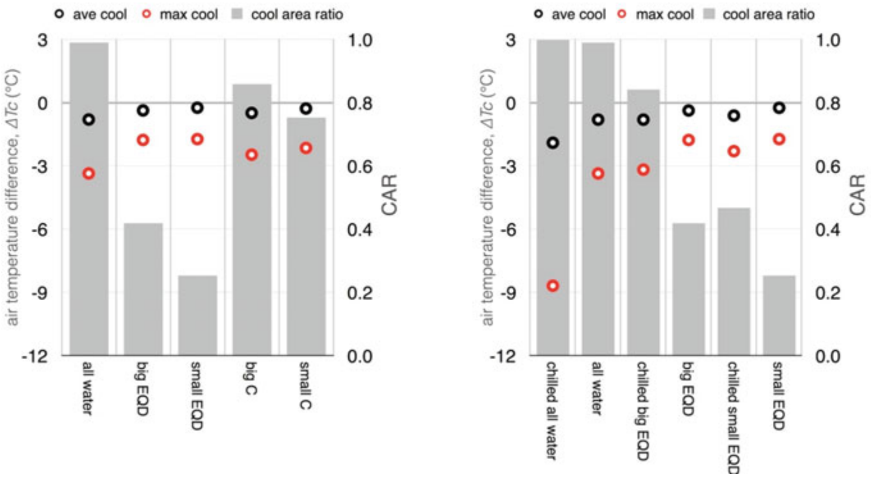


Fig. 11 Correlation of air temperature reduction with the cooler area ratio (A_{Cool}/A_{Total}) and its cool air occurrences

microclimate has been thoroughly documented in order for it to be translated into a clear direction for all of the stakeholders involved with the urban environment, including the designer, the planner, the owner, and so on. This study aimed to better understand the cooling benefits provided by urban water bodies while also attempting to combine theoretical knowledge with the practical design process. Nevertheless, the current research provides substantial evidence of the potential advantages of water bodies for a more wholesome thermal environment. Additionally, the research attempted to add to a general knowledge of the interaction between the characteristics of urban microclimate, notably air temperature, and the physical attributes of water bodies (e.g. size, configuration, orientation). The study highlights the importance of having an adequate water pond layout and composition. For instance, the air temperature reduction achieved by a particular water pond design relies on its positioning in relation to the buildings in the immediate vicinity. According to these research findings, Table 2 outlines the potential advantages of implementing the mitigation strategies.

With this new knowledge, this study suggests the possibility of guiding future design improvements for effective UHI relaxation solutions, taking into account the following points: (1) The positioning of urban bodies of water is something that needs to be carefully considered in order to arrive at the most efficient design solution for a better urban thermal environment; (2) the orientation of bodies of water should be chosen in relation to prevailing winds in order to achieve the optimal distribution of cool air; and (3) water temperature modification (chilled water) opens up possibilities as an effective alternative to improve the thermal performance of bodies of water. The water being cooled and re-cooled multiple times may provide other issues that need further study.

Table 2 Water body's potential cooling benefits

Water bodies intervention	Pond size to canyon area ratio	Potential benefits	
		T_a reduction (°C)	
		Day	Night
3 pond	1	0.36	0.2
2 pond perpendicular	0.66	0.25	0.17
2 pond parallel	0.66	0.33	0.15
1 pond perpendicular	0.33	0.18	0.11
1 pond parallel	0.33	0.18	0.06
Centralised configuration		Have higher T_a reduction, but the cool air accumulates near the pond	
Equally distributed configuration		Have better distribution of cool air	
Chilled water temperature		Improve the cooling benefits (double the occurrence of cool air)	

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Chapter 7
The Challenge of Cooling Rapidly Growing Cities: The Case of Densification and Peri-Urbanisation in Ho Chi Minh City and Adaptation Responses

Antje Katzschner, Nguyen Kieu Diem, Thanh Hung Dang, and Nigel K. Downes

Abstract Climate change and social-economic development are expected to compound climate changes risks. For southeast Asian cities, the phenomenon of urban heat islands and extreme heat waves are a current and future concern for public health, well-being and household energy consumption due to increased cooling demands of urban residents and limited resources to cope. Urban heat island studies using remotely sensed imagery have already revealed that Vietnam's major cities are characterized by strong temperature differences between urban and rural areas. As a result, implementing adaptation measures based on solid science is critical to mitigating the negative effects of heat on urban residents and adapting infrastructure. While different adaptation measures are currently debated by the political authorities in Vietnam, decision-making is hampered by multiple scientific knowledge gaps and the lack of practical tools to support decision-making. This chapter presents methods to investigate and monitor recent urban development in Ho Chi Minh City, an emerging megacity and economic powerhouse of Vietnam.

Keywords Ho Chi Minh City · Urban heat Island · Spatial planning · Adaptation · Megacity · Heat risk · Vulnerability

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1 Introduction

Southeast Asian cities are on the frontline of climate change. Generally, these cities tend to be more exposed to flood risks, foremost as a result of their location, close to the coast, their low elevations, and if located in intertropical regions, the significant annual variations of weather extremes they incur. The threat of future climate change will in all probability exert impacts on cities' urban space, as well as their livability and functionality. The assessment of the influence of space and location as a foundation for intervention is key to the function of spatial planning in responding to climate change (Schmidt et al., 2013; Storch et al., 2011).

In addition to above mentioned risks, rapid urbanization leads to an escalation of the Urban Heat Island effect (UHI), where the temperature in buildup areas are higher than its adjacent areas (Dang, et al., 2018; Katzschner et al., 2016a, 2016b; Oke, 1995; Son et al., 2017). The UHI stresses exacerbate the risk of both climatic and environmental hazards such as heat stress, as well as chronic and acute exposure to air pollutants due to lower ventilation. Climate change that has the potential to influence the severity, temporal patterns, and spatial extent of UHI in urban settings (Dang & Pitts, 2020; Downes et al., 2016). UHI impacts are felt primarily at night because roads and other surfaces that absorb solar radiation during the day emit heat at night (Oke, 1982).

UHI may also be harmful to people's health and cause discomfort. Thermal stress may have a significant impact on human health. For years, climate change research have predicted a rise in temperature. These circumstances, exacerbated by the UHI effect, are predicted to have an impact on the quality of life in cities in the future. Planners must adapt to these changes in urban and regional climates by adopting the precautionary principle and ensuring that thermal stress for individuals outside and indoors is lowered to a bearable level in the future, as well as the use of regional climate maps for land use planning.

Previous studies have shown Ho Chi Minh City as a city at the frontline of climate change challenges (Birkmann et al., 2010; Hanson et al., 2011; Storch & Downes, 2011, 2013; Thuc et al., 2016). The environmental challenges the city is facing are not new to the urban system of HCMC. The region has long worked on adaptation strategies (e.g., settling on elevated ground, building urban structures accordant to winds, trading on and living with- and on- the water). Over the past forty years, however, the impacts of climate change have been increasing. This situation is again intensified by development pressure caused by population growth, economic growth and higher levels of resource consumption (including land) leading to an increase in land coverage, waste production, and—especially within the past years—traffic. Vietnam has struggled to yield policies, approaches, and planning guidelines to combat the adverse impacts of UHI development. The approach of using climate function maps as a planning tool offers the possibility of to analyse the urban climate and identify potential or risk areas. Within the project "Megacity Research Project TP. Ho Chi Minh – Integrative Urban and Environmental Planning Framework - Adaptation to

Global Climate Change” funded by the German Federal Ministry of Research and Education (BMBF) an urban climate analysis map for HCMC was developed.

2 The Growth Challenges of Ho Chi Minh City

Ho Chi Minh City (hereafter HCMC), Vietnams largest metropolis is characterized by rapid socioeconomic and environmental transformations. HCMC’s transformation over the last 30 years has been inextricably linked to the process of rapid industrialization that followed the Doi Moi reforms of 1987. This political move toward market liberalization and an export-driven economy led in extraordinary economic development and poverty reduction. The majority of the country’s growth has been metropolitan, as seen by HCMC’s fast urban expansion. The population of HCMC has essentially more than doubled from 3.78 million in 1986 to 9.22 million in 2020. This is an increase of 2.0% over 2019 data. In 2020 urban population accounted for 77.7% of the total population with 7.17 million people an increase of 1.7% over 2019, while the rural population accounted for 22.3%, 2.05 million people; rising by 3.0% to the previous year (Fig. 1). These estimates, however, do not include an estimated extra 2 million unregistered migrants in the city and do not include exurban areas outside the administrative limits that comprise Greater HCMC (Downes, 2019). The rapid economic growth and evolving residence laws across Vietnam, contributed in a distinct housing shortage, placing the country on a similar trajectory as other Asian tiger economies, with a large net-migration pouring into cities such as HCMC, straining the existing infrastructure.

Fast growing and rapidly expanding cities such as HCMC have intrinsic and characteristic development patterns, which are already affected by current climate change impacts and together with future impacts will lead to a multitude of adverse secondary and cumulative development challenges over the coming decades. Over the previous 20 years, HCMC’s tremendous urbanization and precarious growth

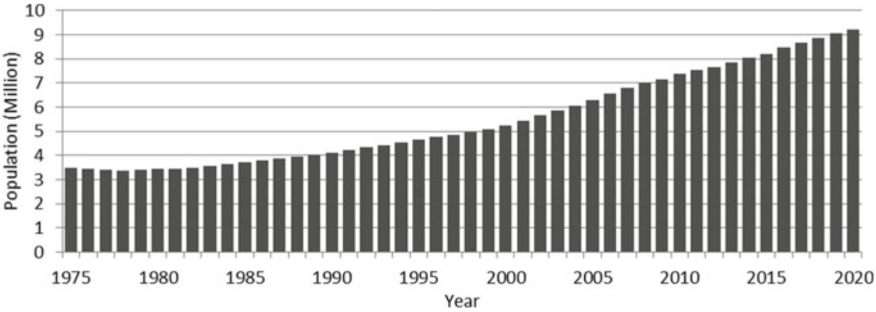

Fig. 1 The evolution of population growth in HCMC 1997–2020 (*Source* Adapted from GSO [2021])

pathways of densification and urban sprawl has resulted in environmental deterioration and increasing exposure to climate-related risks (Fig. 2). Recent recognition of the potential effects of climate change has heralded awareness of the need for action. While a multitude of initiatives, interventions and measures in the spatial planning for climate change have already been identified, considered and partially undertaken in the major cities of the Global North, the inherent complexity of the rapidly emerging megacities of Asia present a somewhat different challenge. Here the focus on climate risks and opportunities remains relatively uncharted. Furthermore, although considerable research has already been undertaken, little is known about synergies between mitigation and adaptation potentials. Additionally, complex interlinkages exist between both the effects of climate change and the rapid urbanization process itself. For HCMC, the challenge of climate change has added a distinct and significant new dimension to the urban sustainability and development conundrum.

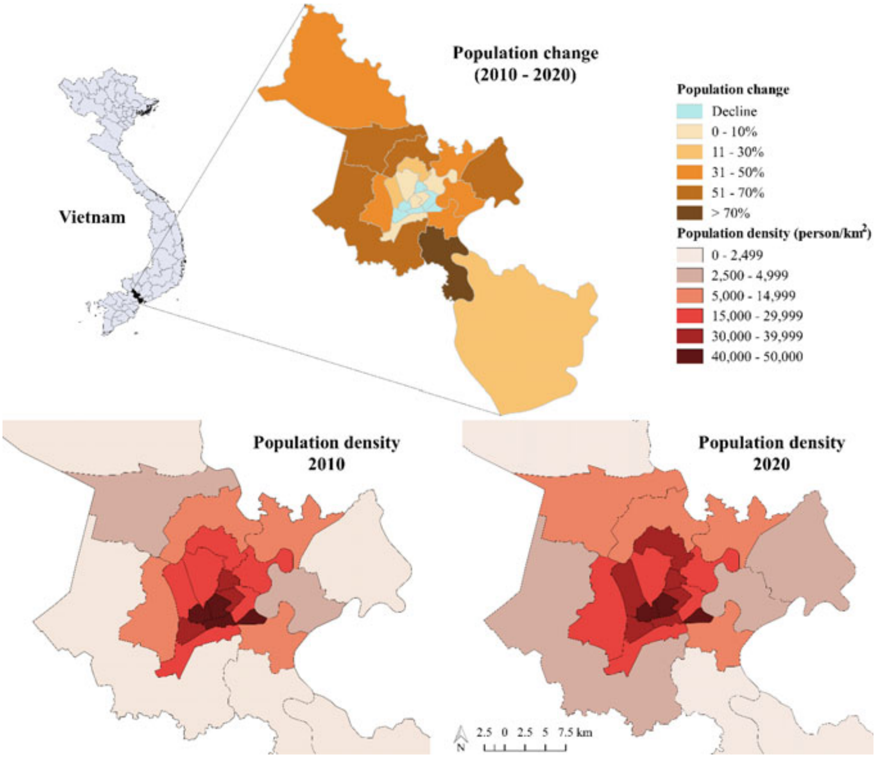

Fig. 2 Location of Ho Chi Minh City and population density per district in the years 2010 and 2020 and population density change in percent (*Source* The authors' own)

3 UHI Risk Accumulation in HCMC

In order to assess impacts and possible climate and environmental change adaptation strategies and the above mentioned urbanization challenges of densification, sealing and sprawl it is first necessary to obtain an overview of the relevant spatial parameters. In order to do so, it is necessary to consider not only the current urban development patterns and pathways, but also include climate change impacts, as they are interrelated. Also, it has to be considered that the urban development in HCMC is highly dynamic, leading to constantly changing patterns of imperviousness, building heights and building density going along with population density (Fig. 3).

In addition, one has to note that climate change impacts are distributed spatially heterogeneous across the city. These indicators influence present and future risks, and must be assessed according to their spatial distribution. Understanding the spatial element of risk is crucial for progressing our understanding of climatic hazards, possible solutions, and obstacles (Downes & Storch, 2014; Downes et al., 2011). HCMC is already particularly affected by a significant rise in inner city temperatures caused by the effects of an urban heat island over the city, demonstrated by a distinct difference between the city's inner core and the vegetated surroundings, which has consequentially caused air quality to deteriorate and decreased the thermal comfort of inhabitants (Katzschner et al., 2015; Son et al., 2017). During the dry month's

Fig. 3 Illustrates the urban expansion from 1988 to 2020 (*Source* The authors' own)

energy shortages and power outages caused by the increasing demand for cooling are a common occurrence. As stated, the urban landscape modifies the microclimate in ways that affect human comfort, air quality and energy consumption (Fig. 4). Nevertheless, in practice, climate issues are often still not considered substantially within the urban planning process, whereas urban climate represents an important issue in the specific vulnerability of a city.

Street geometry is also important for the urban temperature pattern, as it strongly influences wind patterns, which is known to be one of the main factors in urban climate. Density and construction materials also play an important role in heat island intensity, due to their greater ability to retain heat. Therefore, urban climate maps have to be generated and interpreted by analyzing urban climate with respect to every city's specific situation. Referring to that, each city has a unique climate, based on its framework conditions. Wind ventilation direction and air circulation are affected by the spatial patterns of streets, forms and height of buildings and topography. Building density and the proportion sealed ground contribute to heat accumulation contributing to the UHI (Fig. 5). The notion of the Urban Climate

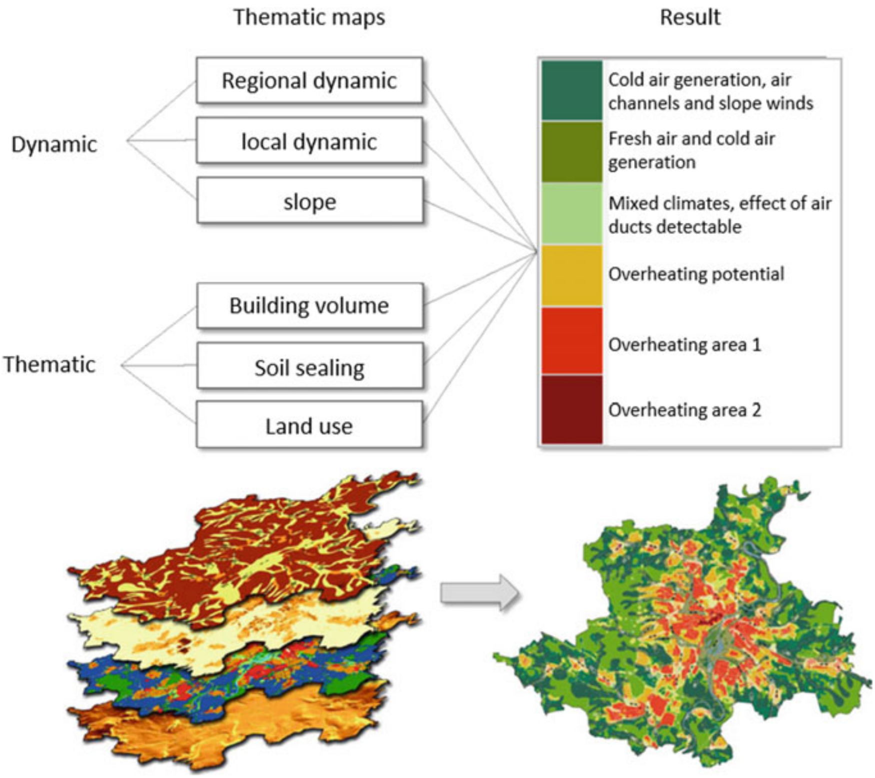

Fig. 4 Schematic representation of urban climate mapping based in dynamic and thematic factors (*Source* The authors' own)

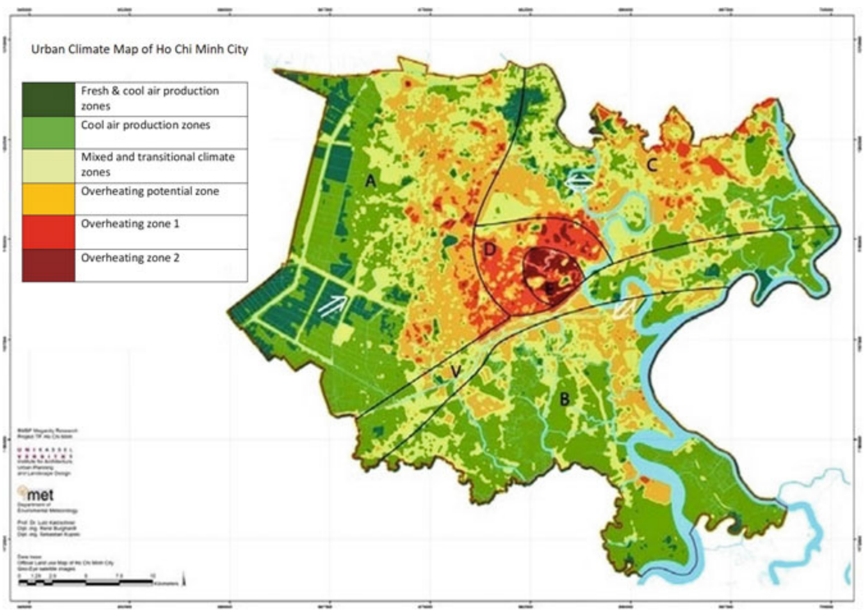

Fig. 5 Urban Climate Map of HCMC] (*Source* Katzschner et al. [2016a, 2016b with permission)

Map (UCMap) has been utilized by German researchers since the 1970s. It has been used as a tool for presenting urban climate phenomena and resulting challenges in two-dimensional spatial maps. The map is first and foremost an examination of the actual urban climate. By meteorologically interpreting it, it is able to give planning recommendations regarding predefined climatopes.

As a product, the Urban Climate Map combines meteorological relevant factors such as wind direction and speed, solar radiation, air temperature, elevation datasets, land use, building volumes and densities, street networks, and surface materials. The technique is separated into two parts: the creation of the Urban Climate Analysis Map (UC-AnMap) and further the development of the Urban Climate Recommendation Map (UC-ReMap) (Katzschner et al., 2016a, 2016b). The UC-AnMap identifies potential and danger areas in the present environment. An important factor is the ventilation (Ng et al., 2007). The Map is used to categorize distinct climatopes based on ventilation and urban heat island features. In addition to physical variables, the UC-AnMap is developed using qualitative and subjective criteria. Weighting factors are generated from a GIS model, provide specific thermal load and dynamic potentials (VDI, 2015). The generated urban climatic analysis from the UC-AnMap is in a next step transferred into the Urban Climate Recommendation Map (UC-ReMap), providing planning advice for practitioners to consider a climatic perspective. The Urban Climatic Analysis Map highlights the scientific based evidence, whilst the resulting Urban Climatic Recommendation Map is a meteorological and planning interpretation thereof, resulting in guidelines to be used as a basis for decision making.

The scope therefore includes urban planning and urban design, residential and urban land use planning, along with community and strategic development planning at the urban block or neighborhood scale.

4 Planning Implications

It is critical to offer standards for evaluating urban climate research results for urban planning applications. It is critical not only to deal large-scale observed or modelled mean climatic conditions, but also to evaluate different observations of finer scale place-specific localities. The major urban climate toolbox offers several scales of urban climatic maps that provide significant information for relevant for planning with additional qualitative and quantitative remarks on thermal and air quality issues. The findings represent the thermal efficiency complexity of the city, which refers to the effect of all meteorologically important urban canopy layer elements (radiant, sensible and latent heat, as well as heat generated from human activities) to HCMC (Katzchner et al., 2016a, 2016b). From the information obtained from urban climatic maps it is fesaible to develop recommendations at varying planning relevant spatial scales (Table 1). Ideally, these maps should be employed in conjunction with urban growth management and planning procedures.

The Urban Climate Analysis Map is a valuable tool for planning decision-making at scales ranging from 1:100,000 to 1:5,000. It provides a comprehensive and strategic perspective and is able to indicate which further studies on a smaller scale should be conducted. The UHI of HCMC is greatest in the urban core, but it is significantly lowered through ventilation (Katzschner et al., 2016a, 2016b). The urban climate map identifies regions with high ventilation potential that can be exploited to provide cooling. Parks and larger green areas exhibit an important influencing factor on urban climate as they produce cold air. Areas like that should be kept free from building and the cold air could be used to cool down the nearby areas. Additionally, green spaces can serve as retention areas for water. If regarding human health and comfort air temperature is not an adequate indicator. Thermal conditions for human comfort is expressed in a thermal index. To calculate the index physiological equivalent temperature (PET) radiation is one of the major parameters—together with wind, air temperature and humidity. To calculate mean radiant temperature, globe temperature measurements were carried out (Lindberg et al., 2016). Using the index PET a calibration of the urban climatic map was conducted.

The intensification of the UHI effect will indicate to increased energy utilization in the future, particularly for air conditioning demand (Emmanuel, 2021). Concurrently, urban development may halt cooler air from entering the metropolis. The UC-AnMap depicts various classes of urban heat based on ventilation potential. Following the wind evaluation, it was determined that south-easterly winds have the greatest influence on the urban heat island. Even in the climatic tropical zones, climate change is noticeable up to 2 °C every year, which means much more in denser places (Katzschner et al., 2015). Overall, the results of the urban climate map for

Table 1 Example development recommendations on the basis of urban climate analysis

Zones	Climate desription	Evaluation
Fresh and cool ar production zones	Open locations with high climate activity, production of cool/ fresh air, and climate relevant spaces in close proximity to residential areas	Oversensitive, areas with regards to changes in land use/function. Prohibt increases in surface roughnesss. Maintain open cool/ fresh air corridors. Minmize bariers toair corridors. Corridors should be completely examined and comprehended
Cool air production zones	Open locations with less climate relevant fresh air production	Surface roughness should only be increased if the ventilation patterns are respected. Development should be only permitted only in exceptional cases that are backed by extensive research and understanding of climatic functions
Mixed areas	Strong daily fluctuation due to incoming radiation, yet effective cooling	Important linking loations, anticipate for direction and density, surface roughness should intensified for fear of loss in ventilation, which will have an influence on the communities
Moderate urban heat	Some heat storage, although mostly mitigrated by greenery and wind	There are no discernible climatic sensitivities in relation to intensification of usage and building agglomerations. Redevelopment is often possible provided ventilation is considered
Remarkable urban heat island	Heat storage, but still wind and cooling potentials	Some dynamic potentials exist in the event of future heat stress caused by adjacent green areas. As a result, the regions should be preserved or improved rather than deteriorated. Only with compensation for climatic consequences can development be permitted. Before any suggested improvements, the existing air circulation should be assessed
Urban heat island maximum	Heat storage with low cooling potentials, as well as poor ventilation	In need of redevelopment in terms of urban climate. Greenery is needed for facades and surfaces. Because of the accumulated issues on thermal load in the high dense built-up region, the climatic conditions in this zone should be improved. No further development is permitted in this zone. Improving air exchange is one significant recommendation, along with shade design

Ho Chi Minh City must be viewed in the light of the wider intertropical circulation pattern and UHI.

The findings also show that for rising Asian megacities like HCMC, rapid urbanization and industrialization driven by socioeconomic development and transformation (including population and economic growth) is proportionately more relevant than the scenario-based projection of global climate-change impacts (O'Neill et al., 2017). In terms of susceptibility, it is clear that HCMC's socioeconomic development and urban expansion are important drivers of future dangers. This leads to the

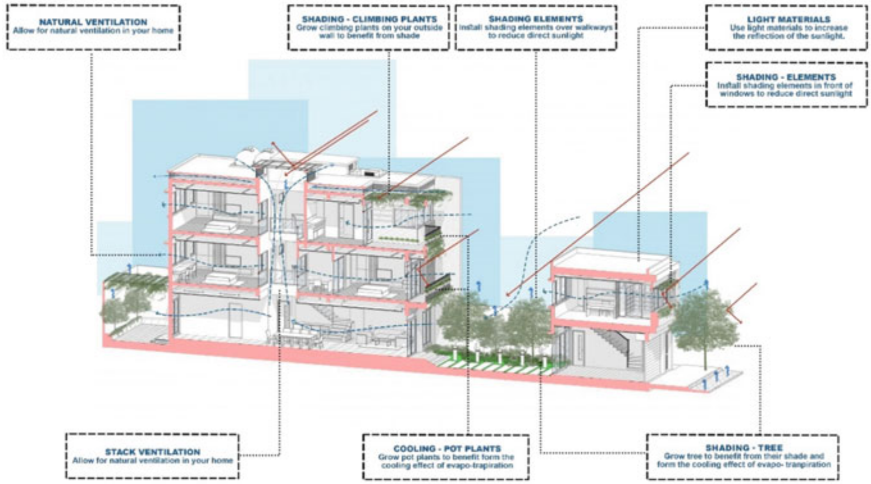

Fig. 6 Low tech building level solutions to factor in urban climate considerations into urban design and built form including urban albedo, ventilation and zoning regulations, thermal storage and thermal emissivity of materials (*Source* The authors' own)

conclusion that rapid population increase must be factored into urban design (Figs. 6 and 7). While socioeconomic data are few, future urban developments, as outlined in the reviewed plans, are expected to have a significant impact on the urban climate. This will enhance the overall sensitivity of urban systems to flooding events and rising temperatures, escalating the situation. Vulnerability assessment maps and the resulting planning suggestion maps can aid in decision-making, particularly when it comes to cumulative indicators. In terms of urban planning timeliness, new urban projects will impact the spatial pattern for many decades; therefore, it is critical to increase awareness at this point in time to optimize prospects for adaptability to future changes. Climate change scenarios for HCMC can be incorporated into sectoral planning as well. Additional land use developments can be viewed by incorporating them as a layer into the Urban Climate Map, revealing changes in the urban climate linked with newly-built areas or similar scenarios.

5 Conclusions and Outlook

This chapter highlights that research needs continued to enhance the resilience of HCMC to both climate hazards such as UHI and also environment changes. Understanding and predicting the urban climate repercussions of urban development pathways and climate related hazards are becoming increasingly important to support urban environmental management decisions within the city. HCMC requires a quicker and more generic approach to roll out adaptation to the effects of UHI

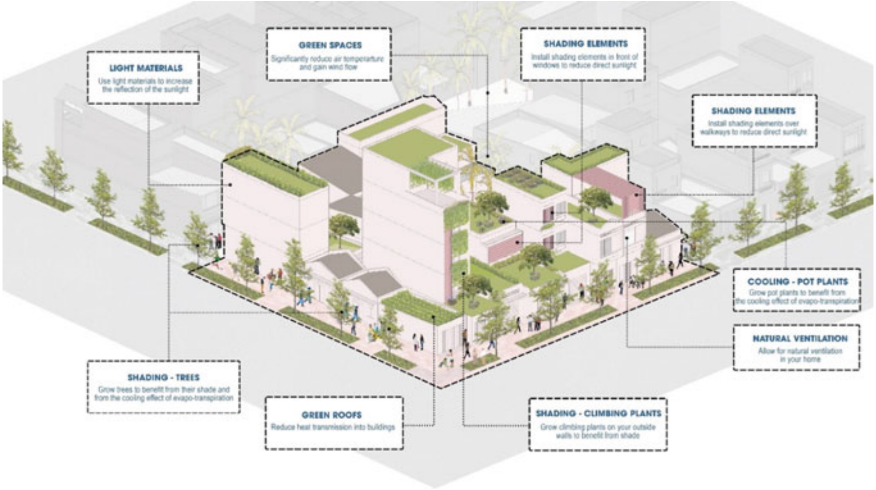

Fig. 7 Neighborhood/block level solutions to factor in urban climate considerations into spatial planning including urban forest, parks, street trees, private and public green and open areas, green roofs, green facades and water elements (*Source* The authors' own)

and make uptake applicable in practice. Here, polices, protocols, planning codes and recommendations and measures to combat the negative consequences of UHI development in HCMC need to be developed. Given that many of the main impacts of the UHI effect have a land-use component planning and land use control mechanisms may be the best adaptation management strategy. Climate change concerns need to be integrated into the existing legislative and policy frameworks. Here going forward, focus should be placed on the priority building regulations and land-use controls, including a better understanding of urban densities, building morphologies, forms and structures. Whilst urban climate analysis, including shading and ventilation analysis, the hotspot mapping of vulnerable groups and the incorporation of nature-based solutions and other planning relevant toolkits to manage urban heat and decrease social vulnerability and increase adaptive capacities should become an integral element of urban master plan preparation, regulations and best-practices.

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Chapter 8
Traditional Dwellings in Four Middle Eastern Cities: Adaptation Strategies to Harsh Climate in Privacy

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Abstract Climate change is one of the most serious environmental issues of the twenty-first century, compelling designers to adapt their work to completely new climate-change-adapted settings. The Middle East's dry environment causes issues with rising temperatures and decreasing humidity. Environmental harmony has long been a priority in Middle Eastern architecture. Designers changed nature to accommodate the limited supply and demand for energy. Concerns about privacy and climate change influence home construction in areas with similar religious and climatic conditions. As a result, the purpose of this research is to look into the environmental and privacy-enhancing characteristics of historic and contemporary buildings. To accomplish this goal, observations and reviews of relevant literature were used to collect qualitative data. Analysis from a variety of research and climate-tested data was used in the following: This study's data and analysis include traditional homes, the Koppen climatic classification, and contemporary house design. Furthermore, research methods have been used in areas with well-established internal residential characteristics, such as Baghdad, Riyadh, Mukalla, and Kashan. The climate and isolation of each instance were studied and compared to nearby, modern dwellings. Our data show that these communities' older buildings made good use of natural heating and cooling resources. Summer and winter rooms are available for rent in historic mansions in Kashan and Baghdad. Summers in these regions are scorching, and winters are bitterly cold due to the different positions of the sun. We have not yet investigated any sun-facing locations in modern architecture. Wind turbines are

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also very important. The wind tower passively cools the structure's air. In modern homes, air conditioning provides ventilation. These items are both expensive and energy-intensive.

Keywords Traditional architecture · Climate adaptation · Urbanism · Middle East

1 Introduction

People have attempted for a long time to live harmoniously with nature (Raja, 2018). Nature's quirks confine human behavior, forcing humans to adapt to new environments. People minimize clothing and shelter to live (Boyd & Banzhaf, 2007). Due to environmental forces, humans have outdone and surpassed their natural counterparts. People have developed dwellings for many climates throughout history (Moser & Ekstrom, 2010). Since prehistoric times, the local climate and features have influenced housing design. Traditional buildings' climate and privacy are examined. In the past, limited energy led designers to use natural materials. Traditional homes prioritize passive heating and cooling (Ding, 2020). Even in Islamic climates, different styles arise. Modern design ignores power and water since they are so plentiful. Designers no longer prioritize energy efficiency, leading to unsustainable buildings (Thébault & Fontaine, 2010). Environmental issues are gaining widespread attention. Climate change, fossil fuel use, and waste accumulation are environmental issues. Traditional building design prioritizes individual interests. This involves home comforts. Because of this, it is crucial to examine the home designs in the historical context of the cities that have made adaptations to their local climate. This study also addresses a significant topic. Throughout history, a number of Middle Eastern towns have featured architectural designs that work with the region's hot, dry climate. In this regard, by examining the housing layouts of Kashan, Makla, Riyadh, and Baghdad, this study has attempted to highlight the characteristics of these cities that are compatible with climatic circumstances on a private sector scale. These cities' old structures are still present and unrenovated, which is arguably one of their most significant characteristics. The private sector, which has made an effort to conserve these tissues, is to blame for this. For modern urban policymakers, architects, and urban planners, the knowledge that the findings of this research provide concerning the suitable housing patterns of these four cities can be valuable. They might be extremely helpful in combating the current era's climate change by offering strategies that are in line with local climatic conditions and scaled for the private sector.

2 Background Knowledge

The most comfortable and environmentally friendly forms of indigenous architecture are traditional homes that have been adapted to the local climate (Wiranti et al., 2019). Studying the history of traditional architecture and figuring out what makes traditional house designs in different climates unique can help solve many problems (Shahamat, 2014). Traditional homes, especially those in desert climates, use passive ways to heat and cool that work well (Kim, 2006; Li et al., 2021). One of their most significant features is that traditional homes block the sun in the summer and benefit from it in the winter.

In traditional architecture, the first stage in creating a traditional home is to identify the crucial elements in climate-related problems and potential solutions in the chosen geographic area (Al-Ban, 2016). Examining climatic data and bio-climate graphs in the suggested region is required. To make sure buildings are comfortable inside, it should be looked into how the local climate affects how they are built (Ding, 2020).

Each district's traditional architecture is based on local demands and lifestyle. Geographical, climatic, local resources, and cultural factors affect building design (Ejiga et al., 2012). Climate and culture affect how indoor and outdoor spaces are built up and connected architecturally (Daoudi et al., 2019). Wind, sunshine, precipitation, humidity, temperature, and air pressure are climatic elements that affect a building's design, construction, and alignment (Barati, 2005). Sunlight is the principal heat source in hot climates. It's crucial to position and orient buildings according to the sun's path. When designing a site, consider the direction of hot gusts. Both the hot and cold seasons highlight these two issues. Well-designed homes heat and cool more efficiently (De Joanna, 2016). The climate determines the building materials used. Options are limited by surrounding options. Each space should use widely available, climate-appropriate materials. Heat resistance and heat capacity are essential physical qualities. Many climates call extreme weather "critical times." Deserts need hot days, for example. So, in these situations, the materials should be good for hot weather so that outside air doesn't affect indoor air. BWH's day-to-night temperature range is large. The most-used rooms should be insulated with dense materials. For nighttime use, consider light, low-heat materials. Stone works well in dry settings because it resists and retains heat (Lang, 2013). Thermodynamics says heat goes from warm to cold. In arid regions, walls warm up during the day and absorb heat into the stones. At night, when it's cold inside, this heat is conveyed. Inhabitants' inner walls are cold during the day and warm at night, making inhabitants comfortable (Almatarneh, 2013). Traditional design uses two main materials: Thermal and solar efficiency of walls and finishes is one. Second, materials' self-efficiency. Traditional construction in hot, arid settings uses stone, adobe, muck, soil, and muck blocks. These materials' thermodynamic qualities make them ideal for desert climates with hot days and cold nights. High thermal capacity and heat isolation are needed. Mud's light tint reflects the sun's rays and traps heat at night (Daoudi et al., 2019). Climate affects a building's energy efficiency and usage. "Green design" is sustainable. Climate-related concerns abound. These include making a house that is comfortable, healthy, and sustainable, as well as making good use of natural resources and energy (Baptista, 2019; Feitelson & Tubi, 2017).

3 Climate-Resilient Strategies and Implications at the City Scale

3.1 Kashan

Kashan is considered one of the ancient cities of Iran. Geographically, a total area of about 9,647 km^2 is covered. Isfahan is the name of this sub-province, which stretches from the Central Desert in the east to the Karkas Mountains in the west. One of the cities in Isfahan is Kashan. Kashan is located at (33°59′ North, 51°27′ East) and 982 m above sea level. Kashan is influenced by the desert climate. In Kashan, there is virtually no rainfall during the year. This location is classified as BWh climate (Köppen-Geiger). The average temperature in Kashan is 19.5 °C and ~128 mm of pre cipitation falls annually. The highest and lowest average temperatures are in July and January, at around 33.2 and 5.0 °C, respectively. The average annual sunshine in Kashan is 2,942 h (Teshnehdel et al., 2020).

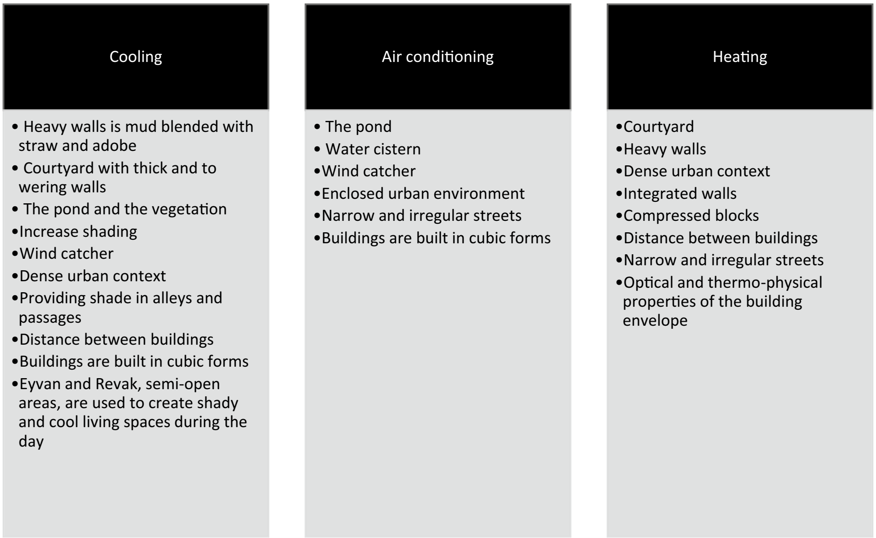
3.2 Impact of Climate Issues in Traditional Architecture in Kashan, Iran

In Kashan's historic homes, a number of architectural techniques were used to regulate the temperature and lessen day-to-night fluctuations. The primary component of the thick, heavy walls is mud blended with straw and adobe (Hosseini et al., 2020). The walls transmit solar energy at night after absorbing it throughout the day (Mirzaei et al., n.d.). The courtyard is surrounded by thick, towering walls that offer shading for the inside area (Leylian et al., 2010). The pond and the vegetation are in charge of cooling and raising the air's humidity (Tahbaz et al., 2022). When a result, ventilation occurs as the air cools by flowing through the yard and over the porch and tree (Eskandari, 2011). In this hot, dry climate with sparse vegetation, the courtyard serves as the social hub of the buildings. Usually, the courtyard was constructed below the ground level. The pond in the middle of the courtyard contains water for aesthetic and air-conditioning purposes. Because Kashan is in a dry area, water resources are taken into consideration when designing the home (Farshchi et al., 2016). It is necessary to dig the ground in order to find water supplies because of this. To add moisture, it is also possible to direct the air over a pond or cistern.

The variation in temperatures affects how the function works. One would wonder how a wind catcher functions when the wind blows slowly. In actuality, air flow is caused by the difference in temperature between the two sides of the hole. The wind catcher is warmer than the air in the veranda space due to sunlight exposure on its southern face. As a result, the heated air is drawn out of the area under the wind catcher by a form of vacuum. In order to make up for this, an airflow is created, bringing the cool air from the northern side of the home inside the building (Fig. 3). The temperature outside starts to drop at night. As long as there is a temperature difference between the outside air and the walls, cold air flows down and cools them (Barati, 2005; Leylian et al., 2010). But typically, the day starts and the wind catcher begins to function as it should before it reaches this equilibrium (Mirzaei et al., n.d.). A semi-private space through a hallway. The semi-private room and the private area are separated by a lengthy hallway. The layout of this building is intended to maximize seclusion while still promoting friendliness and social interaction (Barati, 2005; Eskandari, 2011; Karimi & Hosseini, 2012; Tahbaz et al., 2022). Another environmental condition that affected Kashan's housing plans during the story was the shedding and sunlight effect on people's comfort based in public and semi-public spaces. Few studies address the beneficial effect of shading and sunlit in courtyard houses on the thermal performance of residential buildings, particularly in a hot desert climate (BWh) (Teshnehdel et al., 2020). By looking at Kashan traditional house plans it can be understood that most of them are for better performance in cooling and shading factors designed as courtyard houses. In general, by examining the structure of the historical context of Kashan, it has a dense urban context and the houses that are compressed together have integrated walls (Karimi & Hosseini, 2012). It is suitable for insulating houses against extreme heat and cold, and it also plays a positive role in providing shade in alleys and passages (Akbari & Teshnehdel, 2018). In short, research shows that houses with courtyards in the urban structure of historical cities in the center of Iran, such as Kashan, have played an important role in reducing environmental challenges (Memarian & Brown, 2003).

In a research conducted by Behbod et al., design strategies responsive to the climate in hot and dry areas of Kashan city were presented. They identified the design features of the historical context of Kashan in 3 scales, macro, medium, and micro; In the first level, distance between buildings, enclosed urban environment and narrow and irregular streets were considered as macro strategies. Review and development of these traditional urban patterns should be considered in hot and dry cities. Medium scale strategies cover building form, building envelop, self-efficiency in materials and optical and thermophysical properties of building envelop in this paper. Sustainable architecture force us to re-think what we do and synchronize traditional methods of construction and the use of domestic materials. Finally, micro scale strategies demonstrate some more relevant architectural design methods which are the same as contemporary passive systems. As an illustration, old wind-catchers have been developed into advanced passive cooling systems in recent years. Consequently, consideration and development of the above strategies allow contemporary architects and designers to build contemporary architecture in a more sustainable, comfortable and self sufficient way (Behbood et al., 2010).

It should be pointed out that due to the integrated climatic conditions of the center of Iran, many of the architectural features and traditional urban planning of Kashan city are similar to other historical cities such as Shiraz and Yazd. The climate of most of the central plateau of Iran is hot and dry, and many historic cities that have valuable architectural designs are located in this hot and dry region. In general, the structures of this region are logically integrated with nature, and as a result, traditional Iranian buildings, unlike most modern buildings, are compatible with natural conditions and have a harmonious relationship with them. The most oppressed deserts in the world are located in the center of the large and closed Iranian plateau (Keshtkaran, 2011). Finally, it can be said that the traditional architecture and urban planning of Iran are largely related to the principles of sustainability, and in this regard, the importance of studying urban housing plans such as Kashan from the point of view of climate adaptation doubles (Figs. 1 and 2).


Cooling

- Heavy walls is mud blended with straw and adobe
- Courtyard with thick and to wering walls
- The pond and the vegetation
- Increase shading
- Wind catcher
- Dense urban context
- Providing shade in alleys and passages
- Distance between buildings
- Buildings are built in cubic forms
- Eyvan and Revak, semi-open areas, are used to create shady and cool living spaces during the day

Air conditioning

- The pond
- Water cistern
- Wind catcher
- Enclosed urban environment
- Narrow and irregular streets
- Buildings are built in cubic forms

Heating

- Courtyard
- Heavy walls
- Dense urban context
- Integrated walls
- Compressed blocks
- Distance between buildings
- Narrow and irregular streets
- Optical and thermo-physical properties of the building envelope

Fig. 1 Climate challenges and traditional solutions in Kashan

Fig. 2 Historical urban quarter of Kashan city (Based map from Google Earth)

Cooling	Air conditioning	Heating
• Balconies •The kitchen is on the top floor •Windows are built with tiny holes •The heat conductivity of stone was used as a factor of cooling •Courtyard (rectangular courtyard) •self-shading •Narrow streets •Outdoor courtyards •Orientation of buildings	• Setting and structuring of openings • Windows are built with tiny holes •Outdoor courtyards •Non-use of direct openings •Orientation of buildings	•The kitchen is on the top floor •Type of materials •Thick walls by stone •Non-use of direct openings

Fig. 3 Climate challenges and traditional solutions in Mukalla

3.3 Mukalla

"Yemen is located at the southern part of the Arabian Peninsula". North Yemen and South Yemen were two separate countries; they unified on the 22nd of May 1990 under the name of Republic of Yemen. Since then, Hadhramout is the largest province of Republic of Yemen. This city is situated in the southern part of the country. Also, Coastal Hadhramout is located between the Indian Ocean in south and the plateau in north. Mukalla is placed there. The coastal belt is over 350 km long. Over years, Mukalla is turned to be the largest and the most important city of the coastal Hadhramout (Al-Maashi, 1998). The city of Al-Mukalla is located in the coastal region, at an altitude of 14°5′ north and a longitude of 49°20′ east, and it enjoys a pretty Yemeni-like climate, very similar to other coastal towns in Hadhramout. In the summer, the day temperature reaches 32 °C and while relative humidity might increase to more than 80% (Baangood & Hassan, 2010). The four ancient quarters formed the center of the city and appeared in various local style architectures, interfaces, decorations, and a variety of vocabulary of architectural elements that may differ from one region to another. The influence of Indian, Asian and Turkish style patterns also appears in its public and private buildings. It is more common in vocabulary. Vocabulary and visible elements of the building in the facades, the existence of a strong architectural experience in providing solutions for ventilation and privacy, define the requirements of its society, which creates an extraordinary mental and aesthetic image of the beautiful city and its buildings (Khaled et al., 2016).

3.4 Impact of Climate Issues in Traditional Architecture in Mukalla, Yemen

The fundamental goals of traditional architecture in Mukalla are practicality, cultural sensitivity, and resident demands. The following are some of the key design elements: In order to give families a cool, private place to sleep during the hot summer nights, balconies were created. Additionally, a unique area is available for celebrations. Also, the kitchen is on the top floor so that the heat and smoke from cooking don't spread to other parts of the house (Baeissa & Hassan, 2011). As many openings or windows as possible, spaced no more than 30–60 feet apart, are produced on the walls of rooms. The vertical length of the windows is roughly 182 cm, and they are positioned 30 cm above the ground floor. These sizable apertures make it simple for air to enter the structure. To facilitate ventilation, windows are built with tiny holes. There is a constant flow of air as the warm air rising is sucked out through these tiny apertures.

The scorching weather was taken into consideration when choosing materials and how to use them in the construction. Stone is employed because it has low heat conductivity and can store heat energy. Particularly on lower floors, walls are erected with a thickness of 30 to 60 cm. As a result, interior rooms see less heat buildup on hot days. In addition, the building's massive stone walls keep internal heat from escaping at night when it is chilly (Baeissa & Hassan, 2011). A natural solution of the heat issue was solved by the kind of materials and the way they are used. The heat conductivity of stone was used as a factor of cooling the interiors of those houses. Building thicker walls enforced this character of stone. The thicknesses of walls (as thick as two feet at lower levels) allow smaller amounts of heat to penetrate to the inside of the building. Also, if it ever gets cold, the walls wiU keep the warm air from escaping through them (Al-Maashi, 1998).

One of the most important solutions to deal with climate challenges is the design of courtyard-oriented housing in Mukalla city. The courtyard has different shapes to provide more ventilation and thereby help to reduce the outside air temperature. The most used in Mukalla city is the rectangular courtyard, so self-shading of the courtyard reduces the need for cooling by about 4% on average (Baangood & Hassan, 2010). Also The results show that in general the air temperature in traditional houses is lower than the outside air temperature and in some cases the air temperature is within the thermal comfort range of Hadhramout. Comparing the results of the air temperature inside the courtyard shows that with the increase in the ratio of the dimensions of the courtyard, the air temperature also increases (Abdulla Binthabet, 2007). Research conducted by Rasha Saeed Baangood and Ahmad Sanusi Hassan revealed more facts about the traditional architecture of Mukala city. They showed that the Mukala city housing scheme uses narrow streets and outdoor courtyards to control air temperature and shading percentage by increasing wind speed outside the courtyard and narrow streets that integrate into the building. Also, the non-use of direct openings in the first and second layers of the building has helped to control the wind speed, and the courtyards and passages have been used as ventilation.

Fig. 4 Historical urban quarter of Mukalla city (Based map from Google Earth)

This research showed that the orientation of buildings in Mukalla city was useful in providing natural ventilation and was involved in temperature control (Baangood & Hassan, 2010). But on the other hand, we see the excessive use of glass in the design of traditional buildings in Makla, which researchers show that due to the climate changes of the last century and the increase in sunlight, the excessive use of glass should be reviewed (Figs. 3 and 4). They found the solution. Returning to the traditional architecture of this region, they see that the openings were indirect (Al-Sagaf, 2009).

3.5 Riyadh

Saudi Arabia has experienced rapid growth in urban development during the last four decades with the city of Riyadh transforming from a mud-walled town of 25,000 inhabitants to an international metropolis of 2.5 million. The city belongs to the pre-Islamic era and has transformed over time with rapid urban development. Since the 1940s the city has changed from an isolated and narrow town to a spacious modern city. It lies in the centre of Arabian Peninsula on a plateau with an area of around 1300 sq. km (Dhingra & Chattopadhyay, 2016).

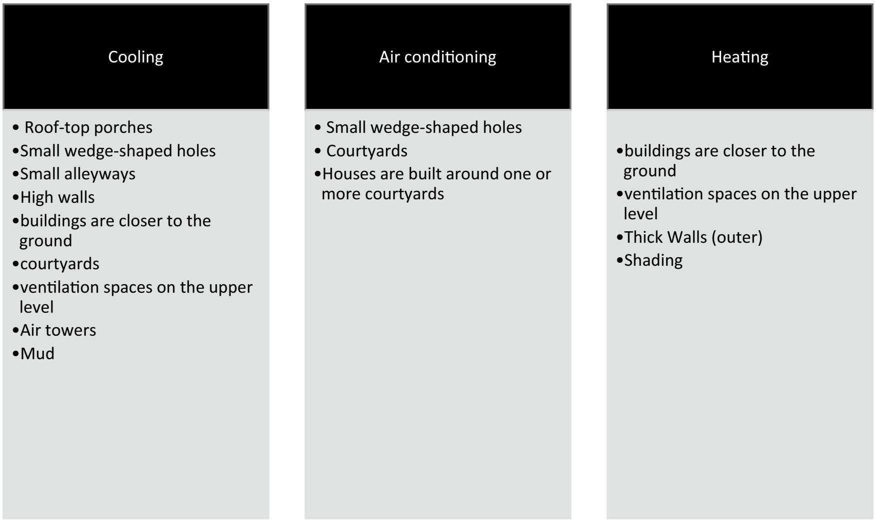
The city is located 240 miles from Dammam on the Gulf and 530 miles from Jeddah on the Red Sea. Riyadh, the Kingdom of Saudi Arabia's capital, has a sizable population. This city may be found in Najd. With an elevation of 600 m above sea level, Najd is a remnant fiord. Due of the fine subterranean water, it is extremely abundant despite the area's dry climate (Ragette, 2003). Riyadh's climate tends to be uniform, dry and hot during the daytime and cooler at night in summer; in winter, nights tend to be cold and days are warm. Daytime temperature can reach 45 °C or more in summer and be as low as 1 °C at night in winter. Rainfall is very low in Riyadh; the rainy season is from December to April, with an annual average of 100 mm (Al-Hemaidi, 2001).

3.6 Impact of Climate Issues in Traditional Architecture in Riyadh, Saudi Arabia

In general, the housing plan of the traditional neighborhoods of Riyadh should be considered as the type of Najd region. A Najd vernacular house can be typified as square or rectangular with rarely more than one floor. Rooms are arranged around the central colonnaded courtyard and have small windows. The adobe walls, floors and roof are between 50 and 80 cm thick, or sometimes even more (Alrashed et al., 2017). In Riyadh, the courtyard inside the home plays a significant role in improving the climate and offering seclusion. Most of the time, the yard's height and size, as well as how important it is, depend on where the house is and who designed it. Traditional homes in Riyadh had roof-top porches for cooling off on hot summer nights. On the first level, there is typically an open space that serves as a living room in the spring, summer, and fall. A wooden platform is built out of caution above the house's entryway. Close to the ceiling of this building, small wedge-shaped holes are cut out to help with ventilation. The alleyways are small, and the outer walls are high for privacy reasons. This arrangement creates a structure shaped like a ditch and offers the most shade. Because of the bright sun, the temperature in places with shade and places without shade is very different (Akbar, 1980).

In Riyadh, The hot and dry climate, along with the need to separate private spaces from semi-private and public spaces, led to introverted urban plans (Dhingra & Chattopadhyay, 2016). The building plan of Riyadh city is such that the buildings are closer to the ground and are placed together to create a cooler environment. On the other hand, having houses with courtyards and ventilation spaces on the upper level caused hot air to rise and convection currents near the ground to cool. Air towers and inner courtyards are used to increase ventilation and cooling, and mud was the most important material that played a role in keeping the house cool (Abu-Ghazzeh, 1997; Dhingra & Chattopadhyay, 2016).

The typical houses of Manjed region (Riyadh) are introverted type, the houses are built around one or more courtyards, which are usually square or rectangular in pure geometric shape. The courtyard element in the design of Riyadh houses plays two roles: regulating the small climate and preserving the privacy of family life. As a microclimate regulator, the courtyard creates three cycles of air movement in the house, which creates an optimal level of comfort for the residents. The outer walls of the houses were made very thick to act as insulation against the intense summer heat. Also houses are generally arranged around courtyards that act as lungs of the houses to regulate the micro-climate even, houses are compactly designed to play an important role in shading and reducing heat and sunlight (Figs. 5 and 6). The use of small openings in the walls to maintain the airflow is also considered one of the distinctive features of the designer of the traditional houses of Riyadh (Babsail & Al-Qawasmi, 2015).



Cooling

- Roof-top porches
- Small wedge-shaped holes
- Small alleyways
- High walls
- buildings are closer to the ground
- courtyards
- ventilation spaces on the upper level
- Air towers
- Mud

Air conditioning

- Small wedge-shaped holes
- Courtyards
- Houses are built around one or more courtyards

Heating

- buildings are closer to the ground
- ventilation spaces on the upper level
- Thick Walls (outer)
- Shading

Fig. 5 Climate challenges and traditional solutions in Riyadh

Fig. 6 Historical urban quarter of Riyadh city (Based map from Google Earth)

3.7 Baghdad

Baghdad's countryside is flat. The city has a sedimentary structure and is situated at a low elevation above the ocean "The River Tigris cuts across a broad plain where the city is situated. Baghdad is divided in two by the Tigris, with the western half known as 'Karkh' and the eastern half known as 'Risafa.' Due to the frequent, significant flooding that has occurred on the river, the terrain on which the city is built is nearly entirely flat and low-lying and is therefore alluvial in origin."

3.8 Impact of Climate Issues in Traditional Architecture in Baghdad, Iraq

Thermal comfort is achieved in traditional Baghdadi homes by making efficient use of available space and selecting the appropriate materials. Sunlight and clean airflow are provided through the central courtyard. In the courtyard, children were playing on a daily basis. The courtyard was successful in adjusting the interior microclimate of the house in Baghdad's extreme weather, which is characterized by lengthy hot days in summer, extremely high temperatures, a broad range of daily temperature fluctuation, and low humidity.

In actuality, the yard controls the temperature. In hot, dry areas, courtyards typically play a significant role in lowering summertime interior temperature. It runs on the principles of convection and radiation, two thermal processes (Goodwin, 1985). The porch and the courtyard's ground serve as intermediaries between the chilly sky and the warm interior, with the chilly area rising at the highest point. Two distinct microclimates were created inside the house, thus the family typically moved from one division to the other as the seasons changed (Agha & Kamara, 2017). The courtyard is the home's breathing structure, controlling the temperature and supplying ventilation. In order to offer shade in the yard, there are typically sunshades or trees. There are also ponds and fountains to add moisture on dry hot days.

South-facing "Iwans" and "Tarma" (varieties of porch) were used in the winter since the sunlight warmed them. In the summer, the household relocates to cooler areas like the basement because these areas are warmer. According to Warren and Fethi (1982), the ridge and courtyard ground have very different temperatures. The courtyard ventilates all staircases perpendicularly. The upper levels are hot and uncomfortable in summer (Jasim, n.d.). The cool basement has a water storage cistern, or "Sardab." The "Talar" and "Ursi" sections orientated south or west were not occupied, even at the courtyard level, because the afternoon sun made them too hot (Al-Azzawi, 1996). Shanasheels can let air through. When the sliding belts are open, air flows freely across the window. Shanasheel has another cooling function: as these windows are made of wood, sunlight would warm the air near them. The rising hot air naturally cools the room. "Shanasheels" provide daylight and fresh air. The street-facing ground-floor walls are made of lumber. The Shanasheel, Ursi, and interior panels are glazed and latticed. These walls have a high heat conductivity, so rooms on this floor are rarely utilized in the summer (Allan, 2012). Three-fronted dwellings are densely packed. A thin passage between them shades the street-facing front of the house. Masonry walls help regulate the home's temperature (Warren & Fethi, 1982). Baghdad's scorching summers make the shade a must. The residences' principal courtyards had sunshades. The scorching summers in Baghdad necessitate the use of shade. Therefore, the principal courtyards of the residences are equipped with sunshades to provide relief from the heat. As a result, the courtyards are cooler and more comfortable on hot summer days. This practice of providing sunshades helps to mitigate the effects of the extreme heat in Baghdad, making outdoor spaces more habitable during the summer months.

A high-columned awning called "Tarma," which is positioned around the rooms on the ground floor, is another mechanism for raising the temperature. This structure keeps the chamber from getting direct sunlight from above in the summer (Figure 13; Warren & Fethi, 1982), but it doesn't have much of an effect on the low-angled sunlight in the winter.

Ventilation or providing air movement is also an important factor in providing comfortable weather inside the house. Ventilation is implemented by shades, openings and lattices. But there is another effective mechanism for efficient ventilation which is called "Badgir" or air-scoops. In traditional Baghdadi houses, "Badgir" is an important discriminative item. This item has been specifically designed to capture the dominant north-western winds in Baghdad region. The air is vacuumed down to the room through a tube. This air has been cooled when it passed this shaft before reaching the down. Although the temperature would be greater than the air temperature of the basement and this is less humid, still waving out the air from the room will take out the exhausted air and improves the atmosphere. Without Badgir the rooms in the basement are cold and unpleasant during the winter. But, the shutters of "Badgir" which are openings to the outside air carry warmed air into the space and enhance the temperature of basement space.

The "Badgir" ventilation system, which is used in Baghdadi traditional homes, was mentioned in the previous section. These air scoops supply fresh air flow to the basement and semi-basement regions. This architectural feature has a vertical duct with a substantial external thickness. The roof-top entrance of the vertical shaft is integrated into the bulwark wall. The basement and semi-basement are both accessible through the scoop's outlets, in addition to Talar. Talar may feature multiple air-scoops due to its size.

Shade, the choice of materials, and air flow are the three most important things in the design of the house that affect the climate. The house's orientation is crucial because it creates microclimates in various areas that the family may move to as the seasons change. Living arrangements alter around September or April. As winter began in September, the family relocated to south-facing rooms with more heat and sunlight. On the other hand, they relocated to the northern rooms around April or May. Daily living space and sleeping space differ during the summer. The family spent the day in the lower-level areas before moving to the roof porch at night (Figs. 7 and 8). So, on hot summer nights, the roof doubles as a bedroom. Additionally, three frontages connect the residences, acting as a heat buffer (Figure 15; Warren & Fethi, 1982).

Cooling	Air conditioning	Heating
• Central courtyard •The porch •Sunshades or trees •Ponds and fountains •water storage •Basement •Shanasheel •Shading •Badgir	• Central courtyard • Ponds and fountains •Shanasheel •Openings and lattices •Badgir •House's orientation	• Appropriate materials • Central courtyard •South-facing "Iwans" and "Tarma" (varieties of porch) •Badgir

Fig. 7 Climate challenges and traditional solutions in Baghdad

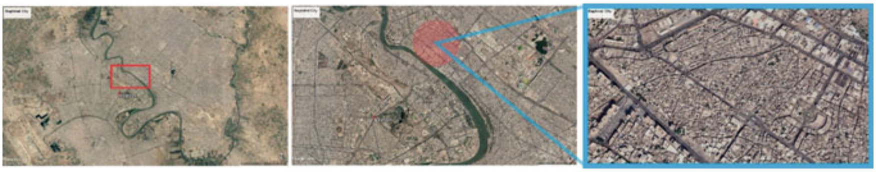


Fig. 8 Historical urban quarter of Baghdad city (Based map from Google Earth)

4 Discussion and Implications

In this study, the research was conducted based on the following steps: Firstly, the study is organized according to the aim of the research. An investigation of the problem needs to identify information resources and collect them. Afterward, data is collected based on the qualitative procedure. The literature review is completed based on books, scientific journal articles, thesis proceedings, and websites. The field study in Kashan is analysed based on the observations and the author's impressions and written data. Finally, the collected data is analysed, compared, and discussed with regard to the purpose of the study. Table 1 shows the results of an analysis done on both of these to learn more about how climatic architecture works in both traditional and modern settings.

A close examination of Table 1 reveals several important findings of this research. First, by comparing the features related to the climate factor of contemporary and traditional architecture, it is realized that in the Middle East, with the expansion of urbanization and the need for rapid urban construction and development, factors such as climate conditions and energy are ignored. This fact can be understood when we consider the four cities studied in this research as many cities in this region. So, it is shown in table one that many features of native architecture and urban planning in the Middle East were victims of the rapid and affordable development of the modern

Table 1 Features of traditional and contemporary architecture in selected cities with regards to climatic factors

Cities	Feature related to climatic factor in traditional architecture	Feature related to climatic factor contemporary architecture
Kashan	1. Water and trees and mud-brick for evaporative cooling in a courtyard (Rahmi, n.d.) 2. Shaded areas in the courtyard (Ivan) (Naseri & Farsani, 2022) 3. Surrounding the courtyard with high walls reduced the floor warmth (Eskandari, 2011) 4. Using open areas during the day (Leylian et al., 2010) 5. Summer and winter rooms (Naseri & Farsani, 2022) 6. Using Badger as an element for cooling (Farshchi et al., 2016)	1. Contemporary Buildings has no specific orientation (Diba, 2012) 2. Using mechanical and electrical systems for cooling and heating and also makes located kitchen near living spaces but in small size (Daneshjoo & Farahani, 2013; Shirazi et al., 2018)
Riyadh	1. Traditional house has a private courtyard for thermal comfort (Yakovlev, 2021) 2. The houses are close to each other (ʿUthmān, 2020) 3. The streets are so narrow to protect from the straight sunlight (Al-Solaiman, 2022) 4. The windows are protected and called Mashrabieh (Al Asadi et al., 2020) 5. Roof-top porch on hot nights of summer is used for cooling (Al-Ibraihm, 1996)	1. They are semi-detached or detached building and exposed to sunlight (Al Asadi et al., 2020) 2. The openings are not protected, which is against the rules for climatic matters (Al-Saif, 1994) 3. The design of the window is useless, and they use mechanical and electrical elements such as fans and ACs for thermal (Sayigh, 1981)
Mukalla	1. Main material is stone, and there are wooden grids (Khaled et al., 2016) 2. Roof terrace for sleeping in hot summer (Nasser Barashed & Essa, 2008)	1. The primary material for contemporary construction is reinforced concrete (Nasser Barashed & Essa, 2008) 2. Using an electrical and mechanical system for cooling and heating (Baangood & Sanusi, 2017)

(continued)

Table 1 (continued)

Cities	Feature related to climatic factor in traditional architecture	Feature related to climatic factor contemporary architecture
Baghdad	1. The house separated between the summer part and winter part (Hasan & Hassan, 2020) 2. Courtyard has the thermal function in the house (Al-Saffar, 2020) 3. Takhtaboosh, tarma, is for thermal comfort in traditional houses (Akram et al., 2016) 4. Badger is an element for cooling the basement for summer (Khaled et al., 2016; Ramdan et al., 2020) 5. Roof terrace for summer sleeping (Khaled et al., 2016) 6. Shanasheel is used for cooling (Al-Hasani, 2012)	1. In front of the house is a garden which surrounds the house from one or two or three side (Hasan & Hassan, 2020) 2. The contemporary houses cooling and heating is by a ceiling fan, a liquid-cooling system (Al-Hasani, 2012) 3. Large windows without any protection (Al-Saffar, 2020)

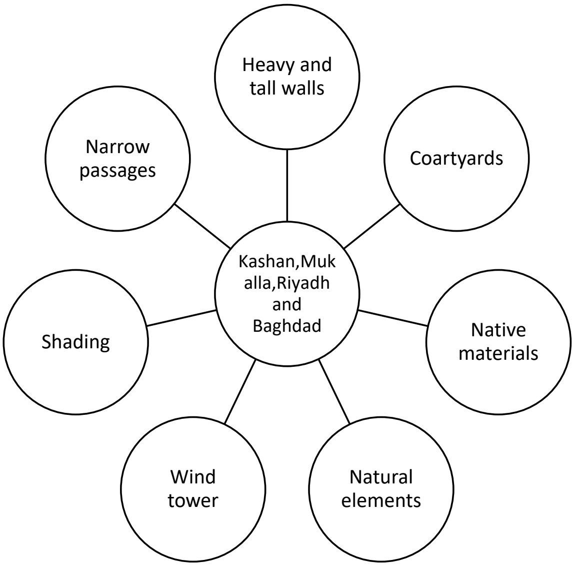
world. However, this fact can be seen in the weakening of the identity and native culture of the Middle East on a large scale.

Second, Table 1 and even Figs. 2, 4, 6, and 8 show the strategies and design indicators of the traditional neighborhoods of the studied cities, which, despite the differences, many commonalities can be found. In the first place, this is due to the almost similar climatic conditions of the cities of Kashan, Mukala, Riyadh, and Baghdad, and in the second place, it can be caused by the common Islamic culture in these areas. As shown in Table 1, the courtyard, both centrally and externally, has been an essential element of traditional design and architecture in the Middle East. This research showed that in urban planning and traditional architecture of the Middle East, such as the cities of Kashan, Mukala, Riyadh, and Baghdad, courtyards are used to increase humidity, and ventilation and keep the environment cool. The importance and role of the courtyard in adapting to the climate of the traditional houses and cities of the Middle East have been presented in various research in support of this study (Abdulkareem, 2016; Ayhan & Neslihan, 2011; Bekleyen & Dalkılıç, 2012). Also, Table 1 reveals that in the foundation of the structure of the 4 studied cities, natural elements were of high importance. In fact, the traditional architecture of these cities, which is the result of years of experience and trial and error, has used nature itself to deal with natural challenges. Something that is no longer seen in the contemporary development of these cities. Using local materials, mud, using water (pond), and trees in the semi-private spaces of houses and controlling airflow is the most important way to get help from natural elements in these cities that this research found.

5 Concluding Remarks

The traditional architecture of these regions has been transformed into contemporary construction. This design typology does not match the weather conditions of these four cities. Passive heating and cooling strategies are also overlooked in contemporary architecture. Efficient designs such as implementing different spaces as cool and warm sections are not observed in contemporary homes. Therefore, ventilation in contemporary homes needs a lot of energy from fossil fuel resources. These days, the natural fossil fuel resources are being faced with being finished. It could cause a big problem for the humans who live in the world for a living. Our analysis declared that in traditional examples of houses in these cities, natural resources were effectively used for heating and cooling. For example, in traditional houses of Kashan and Baghdad, which were analyzed before, summer and winter living spaces are implemented. These sections have different orientations regarding the sun, which makes them cool during the summer or warm during the winter. In the contemporary architectural examples explained before, there is no specific solar-oriented space. Another essential characteristic is wind towers. The wind tower uses a passive mechanism to circulate the cooled air into the interior spaces of the building. Conversely, in contemporary homes, this ventilation is done by an air conditioning system using energy, so spending money is not affordable for everyone. Furthermore, the examples of traditional houses in Mukalla and Riyadh feature roof spaces to be used at night in summer for sleeping. Basements in Kashan traditional example and Baghdad traditional example have ponds, and they are used as cool spaces during the summer. Also, this research was able to show that there are many commonalities between the 4 studied cities in terms of design and policies adaptable to climate challenges, which are shown in Fig. 9. It should be added that the findings of this research can familiarize today's policymakers, architects, and urban planners with traditional useful strategies and strategies adapted to the climate and encourage the private sector to use them again. It should be added that the most important limitation that this research faced was the lack of information and related research in the cities of Mukala and Riyadh. Finally, it could be concluded that both climatic factors and privacy issues were considered in the design of traditional houses in the past. However, the pattern of contemporary homes is almost identical in all regions without considering such matters. People in the contemporary period need to reconsider their design style by using traditional design characteristics as a benchmark.

Fig. 9 Common Strategies and elements of adaptation to the harsh climate in the cities of Kashan, Mukala, Riyadh, and Baghdad



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Chapter 9
Urban Thermal Environment Under Urban Expansion and Climate Change: A Regional Perspective from Southeast Asian Big Cities

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Abstract Southeast Asia (SEA) is a hotspot of rapid urbanisation and climate change, which is supposed to influence millions of people. They altogether exacerbate urban thermal environments and amplify urban heat islands (UHIs). The chapter provides a comprehensive assessment of urban warming trends in SEA big cities over the past thirty years in a connection with urban expansion and climate changes; of which climate change is represented by temperature extremes as an additional element deteriorating UHIs. It reveals a significant warming trend in nighttime extreme indices across the cities against daytime indices. Manila and Kula Lumpur have confronted the most prominent temperature variations. There were drastic transformations in urban areas, urbanisation patterns, and landscape characteristics during urbanisation. The fastest-growing cities during this period are Jakarta, Bangkok, and Ho Chi Minh City. The degradation of the urban thermal environments was also confirmed via spatiotemporal escalations of land surface temperature (LST) and surface UHI (SUHI) over time. The aggravation in urban thermal environments was mainly driven by urbanisation-related elements and temperature extremes as a background climate factor. The changes in surface characteristics are the main driving factors across the cities. Yet, the stimulations of climate on thermal environment

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degradation are uneven among the cities. Ho Chi Minh City, Jakarta, and Manila are the most vulnerable cities due to combined impacts rather than others. It verifies the integrated impacts of climate change and urbanisation on urban microclimate change, it therefore should have long-term strategies to mitigate the adverse effects of SUHI. The general principle is to reduce horizontal urban expansion, ensure urban spatial planning and urban green spaces, and mainstream climate change adaptation into urban planning.

Keywords Climate changes · Megacities · Southeast Asia · Urban heat island · Urban expansion

1 Introduction

Southeast Asia (SEA) has seen significant urbanisation since the middle of the twentieth century. Along with urban expansion, natural landscapes are increasingly encroached upon by urban features. It causes a difference in temperatures along the urban–rural gradient, called urban heat islands (UHIs) (US EPA, 2008). The urban heat island phenomenon is one of the most concerning problems in urban areas since it causes thermal discomfort, heat-related morbidity, mortality, and high energy consumption for cooling demand (Nguyen et al., 2021a; Santamouris, 2020). With global warming and further urban development, the UHI phenomenon will be likely deteriorated. It means urban thermal environments will be more severe because of the integrated impact of continuing urban expansion and global warming (Fig. 1). However, as indicated by Chapman et al. (2017) only about 14% of the existing studies have assessed urban expansion and climate change interactions on urban thermal environments such as land surface temperature (LST) and UHIs.

1.1 Rapid Urbanisation

After the colonial periods, many Asian countries immediately rebuilt their countries. Most countries have rapidly developed with intensive urbanization, increased population, and industrialisation in the primate cities. However, the outstanding development of the economy in Asian countries only began in the 1980s. Such a transition was even faster than in some western regions (Yamashita, 2017). Mingxing et al. (2014) revealed that the annual growth rate and economic growth rate in SEA from 1980 to 2010 were always higher than that in other regions. An assessment based on population growth and economic development (GPD per capita) indicated that Singapore, Brunei, and Malaysia have a high urbansation level; Cambodia, Timor Leste, Vietnam, Laos, and Myanmar have a less advanced economy with medium–low urbanisation; Thailand, Indonesia, and the Philippines place between these two nation clusters (Yap & Thuzar, 2012).

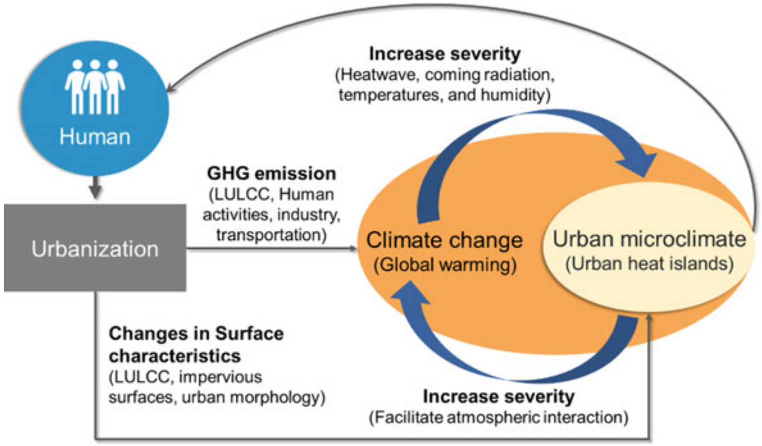


Fig. 1 Conceptual framework about interactions between urbanization, climate change, and urban microclimate change (*Source* Authors' own creation)

SEA is relatively dynamic regarding population growth since this region is the third-highest subregion by population in the Asian continent. Its population was about 662 million in 2019, with half of the population living in urban areas (United Nations, 2019). The urban population is expected to reach 56% in 2030, in which Brunei, Indonesia, Malaysia, Philippines, and Thailand will become spotlights of regional urbanisation in the next ten years. Currently, SEA holds three out of 33 megacities worldwide, including Manila (13.4 million), Jakarta (10.5 million), and Bangkok (10.1 million). The region is also home to 4 of the 48 cities with 5–10 million residents. These cities were Ho Chi Minh city (8.1 million), Kuala Lumpur (7.6 million), Yangon (5.2 million), and Singapore (5.8 million). These are expected to be the next megacities in the future (United Nations, 2019).

Spatial-based assessments on urbanisation (simultaneously or separately) revealed a consistent trend of rapid urban expansion over time. Schneider et al. (2015) confirmed the fast urban sprawl in SEA, in which the built-up expansion was even higher than the regional average (2.0%/year) and Eastern Asia countries, e.g., the Philippines (2.2%/year), Cambodia (2.9%/year), and Laos (3.2%/year). The robust urbanisation was also characterized by nighttime light (NTL), which shows the urban expansion from the centers outwards dominated by the areas of low-intensity NTL (Min et al., 2018, 2020). During the period 1992–2013, NTL data revealed that Thailand, Timor Leste, Myanmar, Vietnam, Laos, and Cambodia developed faster than the entire SEA, in which Cambodia underwent a remarkable rise of approximately 1,800% (Min et al., 2018).

1.2 Climate Change in SEA and Its Impacts on Urban Areas

SEA is among the most vulnerable regions considering global warming and climate change impacts. There is clear evidence of an increase in mean near-surface temperature compared to those observed in 1850–1900 as well as precipitation and extreme events (ASEAN Secretariat, 2021; IPCC, 2021a). In the future, regional climate change will be expected to increase its extremeness. Heat and cold extremes have been detected in two confidences opposing upward and downward trends, respectively. These trends will continue over the coming decades at a high confidence level. Despite the warming trend in SEA being lower than the global average, heat stress impacts are increasingly prominent under the RCP8.5 scenario, especially in Myanmar, Philippines, Thailand, Vietnam, and inland populous cities (IPCC, 2021a).

Moreover, urban areas and cities are the hotspots of global warming since they are mostly warmer than the surrounding areas due to anthropogenic heat sources from human activities, compact urban geometry, and heat trapped in urban materials and impervious surfaces. These factors can accumulatively increase the urban temperature by +3.0 °C to +5.5 °C. Within urban and city areas, there is usually a severe shortage of natural cooling sources, while these landscapes can provide efficient cooling effects, i.e., water bodies (–0.8 °C to –1.2 °C) and vegetation (–1.6 °C to –3.0 °C) (IPCC, 2021a).

Although urbanisation is not the main culprit of warming urban thermal environments, it remarkably contributes to the warming effect in urban areas against surrounding areas. The exacerbation of urbanisation on the total warming is from one-eighth, especially this proportion may reach over a half of the total warming in some cities in the Eurasian continent. Future urban development will amplify the urban air temperature regardless of the cities' background and climate patterns, especially the warming signal on minimum temperature, which will be even more prominent than global effects. There will be far-reaching impacts caused by a synergy between urban expansion and more frequent heatwaves with more hot days and warm nights. It will negatively push the cities into more extreme conditions when urban dwellers' thermal comfort is stressed (IPCC, 2021b).

Therefore, the major research questions leading to this chapter are: How SEA cities have faced local and global changes in urban sprawl, microclimate, and climate extremes over the past three decades? Is there an interaction between climate extremes and urban expansion to urban microclimate change? And, how does this dominance differ across the cities? The chapter begins by monitoring temperature extremes, built-up area expansion, and surface temperature changes from 1990 to 2020 before the interactions among them are then explored to figure out the highlights in each city. Thereby discussing points that should be noted in urban planning for cooler cities.

2 Materials and Methods

This chapter is concerned with five big cities in SEA in terms of population size, including three megacities of Manila (MNL: 13.4 million), Jakarta (JKT: 10.5 million), and Bangkok (BKK: 10.1 million) and two other big cities of Ho Chi Minh City (HCM: 8.1 million) and Kuala Lumpur (KLP: 7.6 million) (Fig. 2). SEA lies around the low latitude, so this physical pattern contributes significantly to forming distinctive regional climates. This region is influenced by two climate systems: the monsoon winds system (i.e., northeast and southwest) and the humid equatorial climate (Gupta, 2006). The seasonal variation increases in higher latitude regions, but the average variation of annual temperature does not exceed 5 °C, while the maritime region's climate tends to be more stable.

Extreme temperature indices represented climate changes, specifically as global warming and temperature increase. Observation data collected from weather stations, especially those placed in urban areas, often face overestimation since it is a result of a complex interaction (Yaung et al., 2021). Therefore, reanalysis data of TerraClimate was adopted to limit this effect in the calculation of seven temperature indices of mean minimum temperature (TNMEAN), minimum of minimum temperature (TNN), maximum of minimum temperature (TNX), mean of maximum temperature (TXMEAN), minimum of maximum temperature (TXN), maximum of maximum

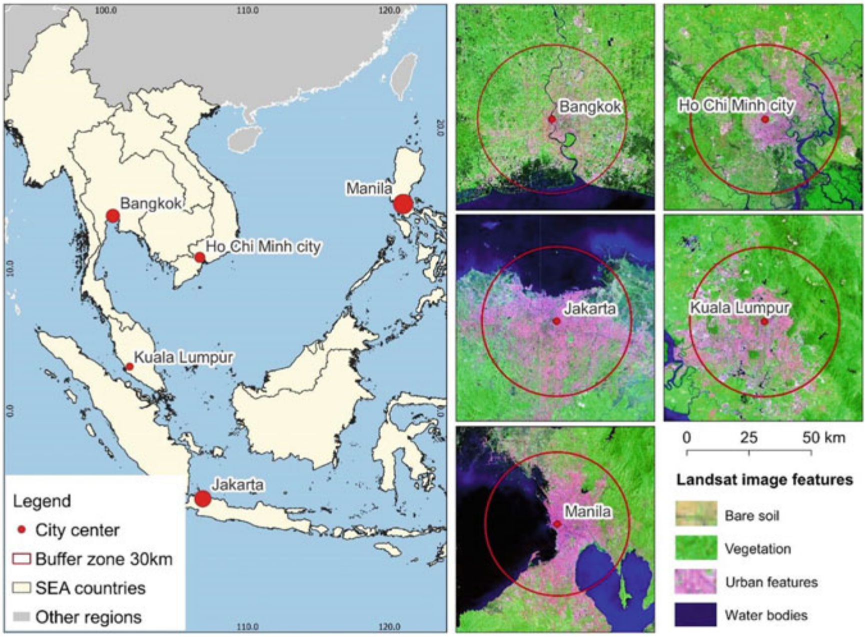


Fig. 2 Location of selected cities in SEA with dot size presenting population scale and false colour composite of Landsat images in 2020 within a 30-km buffer region from the nominal city centers

temperature (TXX), and heat index (HI)—a function between temperature and humidity. The trend of extreme indices was analysed by Mann–Kendall analysis to recognize the monotonic trend (Sein et al., 2018).

Landsat imagery (i.e., Landsat 5-TM, 7-ETM, and 8-OLI) is the core dataset to retrieve land surface temperature (LST), surface urban heat island (SUHI), and delineate urban land use, land cover (LULC) maps. LST was extracted using reflective information from the thermal infrared band and emissivity based on NDVI (Normalised Difference Vegetation Index). SUHI was then identified as LST differences between urban and rural areas, whereas urban–rural boundaries were defined based on LST changes along the urban–rural gradient (Wemegah et al., 2020).

LULC maps in each city were classified from Landsat multispectral bands and spectral indices adopted a classification framework introduced by Nguyen et al. (2022), which releases the dependency of training and validation datasets on field survey data. Specifically, the training and validation datasets were randomly selected based on confident regions, which were detected using spectral indices corresponding to each LULC category (Nguyen et al., 2021b; Tucker, 1979; Xu, 2006). Subsequently, the LULC layers were adopted by using support vector machine classifier (SVM).

Urban features were then extracted for urban expansion analysis to recognise the main urban sprawl trend in each city, which could be infill, extension, or leapfrog patterns. Landscape metrics were calculated for both urban and vegetation features to reflect characteristics of urban and vegetation changes over time, such as AI (aggregation index), ENN (Euclidean nearest neighbor distance), LPI (largest patch index), LSI (landscape shape index), NP (number of patches), PD (patch density), and PLAND (proportion of landscape).

The individual parameter was examined through change detection analysis before they were scrutinised by Partial Least Squared Regression (PLSR) model with dependent variables of LST and SUHI. The PLSR is also a variable reduction method similar to principal component analysis. Yet, it considers independent variables with controls from a/a few dependent variables. Important variables were retained using variable importance on projection criteria (VIP > 1) to reveal the critical controlling factors (Lew et al., 2019).

3 Results and Discussion

3.1 *Manifestations of Climate Change Through Extreme Temperatures*

During 1990–2020, the SEA cities have seen consistent warming and severity trends for extreme temperature indices through significant Mann–Kendall analysis and Thiel-Sen slope (Table 1). The severity is the most evident for heat index and nocturnal temperatures across the cities.

Table 1 Thiel-Sen's slope presents changing magnitude for temperature-based extreme indices over the whole period (°C/decade)

Temperature index	BKK	HCM	JKT	KLP	MNL
HI	0.42*	0.70*	0.43*	0.80*	0.57*
TNMEAN	0.12	0.24*	0.31*	0.35*	0.23*
TNN	0.12	0.30	0.30*	3.70*	0.16
TNX	0.06	0.24*	0.29*	0.33*	0.30*
TXMEAN	0.04	0.05	0.06	0.17*	0.09
TXN	0.04	0.04	0.05	0.19*	0.14
TXX	–0.08	–0.07	0.20*	0.20	0.09

Symbol (*) indicates statistical significance

The changes in TN-based indices were more apparent, which were detected in almost every cities. TNMEAN and TNX are noteworthy regarding the number of detectable cities with significant enlargements (except for BKK), while TNN has a relatively higher increasing magnitude than the other two indicators. The warming trend of TNX was consistently identified across the cities. KLP has experienced the highest warming among other cities for every nocturnal index. However, the warming trend in TNN was rarely found, which was only significant in JKT (+0.3 °C/decade) and KLP (+0.37 °C/decade). The daytime warming was also detected, however, this change is less significant compared to those observed during nighttime. The significant warming was only found in KLP (TXMEAN and TXN) and JKT (TXX).

During the thirty years, there have been critical increasese in the city's daytime and nighttime temperatures and heat index. These variations were observed through changes in extreme indices, which describe different temperature aspects. Nocturnal warming is more apparent compared to daytime warming. However, daytime warming can be detected when considered together with the corresponding relative humidity, reflected via heat index. The severity of extreme indices was recognised in most cities via at least one significant indicator. And, the cities in this region exposed to high heat index were KLP, JKT, and HCM.

3.2 Urban Expansion and Alternations of Surface Characteristics

3.2.1 Urban Expansion Trends from 1990 to 2020

The cities have experienced urbanisation along with LULC changes (LULCC) over the past thirty years to different extents. The primary dynamic is none other than urban expansion, which is observed through urban sprawl and vegetation shrinking. The primate city cores in 1990 have expanded outwards by unique forms depending on each city's characteristics in terms of geographical location and topography, but mainly in the flat plains and valleys along transportation systems. These forms of expansion are prominently observed in BKK, HCM, and JKT (Fig. 3).

In the 1990s, it indicates that BKK held the largest urban areas, about 448 km^2. It was then followed by MNL and JKT, which were approximately a quarter of the urban areas in BKK. The urban areas in HCM and KLP only sealed a relatively small proportion. After thirty years of development, BKK was still the largest metropolitan in terms of urban areas. There were 1,114 km^2 of built-up areas in the buffer zone of the BKK metropolitan. JKT has rapidly expanded its urban areas to gain an extensive area of 1,070 km^2 and to be the second-largest city. The proportion of built-up areas in these two megacities is approaching 50%, i.e., 45.3% in JKT and 39.6% in BKK. Notably, the urbanisation in HCM has considerably developed since the 2010s and became the next largest city with 694 km^2 of urban areas in 2020.

The entire region has experienced rapid urbanisation over the past three decades. Some cities have made enormous strides over this period, which have been witnessed through the annual urbanisation growth rate (AUGR). More explicitly, JKT is the fastest growing city among the others with AUGR = 137%/year. The growth rate was relatively even throughout the whole period, and it was always higher than 100%/year for each ten-year interval. BKK, HCM, and MNL have relatively similar characteristics of urban growth, which underwent a moderate-fast urban expansion with an average AUGR for the whole period of around 75–79%/year. The AUGR gradually augmented over time and achieved the highest rate in the last ten years.

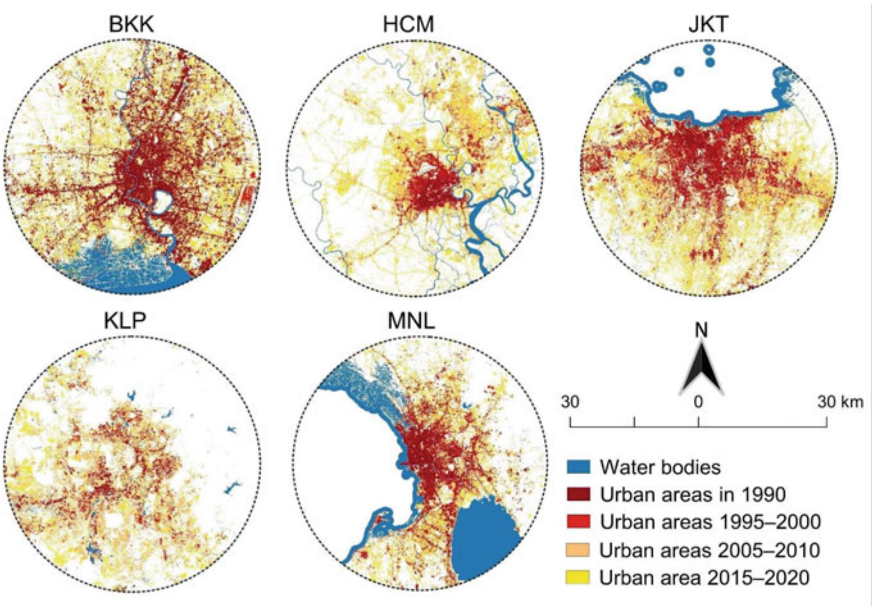


Fig. 3 Spatial distribution of the expended urban areas from 1990 to 2020

Table 2 Proportion of urbanisation patterns in SEA cities over the past thirty years

City	Area (km^2)				Proportion (%)		
	Infill	Extension	Leapfrog	Total	Infill	Extension	Leapfrog
BKK	58.1	555.6	100.0	713.7	8.1	77.8	14.0
HCM	7.8	456.9	181.3	646.0	1.2	70.7	28.1
JKT	12.2	779.3	187.8	979.3	1.3	79.6	19.2
KLP	1.4	334.6	220.6	556.6	0.3	60.1	39.6
MNL	16.7	348.1	75.6	440.3	3.8	79.1	17.2

During the urban expansion, it is similar to others developing cities when the major urbanisation form is the extension—a new urban area developed at the fringe of the already developed urban areas. This form always accounts for more than half of total urbanised areas (Table 2). It even reaches nearly 80% of urbanized areas in the fastest growing city of JKT (79.6%) and the city with limited potential areas for urbanisation like MNL (79.1%). Leapfrog form, which develops separately outside the previous urban areas in the rural areas, is the second main form. Leapfrog is the popular urbanisation form in the newly developed cities or "young cities" as they plan to establish new residential areas independently at potential locations in rural areas (Hong Diep et al., 2021). Then, urban infrastructures connect these "satellite cities" with the primate city to form a great metropolitan. KLP and HCM are the prominent cities with a noticeable proportion of leapfrog patterns, 39.6% and 28.1%, respectively. Infill is the least popular form among the three urbanisation patterns, which is constructed between already developed areas. It intends to be encountered in developed and more mature cities such as BKK (8.1%) and MNL (3.8%).

3.2.2 Alterations in Landscape Characteristics

Along LULCC and urban expansion, landscapes have been profoundly transformed that leading to a significant shift in landscape composition and configuration. The landscape characteristics of built-up and green spaces are the most sensitive quantities during these transformations, which change towards urban agglomeration and vegetation fragmentation. The landscape metrics mainly reflect two focused characteristics of area/edge and aggregation/fragmentation (Table 3). In general, the trends of built-up and green space features are opposite each other.

PLAND and LPI indicate edge and area attributes. It is in line with the findings of urban expansion and increases in city size since urban PLAND was remarkably elevated in all cities, approximately 0.73–1.38%/year. LPI also reveals the enlargement of built-up patches. It is prominent in JKT with PLAND increasing by 1.38%/year and 1.07%/year (LPI). The large urban patch in BKK and MNL grew faster than in HCM and KLP. At the same time, vegetation presented the corresponding shrinking trend over time. JKT, BKK, and KLP have faced considerable degradation in green coverage. The green spaces in almost every city have also been shrunk into

Table 3 Variations in average landscape metrics for urban features and green spaces

Features	Metrics	BKK	HCM	JKT	KLP	MNL
Built-up	AI	−0.03	0.05	0.36*	0.49*	0.2*
	ENN	−1.36*	−3.98*	−1.29*	−1.67*	−1.5*
	LPI	0.81*	0.41*	1.07*	0.26*	0.63*
	LSI	2.31*	3.09*	1.76*	2.52*	1.09*
	NP	265*	496*	174*	327*	86*
	PD	0.09*	0.18*	0.07*	0.12*	0.04
	PLAND	0.78*	0.75*	1.38*	0.75*	0.73*
Green spaces	AI	−0.26*	−0.1	−0.32*	−0.12*	0.05
	ENN	−0.31*	0.14	0.10	0.01	−0.06
	LPI	−0.68*	−0.26*	−2.42*	−0.59*	0.18
	LSI	2.87*	1.27	3.17	1.77	−0.29
	NP	266*	118*	295*	120*	16
	PD	0.09*	0.04*	0.13*	0.04*	0.01
	PLAND	−0.74*	−0.37	−1.24*	−0.50*	0.17

Symbol (*) indicates statistical significance

smaller patches. Notably, the green spaces in MNL have been improved steadily since 2000, this advance is however insignificant during the considered time.

Landscape aggregation and fragmentation were assessed using LSI, ENN, NP, PD, and AI. For urban features, there were consistent trends of increasing LSI and decreasing ENN entire the cities, revealing that built-up patches have developed more closely together and formed more complex shapes. Among the cities, HCM has seen sharp changes in NP, PD, ENN, and LSI for urban features. It implies that HCM is the most dynamic city in terms of quantity, distribution, and shape, becoming more aggregated, compact, and complex. The same trends were found in JKT, BKK, and KLP at a lower rate, while the urban development in MNL was relatively moderate.

The vegetation patterns were significantly changed towards increase in fragmentation. There were increases in the number of green patches (NP) and PD in almost all cities along with the complexity of green spaces (LSI), while LPI declined over time. The extensive green patches are strongly fragmented into smaller discrete patches by constructions and residential areas, which then leads to a compounded landscape with degraded green coverages. JKT, BKK, and KLP have encountered noticeable vegetation shrinking. It was reported that urban green space per capita in BKK and HCM has even much improved compared to the first decade of the century, however, it is still lower than the WHO recommendation (Nguyen & Chidthaisong, 2022). Meanwhile, the vegetation dynamics in MNL tend to be more stable throughout the period than in other cities as a sign of urban reforestation.

3.3 Escalation in Urban Surface Temperatures

Urban thermal environments observed by LST and SUHI showed deterioration in both spatial and temporal aggravations (Fig. 4). All cities have increasingly warming trends and expand the dominated areas occurring in SUHI over the past 30 years. Long-term observation of spatial changes in SUHI indicated that about one-third of the total area in MNL (32.9%) and KLP (31.3%) has confronted the prolonged SUHI (i.e., area with SUHI frequency of higher than 20 years). This region in JKT and BKK also accounts for a significant share of the area, about one-fourth of the total area. Besides, the majority of HCM areas are dominated by the newly formed SUHI with a frequency of fewer than 10 years, about 64.2%. MNL and HCM are the most severe cities within the last three decades because their annual average LST is relatively hot, about 26.0 °C and 25.0 °C.

LST and SUHI have significantly increased over time. A group of three cities, including BKK, JKT, and KLP, has overcome considerable warming in LST, which varies from 1.23 °C/decade to 1.28 °C/decade. MNL and HCM are more modest when their LST have been warmer, about 1.17 °C/decade and 1.08 °C/decade, respectively.

The SUHI has been aggravated at a high significance level ($p < 0.01$) except for HCM ($p < 0.1$). MNL is the harshest city with the most intensive SUHI intensity throughout the time (SUHI $\approx$ 3.01 °C). The second severe city is KLP with average

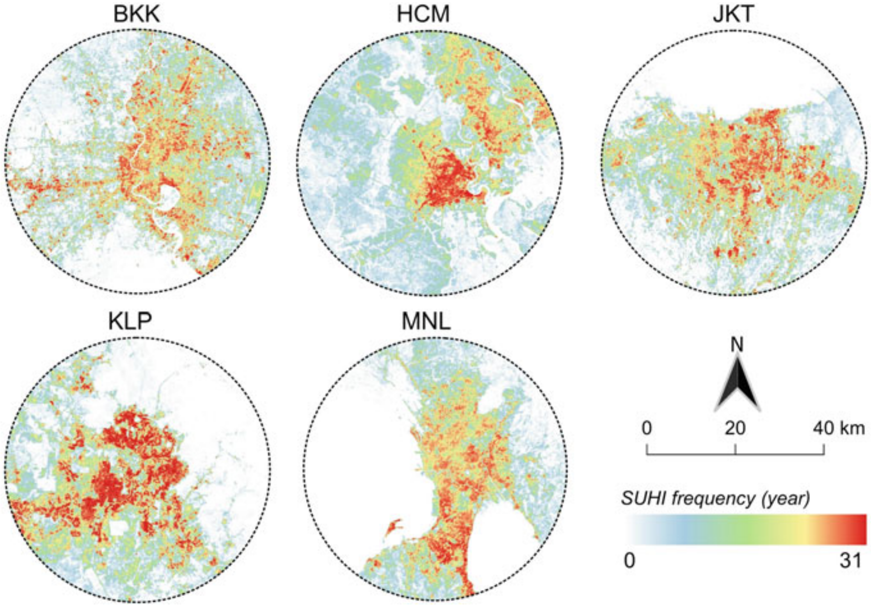


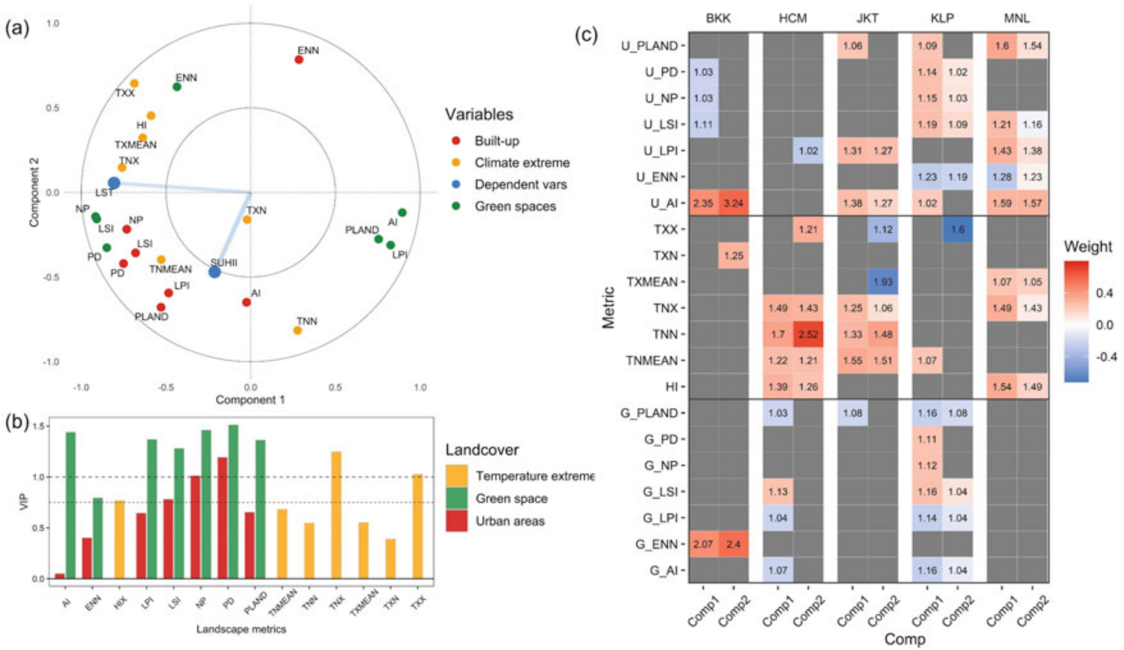
Fig. 4 Spatiotemporal changes in SUHI over the past thirty years observed by SUHI frequency (unit: years), which represents number of SUHI occurrence. Red represents consistent and prolonged SUHI regions, while green and cyan are new and less prolonged SUHI regions

SUHI intensity of about 2.21 °C. These two cities have apparently overcome the fastest-growing SUHI intensity, approximately 0.35 °C/decade (MNL) and 0.37 °C/decade (KLP). They are then followed by JKT (0.23 °C/decade), HCM (0.19 °C/decade), and BKK (0.15 °C/decade).

3.4 Integrated Impacts on Urban Surface Temperatures

Dominant mechanisms of landscape configuration and climate changes for regional urban thermal environments are explained by a significant PLSR model (Fig. 5a–b), with a 62.3% variance of thermal environments described by the first component (Comp1). Specifically, the first component's variations of LST are highly interpreted ($R^2 = 0.68$). The most important variables (VIP > 1) are constituted by landscape patterns of urban features (NP and PD) and green spaces (AI, LPI, LSI, NP, PD, and PLAND). Climate extremes also contribute to changing thermal environments by TNX and TXX. More explicitly, the increases in built-up areas with vegetation fragmentation will warm up the LST in a city, while extreme climate such as an increase in the maximum daytime and nighttime temperatures will exacerbate this severity. Although the SUHI intensity is less characterized by the considered independent variables ($R^2 = 0.22$), it potentially explains the escalation of SUHI intensity by most of the urban features except for LSI and NP, in which urban agglomeration facilitates SUHI deterioration. The fragmentation of vegetation represented by PD will increase SUHI, while increasing the proportion of green spaces is able to diminish the formation of SUHI significantly. Similar to LST, SUHI is also driven by climate change via an increase in the nocturnal temperatures of TNMEAN and TNN.

The unique driving factors of SUHI in each city were depicted by separated PLSR models (Fig. 5c). The SUHI in SEA cities is stimulated by combined impacts from the dynamics in urban expansion and green spaces and climate changes at different extents. Urbanisation was detected to highly exacerbate SUHI in MNL and KLP, reflected by several landscape composition and configuration indicators. This impact is more moderate in JKT and BKK, where changes in urban aggregation and morphology tend to adjust the SUHI escalation significantly. In HCM, the key element controlling its SUHI is the expansion of urban strips. The impact of vegetation dynamics was found to have a less pronounced impact than urban features. For instance, it is invisible in MNL, which means the SUHI growths during the period were not mainly contributed by vegetation changes. In contrast, the increase in SUHI in JKT was caused by a decline in vegetation proportion, while the fragmentation of green spaces was the main culprit inducing SUHI in BKK. Noticeably, HCM and KLP are the places that have encountered SUHI aggravation due to vegetation shrinking and fragmentation. HCM has undergone a quantitative decline, while the vegetation coverage in KLP has degraded proportion and fragmentation. With respect to climate extremes, all cities tend to be influenced by changing climate and ultimately reflecting via SUHI. The most severely affected cities are HCM, JKT, and



Metric	BKK Comp1	BKK Comp2	HCM Comp1	HCM Comp2	JKT Comp1	JKT Comp2	KLP Comp1	KLP Comp2	MNL Comp1	MNL Comp2
U_PLAND					1.06		1.09		1.6	1.54
U_PD	1.03						1.14	1.02		
U_NP	1.03						1.15	1.03		
U_LSI	1.11						1.19	1.09	1.21	1.16
U_LPI				1.02	1.31	1.27			1.43	1.38
U_ENN							1.23	1.19	1.28	1.23
U_AI	2.35	3.24			1.38	1.27	1.02		1.59	1.57
TXX				1.21		1.12		1.6		
TXN		1.25								
TXMEAN						1.93			1.07	1.05
TNX			1.49	1.43	1.25	1.06			1.49	1.43
TNN			1.7	2.52	1.33	1.48				
TNMEAN			1.22	1.21	1.55	1.51	1.07			
HI			1.39	1.26					1.54	1.49
G_PLAND			1.03		1.08		1.16	1.08		
G_PD							1.11			
G_NP							1.12			
G_LSI			1.13				1.16	1.04		
G_LPI			1.04				1.14	1.04		
G_ENN	2.07	2.4								
G_AI			1.07				1.16	1.04		

Fig. 5 PLSR analysis shows (a) correlation circle between landscape metrics of built-up and green spaces, climate extreme indices, and thermal environments; (b) important variable selection; and (c) important variables in each PLSR model to characterize SUHI in each city. Numbers show VIP values; color shades represent impact tendency (blue: negative and red: positive), and gray cells are insignificant variables

MNL, where variations in heat index and nighttime temperatures prominently link to SUHI formations.

3.5 Implications for a Long-Run Vision Toward Cooler Cities

SEA cities have been undergoing rapid urbanisation causing urban thermal environment changes throughout the cities. It will worsen due to unceasing urban expansion and the amplification of climate change. Therefore, an insightful understanding and long-term strategies to mitigate UHIs are essential, which could achieve by controlling each corresponding element. In general, the urban sprawl in developing cities in the global South and megacities is dominated by infrastructure-led development (ILD), e.g., built-up mainly expands along the transportation systems in BKK, HCM, and MNL. In addition to its benefits in connecting development nodes and resource frontiers, ILD raises different socioeconomic and environmental issues, such as high land budget demand and daunting land acquisition (Sisson et al., 2018). ILD also causes uncontrolled urban growth because this urban sprawl form often goes beyond the administrative boundary, e.g., the Thailand Eastern Economic Corridor (Can et al., 2021). Therefore, urban and land use plans should be considered at regional levels and cross-boundaries rather than individual counties to better manage urban development and then impede UHI growth. Uniform urban growth among primate and secondary cities should be encouraged to relieve burdens for megacities, especially migration waves for jobs that may lead to unintended development of infrastructures due to shelter demands. It ultimately causes UHIs because of an increase in built-up areas.

Built-up areas in all cities drastically expand horizontally. This expansion will gradually encroach on neighboring areas, especially in green/blue spaces such as forests, agriculture, and wetlands. Besides, the nominal mature cities of BKK, MNL, and KLP expanded mainly by infill form, which is hotter than the other two patterns (Zhang et al., 2021). Therefore, constructions between already urban areas in these cities should be carefully considered as to whether they should be for construction or green space conservation to mitigate UHIs. Compacting urban areas by vertical increase with height-rise buildings, multifunctional stories, and apartments are also a potential solution to prevent further expansion outwards. However, it should be thoroughly considered urban morphology and ventilation to avoid adverse effects. Especially, the severity of nighttime temperatures in HCM, JKT, and KLP is a critical sign implying the problem in urban morphology and compactness, which need prompt attention to avoid accompanying consequences.

There is a scarcity of urban green spaces presently in SEA cities. The reduction rate of green spaces is speedy, and the remaining green spaces are also degraded and severely fragmented. Although the governments have made efforts to improve average green space per capita, it is still lower than the recommendation. Therefore, urban green space areas need to optimize in the downtowns of these cities. Also, the concept of ecosystem services should be strengthened and integrated into land use planning and urban green infrastructure projects to mitigate UHIs.

Presently, it is relatively rare for a developing city to mainstream global warming and climate change into urban planning since it is not a main diver of urbanisation. Yet, climate change along with urbanisation is supposed to influence the urban thermal environments significantly to different extents in each city. It should incorporate climate change into the master plan as an important challenge to address throughout the development of vulnerable cities due to climate changes (e.g., HCM, JKT, and MNL). Subsequently, there is appropriate design planning for temperature changes and SUHI formation and the risk of sea-level rise, urban inundation, and tropical storms to sustainably develop toward more livable cities.

4 Concluding Remarks

Climate change through global warming plays as an additional driver along with urban expansion and alternations in surface characteristics exacerbating urban thermal environmental changes. A warming trend was found in entire SEA cities regardless of daytime and nighttime, of which MNL and KLP have confronted the most prominent noctural variations. All the cities are relatively dynamic in terms of urban development with dramatic transformations in urban areas, urbanisation patterns, and landscapes. The fastest expanding cities are JKT, BKK, and HCM. The degradation of the urban thermal environments was also confirmed via escalations of both LST and SUHI. The aggravation in thermal environments was mainly driven by urbanisation-related elements and climate change as a background climate factor. The surface changes are the main driving factors across the cities. Yet, the stimulations of climate on thermal environment degradation are uneven among the cities. The most affected cities by climate changes are HCM, JKT, and MNL, these cities therefore are supposed to be more vulnerable due to combined impacts than the other cities.

Climate change is considered as a return effect, further amplifying the urban thermal environments, even though the forward effect of urbanisation on near-surface temperature is widely accepted. The urban thermal environments in SEA cities are dramatically affected by the integration of both climate change and local transformations from urban development. Therefore, they should have suitable strategies to mitigate UHIs growth by controlling horizontal urbanisation, introducing ecosystem services of urban green spaces, implementing urban green infrastructure projects, and developing climate change resilience interventions. Yet, it is necessary to adjust flexibly for each city depending on its characteristics and priorities. For example, dense cities need to firstly improve the green space per capita, while climate change-prone cities need to immediately develop adaptation and response strategies.

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Chapter 10
Climate-Responsive Designs to Enhance Outdoor Thermal Comfort in Urban Residential Areas

Tingting Yuan, Hongyun Qu, and Bo Hong

Abstract Our study aims to determine relationships among microclimate, outdoor thermal perception, and residents' behavior in a residential area in Xi'an, China. Four typical open spaces in the residential area were investigated using meteorological measurements, questionnaire survey, and behavioral records to determine how individuals' thermal comfort relates to their outdoor activities. Physiological Equivalent Temperature (PET) was applied to quantitatively determine the outdoor thermal benchmarks in Xi'an, and climate-responsive strategies for open spaces were proposed based on thermal benchmarks. Results showed that: (1) spaces differed significantly in air temperature, wind speed, solar radiation, globe temperature, mean radiative temperature, and PET, but not relatively humidity, (2) in summer, residents preferred activities in shaded environments and attendance was inversely linearly related to PET, and (3) optimum design strategies for open spaces were proposed to consider shelterbelts, shaded facilities, plants, water, and underlying surfaces. These results will help urban designers improve their understanding of the relationship between behavior and thermal comfort and provide design advice for open spaces in residential areas in China's cold region.

Keywords Outdoor thermal comfort (OTC) · Bioclimatic design · Residential areas · Outdoor activity · Physiological Equivalent Temperature (PET) · China's cold region

1 Introduction

More than half of the world's population lives in urban areas, and most live in residential communities (UN, 2014). This is particularly true in China, a country with a relatively high population density in the world. Well-designed urban residential areas offer a high degree of comfort that improve the quality of the residential space

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and the livability of cities (Klemm et al., 2015). High-quality outdoor space can attract more residents to have outdoor activities and increase their use of outdoor space while reducing energy consumption. There are many factors influencing the quality of residential outdoor spaces. Among them, outdoor thermal comfort (OTC) is the most important (Eliasson et al., 2007; Lai et al., 2014b; Zhao et al., 2018). Types of outdoor activity of residents are closely related to the thermal environment and thermal comfort of these spaces (Mi et al., 2020). This correlation is of significance to urban designs (Lenzholzer et al., 2013). Recently, researchers have begun to consider how to create appropriate open spaces to assure human thermal comfort during outdoor activities. Existing studies have shown that spatial design and function as well as people's responses to their physical environments may influence their perception and use of outdoor environments.

The outdoor thermal environments are greatly affected by design quality. Many studies assessed shade on urban streets through the height/width (H/W) ratio (Yin et al., 2022). Lin et al. conducted a study on campus and found (intuitively) that shade-free areas are more likely to be hot in summer compared to high-shade areas and that people in these regions were more likely to feel thermal discomfort (Lin et al., 2010). Hwang et al. reported that slightly shaded areas increase the frequency of high temperatures, especially at noon. Moreover, the thermal comfort with shade in summer was the best indicator of the use (Hwang et al., 2011). Mahmoud further demonstrated that when thermal conditions were warm or hot, people were likely to move from places with full sunshine to cool spaces (Mahmoud, 2011). In general, thermally comfortable open spaces can encourage residents to participate in outdoor activities better and increase usage (Huang et al., 2019).

In addition, most detailed microclimate analyses and OTC assessments in China have been carried out in urban squares, parks, and campuses (Chen et al., 2015; Lin, 2009; Lin et al., 2010). Results to date have shown that psychological adaption and behavioral adjustment have significant influences on thermal comfort (Lin, 2009; Nikolopoulou et al., 2001). Studies that investigate how psychological factors influence thermal comfort have found that experiences in a specific space in a specific season may change people's thermal perception (Knez & Thorsson, 2008), and residents may adjust their thermal expectations among seasons (Lai et al., 2014b; Ng & Cheng, 2012; Shooshtarian et al., 2018). Some studies have demonstrated that the number of users is closely related to the thermal environment (Eliasson et al., 2007; Lin, 2009). Generally speaking, the number of visitors to spaces in cool seasons is positively related to air temperature (T_a) or mean radiant temperature (T_{mrt}), but it is negatively related to these parameters during hot seasons (Lin, 2009; Lin et al., 2012). Some have indicated that the utilization rate of outdoor spaces reaches its maximum under neutral thermal sensation in autumn (Lai et al., 2014b).

Ever more studies concerning thermal comfort have demonstrated the necessity of studying OTC in different climate regions. However, most studies in China have focused on severe cold regions (Chen et al., 2018, 2019), hot summer/cold winter regions (Chen et al., 2015, 2019) and hot summer/warm winter regions (Fang et al., 2019; Zhao, et al., 2016). There have been relatively few studies in the cold region. China's cold regions have unique climatic characteristics (cold and dry in winter, hot and humid in summer) that can induce significant differences in people's thermal perceptions. Studies about thermal comfort assessment in cold regions have mainly focused on parks (Huang et al., 2021; Ma et al., 2021) and campuses (Niu et al., 2020; Zhang et al., 2021), but have rarely involved the thermal comfort of open spaces in residential areas. Compared with other urban public open spaces, spaces in residential areas in cold regions have unique microclimate, user population attributes, and spatial features and the users display different behavioral modes (e.g., seasonal adaptations, activity types, and behavioral habits). Hence, it is necessary to study thermal comfort in residential areas in cold regions.

Relationships among microclimate, thermal perception, and residents' behavior in residential areas are expected to provide guidance and improve outdoor space design, planning, and practices in residential areas. We studied these features in outdoor spaces within a residential community in China's cold regions in summer. The objectives of our study were to (1) determine the relationship between the outdoor thermal environments and the behavioral activities and spatial use of residents, and (2) propose a summer thermal calendar to provide a reference for space optimization strategies based on thermal comfort benchmarks in residential areas.

2 Methodology

2.1 Study Area

According to Koppen's climatic classification, Xi'an is located at the boundary between semi-arid (BSk) and humid subtropical climate zones (Cwa) (Peel et al., 2007). The study area belongs to the subtropical humid zone which the climate is hot and humid in summer, but cold and dry in winter. According to meteorological data from 2010 to 2019, the maximum monthly mean T_a occurred in July (28.07 °C), with a maximum T_a of 39.1 °C (Tian et al., 2022).

In this study, the Hengda Community in Xi'an, China (34°15′44″N, 108°5′18″E) was chosen as representative of the urban residential area. In this community, most buildings were multi-story apartments; 32-floor buildings arranged in parallel. The floor area ratio was 3.3 and the greening rate was 38%. Based on the frequency of space use and the ratio of landscape elements, we selected four representative types of outdoor spaces in residential areas: road between buildings (RB), landscape pavilion (LP), exercise plaza (EP), and waterfront platform (WP) (Fig. 1). Detailed descriptions, fish–eye photos and sky view factor (SVF) values of the four spaces are provided in Table 1.

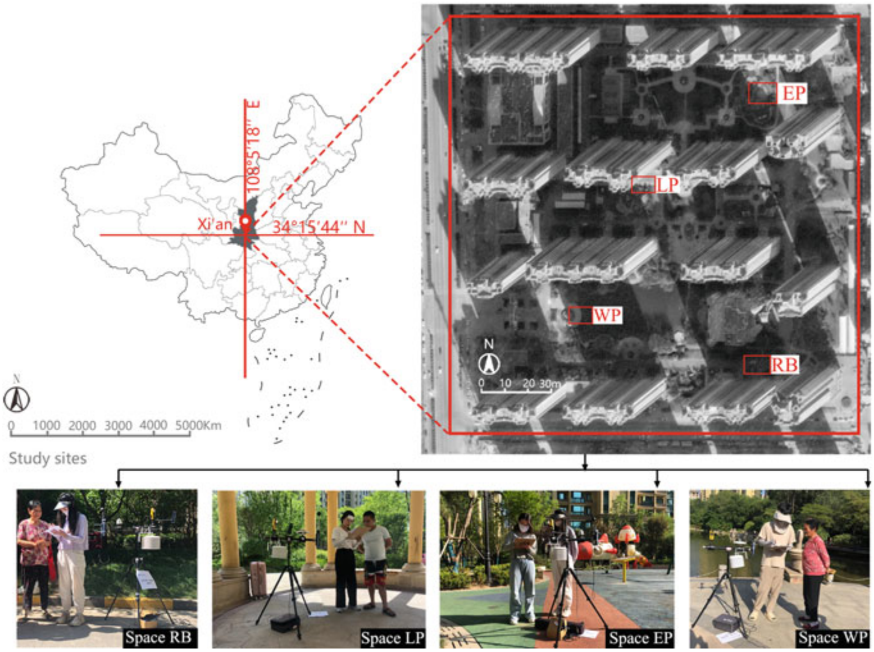


Fig. 1 Site locations and measured spaces

2.2 *Experimental Design*

2.2.1 Meteorological Measurements

Field investigations were conducted in summer (July 6–8, 2022). Meteorological parameters, including *T*, Relative humidity (*RH*), wind speed (v_a), Global radiation (*G*) (and black globe temperature (T_g), were recorded every minute. All instruments were installed at a height of 1.1 m above the ground (Table 2). The T_{mrt} was calculated using ISO7726 standards (ISO, 2005).

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273 \tag{1}$$

where *D* is the globe diameter (*D* = 0.05 m in this study) and Ɛ is the emissivity (Ɛ = 0.95 for a black globe).

Table 1 Descriptions of the four open spaces

Site	Site characteristic	Fish-eye photos
RB	This space is an east-west strike and locates on the south side of the residential building. *Melia azedarach* is used as the sidewalk planting and concrete pavement is applied. The landscape elements include buildings (9%), vegetation (29%), and pavement (62%)	 SVF = 0.19
LP	The landscape pavilion is adjacent to the main district road on one side and a plant community with trees, shrubs, and grasses on the other. The landscape elements consist of buildings (48.56%), vegetation (9.23%), and pavement (42.21%)	 SVF = 0.04
EP	The space is dominated by fitness equipment and a rubberized surface surrounded by a rich plant community with layers of trees, shrubs, and grasses. The landscape elements consist of buildings (16.32%), vegetation (25.87%), and pavement (57.81%)	 SVF = 0.29
WP	Adjacent to the south bank, the surrounding vegetation is dominated by shrubs. The surface is brick and concrete. The landscape elements consist of water (10.05%), buildings (13.68%), vegetation (22.83%), and pavement (53.44%)	 SVF = 0.39

Table 2 Technical details of meteorological equipment

Instrument	Parameter	Range	Accuracy
HOBO onset U23-001	Air temperature	–40–70 °C	± 0.21 °C
	Relative humidity	0–100%	± 2.5%
Kestrel 5500	Wind speed	0–40 m/s	0.1 m/s
DeltaOHM HD 2107.2	Globe temperature	–30–120 °C	± 0.25 °C
JTR05	Global radiation	0–2000 W/m^2	± 2%

2.2.2 Questionnaire Survey

Residents participating in free activities at the study sites were asked to complete questionnaire surveys while we measured meteorological parameters. Residents who had activities in the spaces were chosen randomly in the questionnaire survey. Each one took about 5 min to fill in the questionnaire.

The questionnaire was composed of two parts. Part I collected personal information of respondents, including gender, age, height, body weight, clothing insulation, thermal adaptive behaviors of respondents when they felt hot, and main activity type in the past 20 min. Clothing insulation was assessed using the ASHRAE standard 55–2017 and ISO standard 7730 (ASHRAE, 2017; ISO 7730, 2005). Respondent activity type in the past 20 min was recorded to determine the metabolic rate (W/m^2).

Part II of the questionnaire investigated thermal perception (sensation, preference, comfort and acceptability) of respondents. Thermal sensation used the ASHRAE 7-level scale, thermal preference used the 3-level scale, thermal comfort was recorded using a 5-level scale and the thermal acceptability vote was selected from a 2-level scale.

2.2.3 Records of Space Use and Attendance

During trials, the number and types of activities of residents in the four spaces were recorded by direct observation method (Martinelli et al., 2015; Shooshtarian et al., 2018). The investigators stood in a position where they could see the complete measurement space and recorded the number of residents and the type of activity in the area every 60 min. Only residents who were active in each space for more than 10 min (e. g. walking, running, talking, etc.) were counted in this study to reflect their true intention to use the space, excluding residents who were only passing by or temporarily staying.

3 Results

3.1 Descriptive Analyses

3.1.1 Volunteers' Attributes

In this study, a total of 398 questionnaires were collected, of which 381 were valid. There were 325 questionnaires filled in by female respondents and 56 filled in by males. According to statistics, most urban visitors participated in mild and moderate activities and few participated in high-intensity activities. All respondents have lived in the studied community for at least one year and they were familiar with the local

Table 3 Volunteers' attributes

Gender		Age	
Male	56(14.7%)	<18	44(11.6%))
Female	325(85.3%)	18–65	197(51.7%)
		>65	140(36.7%)
Height (cm)		**Weight (kg)**	
MAX	186.00	MAX	92.00
MIN	66.00	MIN	20.00
Mean ± SD	157.61 ± 10.08	Mean ± SD	57.85 ± 12.45
Metabolic rate (**W/m^2**)			
MAX	180.00		
MIN	50.00		
Mean ± SD	94.55 ± 33.42		

climate. They all were capable of choosing appropriate clothing according to weather conditions and objectively evaluating the outdoor thermal environment (Table 3).

3.1.2 Meteorological Parameters

In summer, the maximum mean T_a, RH, G, T_g, and T_{mrt} were in space WP (37.5 °C, 37.7%, 628.9 W/m^2, 47.0 °C, and 67.3 °C). RH in space WP was the highest, which is likely because space WP was surrounded by a static pool and continuously running fountain, providing humidification and evaporation. The mean RH in space EP was the lowest (33.6%). The mean V_a of space LP (0.9 m/s) and space WP (0.9 m/s) were relatively high compared to those of the other two spaces. Mean V_a and mean T_a of space RB that was shaded by sidewalk plants and high-rise buildings were the lowest (V_a: 0.5 m/s, T_a: 34.7 °C). The minimum G and T_g were in space LP (52.8 W/m^2 and 38.1 °C) (Table 4).

We conducted an ANOVA of the mean of meteorological variance (T_a, RH, V_a, G, T_g, T_{mrt}) indicating that all meteorological parameters (T_a, V_a, G, T_g, and T_{mrt}) except RH differed significantly among four spaces (Table 5).

3.1.3 Space Use, Attendance and PET

During trials, the number of people in the space and their type of activities (e.g., sitting, talking, exercising, walking) were recorded every half hour. To study the influences of the outdoor thermal environment on residents' activities, the spatial–temporal distribution map of residents' activities was plotted for each observation (Fig. 2).

In space RB, "walking" was the dominant activity type of residents. In space LP, residents preferred "sitting" and "talking". In space EP, residents mainly visited the

Table 4 Meteorological variables in each measured space

		RB	LP	EP	WP
T_a(°C)	MAX	38.7	39.5	40.5	41.4
	MIN	28.3	29.0	29.1	33.6
	Mean ± SD	34.7 ± 3.0	35.5 ± 2.8	36.1 ± 3.4	37.5 ± 2.3
RH (%)	MAX	52.6	50.7	50.3	48.2
	MIN	20.8	20.2	19.4	26.7
	Mean ± SD	36.6 ± 7.3	34.1 ± 7.0	33.6 ± 7.5	37.7 ± 5.3
V_a (m/s)	MAX	1.2	1.7	1.0	1.6
	MIN	0.0	0.4	0.2	0.4
	Mean ± SD	0.5 ± 0.3	0.9 ± 0.3	0.6 ± 0.2	0.9 ± 0.3
G(W/m^2)	MAX	853.8	127.9	895.6	935.9
	MIN	36.0	14.7	62.1	119.4
	Mean ± SD	274.5 ± 293.7	52.8 ± 17.0	562.7 ± 282.4	628.9 ± 225.0
T_g(°C)	MAX	49.5	41.6	52.0	51.5
	MIN	30.4	33.4	32.1	42.1
	Mean ± SD	38.9 ± 5.5	38.1 ± 2.0	45.8 ± 6.3	47.0 ± 2.0
T_{mrt}(°C)	MAX	68.8	47.6	77.1	80.2
	MIN	32.4	38.4	34.9	53.9
	Mean ± SD	44.3 ± 10.8	44.0 ± 2.3	61.9 ± 13.5	67.3 ± 6.7

space to “take care of children” and “exercise”. In space WP, residents mainly chose “exercising” (Fig. 2).

In summer, most residents preferred being active in the morning. With the increase of T_a, the number of visitors in each space during 11:00–15:00 was the lowest but kept increasing during 15:00–17:00 with a gradual decrease in T_a. Attendance in space RB was higher than those in other spaces, which might be attributed to building shade on two sides that were present most of the time. Attendance in space WP was the lowest. We attribute this to it having the highest SVF (0.39) and mean T_a (37.5 °C) as well as small shade in space WP, so that residents were more likely to feel thermal discomfort. Generally speaking, the attendance of residents in each space decreases gradually in summer with an increase in PET (Figs. 2 and 3).

3.2 *Research for Design*

ASHRAE 55 defines thermal acceptability range (TAR) as the temperature range that at least 80% (normal condition) or 90% (strict condition) of respondents can accept. In contrast, the local temperature is not acceptable to only 20% or 10% of respondents are unacceptable. In this study, the temperature range that was accepted

Table 5 Results of analysis of variance (ANOVA) for meteorological variables

Variable		Sum of squares	df	Mean square	F	Sig
RH	Between Groups	152.42	3	50.807	0.758	0.518
	Within Groups	25,253.51	377	66.985		
	Total	25,405.93	380			
T_a	Between Groups	880.54	3	293.513	25.143	0.000
	Within Groups	4400.932	377	11.674		
	Total	5281.472	380			
V_a	Between Groups	6.779	3	2.26	31.753	0.000
	Within Groups	26.828	377	0.071		
	Total	33.607	380			
G	Between Groups	16,076,766	3	5,358,922	113.699	0.000
	Within Groups	17,768,980	377	47,132.57		
	Total	33,845,746	380			
T_g	Between Groups	4898.966	3	1632.989	73.804	0.000
	Within Groups	8341.561	377	22.126		
	Total	13,240.53	380			
T_{mrt}	Between Groups	32,453.54	3	10,817.85	129.482	0.000
	Within Groups	31,497.28	377	83.547		
	Total	63,950.82	380			
PET	Between Groups	13,301.47	3	4433.822	105.922	0.000
	Within Groups	15,780.89	377	41.859		
	Total	29,082.36	380			

by 90% of respondents was chosen. The thermal unacceptable rate every 1 °C of PET was calculated and fit into a quadratic polynomial (Fig. 4). Here, other PET calibrations of thermal sensation vote (TSV) were determined according to thermal unacceptability of 33.3%, 56.7%, 80% and > 80% (Table 6).

To improve the thermal comfort of open spaces and meet the behavioral needs of residents in summer, the key design feature is to relieve heat stress. A summer thermal calendar was proposed and heat stress modes in each space at different times in summer were analyzed, to provide reference data for a space optimization strategy based on thermal comfort benchmarks. Considering local climatic characteristics of a hot and humid summer and cold and dry winter, the design strategy not only should meet needs for shade in summer, but also should consider access to sunshine in winter. We realized cooling and humidification by planting abundant deciduous trees, changing the underlying surface, and building artificial facilities (sunshades and corridors) as well as water features (e.g., fountains and spraying devices), thus relieving thermal discomfort and increasing use of the leisure space. The optimal

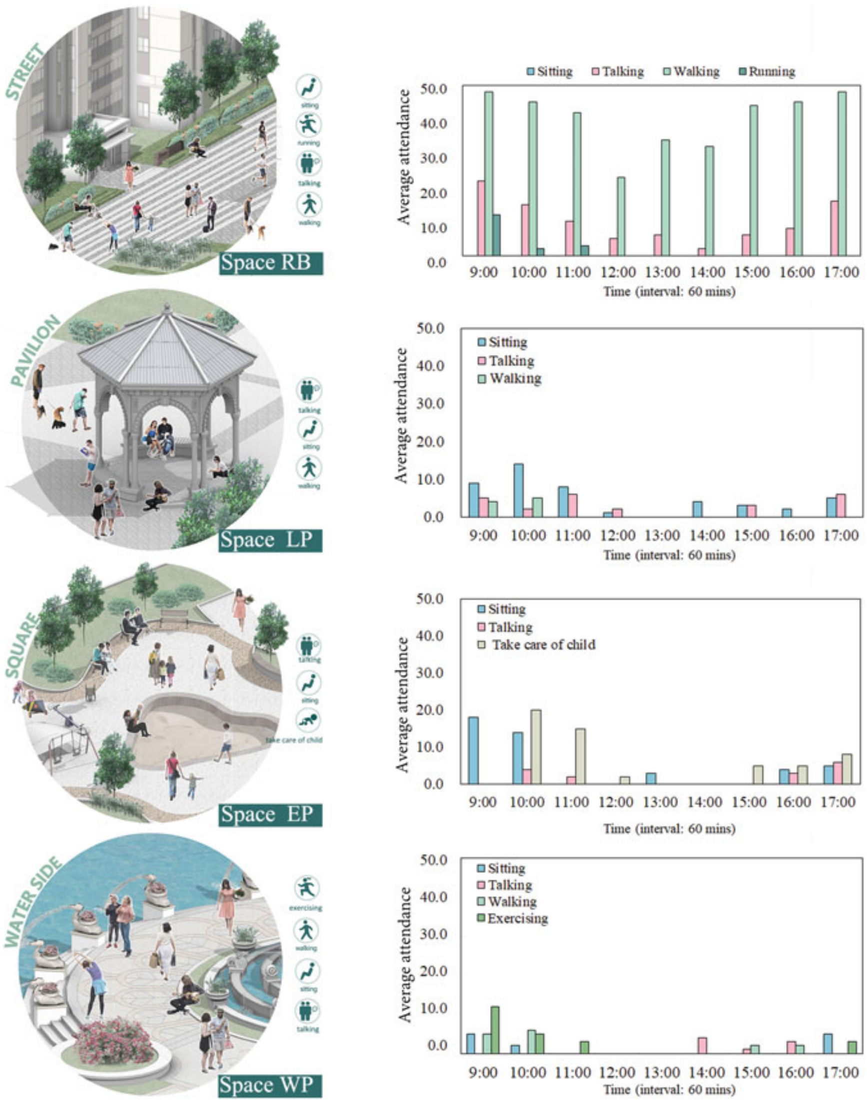


Fig. 2 Attendance of residents in summer

optimization strategies of the four open spaces were analyzed using thermal correlation. Optimum design examples were introduced in the following text (Figs. 5 and 6, Table 7).

Fig. 3 Relationship between attendance and PET in each space in summer

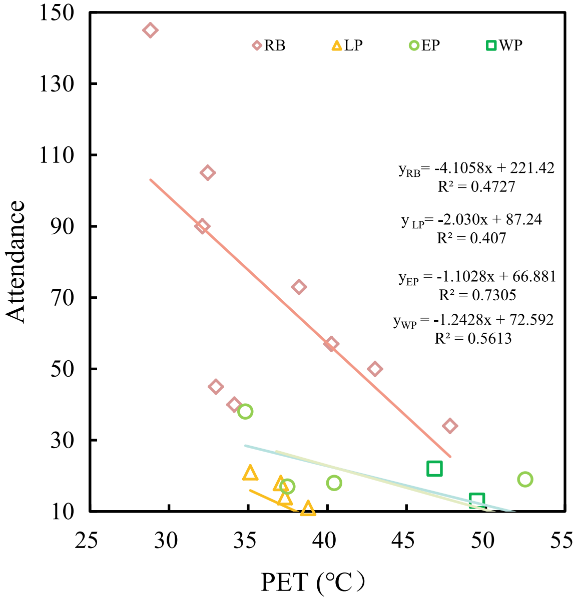


Fig. 4 Relationship between the thermal unacceptable rate and PET

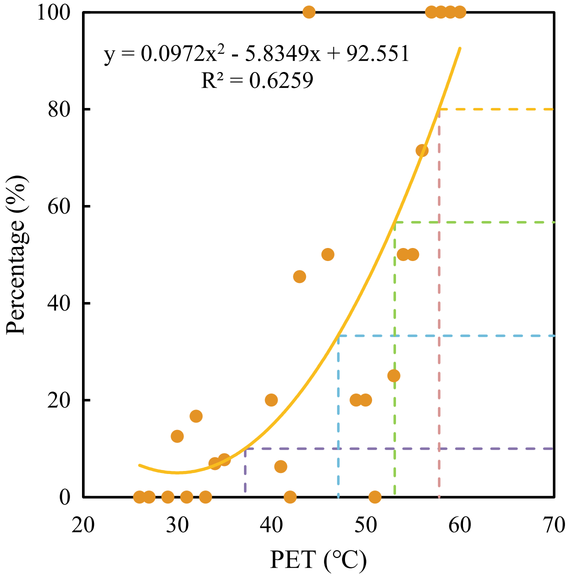


Table 6 PET calibrations of TSV for Xi'an

Thermal sensation	Thermal stress	PET range (°C)
Neutral (comfortable)	No thermal stress	22.84–37.2
Slightly warm	Slight heat stress	37.2–47.1
Warm	Moderate heat stress	47.1–53.1
Hot	Strong heat stress	53.1–57.8
Very hot	Extreme heat stress	>57.8

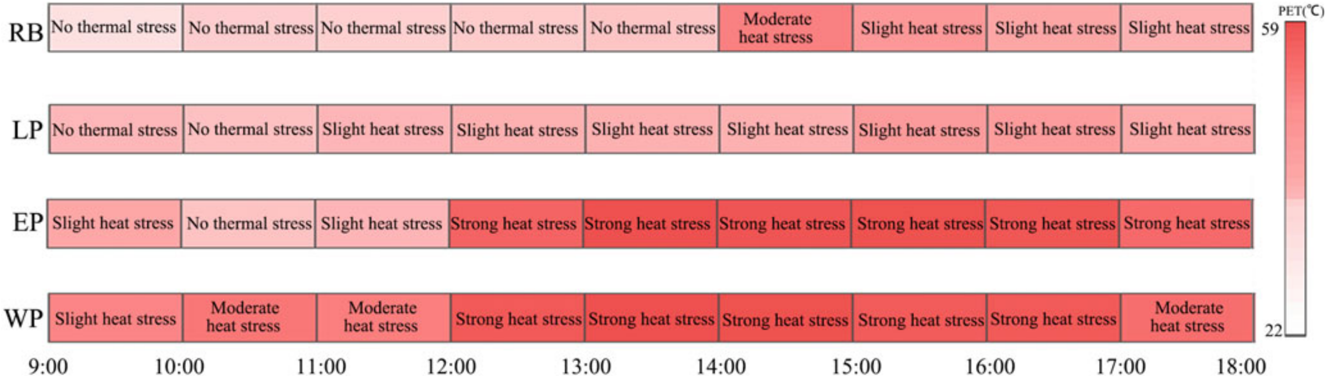
4 Discussion

4.1 Outdoor Thermal Environment and Space Use

The thermal environment may influence the behavioral modes of residents depending on the daily distribution of outdoor activities and participation of residents (Zhao et al., 2018). Our research showed that in summer, attendance of outdoor spaces in a residential area had a negative linear relationship with PET, similar to previous research reporting space use in hot seasons declining as T_a increased (Lin, 2009; Lin et al., 2012). Another study indicated that more than 75% of users preferred cool places and people were more likely to engage in active pursuits in shaded environments (Lin et al., 2015). This was consistent with our results that activities of residents in shaded spaces (space RB) were significantly higher than that in spaces exposed to sunshine (space WP). Residents had relatively poor tolerance to high summer temperatures. They cannot tolerate high temperatures and excessive solar radiation in summer. Therefore, the number of people in all spaces in summer decreased during 11:00–15:00. This was consistent with what Mi et al. (2020) proposed. We noted that all four spaces in the residential area were at "slight heat stress", "moderate heat stress" and even "strong heat stress" stated most of the time. Only space RB had the longest period of "no heat stress" due to building shade and its occupation was far higher than in other spaces. These phenomena suggest that the behavioral activities of residents depend on the thermal environment and demonstrate the importance of summer shade even in China's cold regions.

4.2 Bioclimatic Design

Although numerous studies have indicated that strategic optimization of plants, water, buildings, and surfaces can provide significant cooling effects and relieve urban heat islands (UHI), their synergistic effects are not well understood nor tested in microclimatic studies (Gunawardena et al., 2017). Some studies have reported that a combination of designs is the most beneficial strategy to provide thermal relief (Tseliou et al., 2022). In this study, the mean *RH* of space EP was the lowest, so a



	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00	15:00–16:00	16:00–17:00	17:00–18:00
RB	No thermal stress	No thermal stress	No thermal stress	No thermal stress	No thermal stress	Moderate heat stress	Slight heat stress	Slight heat stress	Slight heat stress
LP	No thermal stress	No thermal stress	Slight heat stress	Slight heat stress	Slight heat stress	Slight heat stress	Slight heat stress	Slight heat stress	Slight heat stress
EP	Slight heat stress	No thermal stress	Slight heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Strong heat stress
WP	Slight heat stress	Moderate heat stress	Moderate heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Strong heat stress	Moderate heat stress

Fig. 5 Daytime thermal stress in the four open spaces in summer

Table 7 Bioclimatic design strategies suitable for open spaces in the residential area

Spaces	Heat stress analysis	Optimal design strategies
RB	The space has "moderate heat stress" during 14:00–15:00 and "slight heat stress" during 15:00–18:00	Plant large deciduous trees. In summer, deciduous trees can meet shade needs. In winter, they lose leaves and allow sunlight through Plant evergreen shrubs can both improve ventilation in summer and hinder cold wind in winter
LP	The space has "slight heat stress" during 11:00–18:00	Plant deciduous vines surrounding the space. Provide shade in summer and plant evaporation can increase humidity. In winter, leaves fall allowing sunshine to reach the ground Add spraying facilities on grassy areas to cool and humidify Provide movable chairs in the pavilion. Change the location to meet residents' needs for sunlight
EP	The space has "slight heat stress" and "no heat stress" during 9:00–12:00. As T_a and G increase, the space reaches the "strong heat stress" state during 12:00–18:00	Add corridor facilities. It can provide shade in summer; the hollow structure can provide sufficient sunlight in winter Increase defoliation with a broad-leaved arbor. Deciduous trees provide shaded spaces in summer and won't block winter sunlight after leaves fall off Add a fountain in the vicinity. Fountains not only cool and humidify spaces, but do not hinder the daily activities of residents
WP	The space has "slight heat stress" during 9:00–10:00, then changes to "moderate heat stress" during 10:00–12:00, and to "strong heat stress" from 12:00 to 17:00	Add removable awnings and water spraying facilities. Awnings block sunshine in summer and decrease local temperature. In winter, they can be removed to meet residents' need for sunshine

fountain was added to our recommendation to improve cooling and humidification effects. Indeed, tall deciduous trees were planted to meet residents' need for shade. It has also been demonstrated that thermal comfort can be improved by 15% through the synergistic cooling effects of trees and fountains (Tseliou et al., 2022). This is similar to the findings of Mazhar that a combination of vegetation and water pools could improve comfort (Mazhar et al., 2015). Martins et al. (2016) also suggested that vegetation and water have clear cooling effects (PET decreased by 7 °C and 2 °C, respectively) (Martins et al., 2016). Cooling effects when trees are close to the water were better (Jacobs et al., 2020). We planted deciduous trees and deciduous vines in space RB, space LP, and space EP to meet residents' need for shade and improve the thermal comfort of residents. When assessing the influence of vegetation species, Zheng et al. (2016) reported that trees (compared to lawns) provided the most comfort (Zheng et al., 2016). Space WP exhibited "strong heat stress" for a long period. Hence,

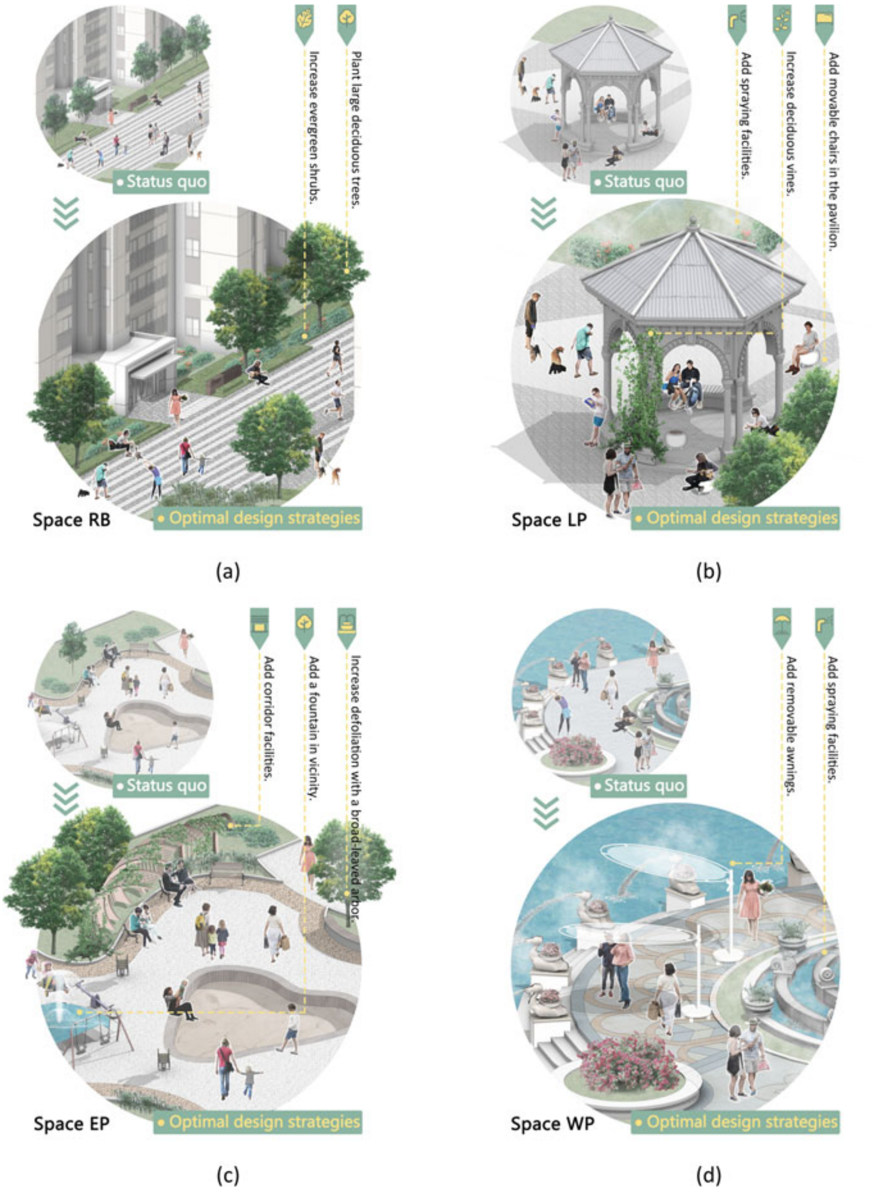


Fig. 6 Diagrammatic sketches of optimum designs of each open space optimal design. **a** space RB. **b** space LP. **c** space EP. **d** space WP

we set movable shading structures as well as spraying facilities in space WP to cool residents and improve thermal comfort. Li et al. (2022) compared three groups of people in shade, sprayed, and shaded + sprayed and reported that combining shade and spraying could decrease UTCI most effectively (Li et al., 2022). Some have also argued that surrounding environments with water cool due to the shielding effect of trees, fountains, or water sprays (Jacobs et al., 2020).

Different relief strategies have different effects on urban open space microclimates. A study compared the properties and characteristics of different heat relief strategies and their synergistic effect of these strategies. Results demonstrated that UTCI of shade, spray, and shade + spray decreased by 3.48 °C, 8.03 °C, and 12.31 °C, respectively (Li et al., 2022). Taleghani compared vegetation and high-reflective materials and believed that although both can lower T_a, a high-reflectance surface reflected sunshine causing discomfort. Hence, vegetation was recommended more as the thermal relief strategy (Taleghani, 2018). The results of a comparative study (water, vegetation, and high-reflective materials) on a campus of a Northwest China university. Water surface had a very small effect in decreasing T_a and T_{mrt}. High-reflective materials at the surface had the best cooling effect, while greening did not contribute to air temperature reduction (maximum 0.3 °C), but it appeared to have significantly decreased mean radiant temperature (32.1 °C) (Huang et al., 2016). A study in Greece suggested the opposite conclusion that more water bodies can provide better improvement for OTC. Such differences may be attributed to different climatic regions (Gaitani et al., 2007).

Thermal comfort is critical to the outdoor activities of citizens in residential open spaces. Our findings, such as the behavioral characteristics of space users and thermal perception in China's cold region, provided insights for the design of improving outdoor space utilization in urban designs. It is important to consider not only the aesthetic functions but also the thermal perception as well as the behavioral patterns of residents. Residents in cold regions tend to seek sunny areas in winter and shaded areas in summer to achieve a comfortable thermal environment (Lai et al. 2014a). In summer, we recommend increasing shaded spaces by planting trees with large crowns around spaces (i.e., *Liriodendron chinense, Aesculus chinensis, and Platanus acerifolia*). Sunlight and shaded spaces should also be considered to provide more opportunities for residents to interact with the environment, thus increasing their thermal comfort and usage (Li et al., 2016), and can be achieved by optimizing the arrangement of thermal mitigation measures such as buildings, vegetation, and water sprayings. Finally, residents engaged in static activities are more sensitive to thermal comfort than in dynamic activities. Therefore, the reasonable layout of dynamic and static spaces should be considered. We suggest setting the static spaces with a relatively more comfortable microclimate (Mi et al., 2020).

5 Conclusions

We investigated the relationship among microclimates, thermal perception of residents, and behaviors of residents in four common space types in residential areas in Xi'an, China through physical measurement, questionnaire survey, and behavior records. Based on the summer thermal calendar, we suggested climate-response design strategies for open spaces in residential areas based on thermal benchmarks. We drew the following conclusions:

1. Meteorological parameters (T_a, V_a, G, T_g, and T_{mrt}) differed significantly among typical spaces.
2. We found residents used modes of temporal and spatial distributions of outdoor activities. Activity type differed among spaces. There was a negative linear relationship between the use of space and PET. Attendance was lower when PET was high.
3. PET calibration of TSV was very hot (>57.8 °C), hot (53.1 ~ 57.8 °C), warm (47.1 ~ 53.1 °C), slightly warm (37.2 ~ 47.1 °C) and neutral (22.84 ~ 37.2 °C).
4. We recommend comprehensive vegetation, appropriate surfaces, artificial facilities (sunshade and corridors), and water landscape facilities (fountains, sprayings, and spraying irrigation facilities) to create comfortable thermal environments in open spaces in residential areas in summer.

For climate-responsive designs in residential areas, attention should be paid not only to the function and aesthesis of spaces but also to the thermal sensation and behavioral modes of users. Relieving heat stress in summer can improve outdoor environments and meet daily behavioral needs in residential areas. Behavioral needs and thermal perceptions of residents are different among climatic regions. For example, residents in cold regions might be more apt to seek shade in summer, and sufficient sunshine in winter. Hence, we should consider local climatic conditions and residents' needs when optimizing microclimatic relief strategies for residential areas. Optimal designs by combining buildings, vegetation, water, and underlying surfaces are proposed to effectively relieve heat stress.

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Chapter 11
Dynamic Annual Solstice Patterns and Urban Morphology: Bioclimatic Lessons for In-situ Adaptation Measures within the Warming City of Ankara, Türkiye

Andre Santos Nouri, José Abel Rodriguez-Algecíras, and Andreas Matzarakis

Abstract Within the existing literature, there already is a wealthy initiation into how different types of local adaptation measures can help urban fabrics respond to increasing temperatures as a result of climate change. Arguably propelled by the climate change adaptation agenda, different typologies of thermal sensitive measures are becoming continually more organised and solidified to improve the bioclimatic responsiveness of the consolidated urban fabric. Along with this growing body of knowledge, is the recognition that the in-situ efficacy of different measure typologies in counteracting increasing urban heat levels depends on two interrelated factors, these being: (1) how well the dynamic microclimatic conditions are assessed and understood; and (2) how well characteristics such as urban morphology are understood. Following this line of reasoning, in order to be utilised to their full potential, and moreover avoid symptoms of mal-adaptation, thermal sensitive adaptation measures must account for the unremitting and symbiotic cause-and-effect between these factors. Today, it is widely known that mean radiant temperature (MRT) is

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one of the most significant factors upon human thermophysiological thresholds. In addition, it is furthermore a particularly dynamic variable as a result of the continuously shifting annual solstice. Accordingly, MRT must be understood as a variable which modifies not just on a diurnal bases, but in addition one which oscillates throughout the different months and seasons of the year. Depending on the time of year, as dictated by the Urban Energy Balance, radiation fluxes interact with the static structures of the urban fabric through different seasonal energy exchange patterns/quantities. Such an understanding calls upon the approach of both yearly and different seasonal analytical scopes to better comprehend the symbiotic relationship of urban morphology and solstice patterns. It permits a finer understanding of the impacts associated to crucial climatic variables that play a significant role in human thermal comfort. Invariably, this consequently includes the fundamental role of in-situ dynamic radiation fluxes that are undeniably dictated by modifying yearly/seasonal solstice patterns. Grippingly, and unlike encircling air temperature, MRT can more easily be manipulated through different measure typologies within the urban fabric, and in addition, presents means to alter the cause-and-effect relationship with other encircling microclimatic variables. Within this book chapter, a structured reflection will be undertaken for Ankara, Türkiye—and how an innovative methodical case study presents bioclimatic lessons pertinent to the crucial role of in-situ dynamic radiation fluxes within a densifying and warming urban fabric in an era of growing climate change.

Keywords Physiologically equivalent temperature · Urban morphology · Heat/cold stress detection · *In-situ* climatic adaptation · Climate change · Ankara

1 Introduction

Given the continual densification patterns of many cities and the adjoining effects of climate change upon cities, ensuring urban human wellbeing and safety has never been as critical. Whether for indoor outdoor environments, such recognition has been growing extensively as identified in numerous studies (e.g., in Charalampopoulos et al., 2016; Ebi et al., 2021; Jay et al., 2021; Lomas et al., 2021; Matzarakis, 2021; Matzarakis & Nouri, 2022; White-Newsome et al., 2012). As a result, the international community is continually seeking to develop processes of local thermal sensitive urban design and planning attitudes that salient the direct understanding of both local microclimatic risk factors, and their symbiotic relationship with urban morphological characteristics (as discussed in e.g., Alcoforado & Matzarakis, 2010; Charalampopoulos et al., 2013; Ketterer & Matzarakis, 2014; Nouri et al., 2017; Oke, 2016; Oke et al., 2017; Rodríguez-Algeciras et al., 2021; Xiong et al., 2022).

Within the concrete context of Türkiye, the study conducted by Can et al. (2019) identified that within urban fabrics, little work has been done regarding the impacts of heat related risk factors on humans, including with regards to their intensity and frequency rates. Additionally, and as conducted in the top-down based study undertaken by Ozturk et al. (2015), climate change projections are expected to amplify such local intensity and frequency levels, particularly during the summer season, which are already not being correlated effectively with human wellbeing standards in cities such as Ankara (Nouri, Çalışkan et al., 2022; Nouri et al. 2022). As a result, and given Türkiye's considerable climatic variability across the country as a result of its unique geographical and topographical characteristics (Nouri et al., 2021; Unal et al., 2003; Yılmaz & Çiçek, 2018); lessons suggested by other studies pertaining to the synergy with local climatic conditions as heat risk identification and/or launching of bioclimatic adaptation in urban design and planning approaches becomes all the more essential (Matzarakis et al., 2018; Nouri & Matzarakis, 2021, 2021; Nouri et al., 2023; Piticar et al., 2019; Yang & Matzarakis, 2019).

Within this book chapter, an introductory comparison with three other major urban centres in Turkey was undertaken to complement existing top-down climatic determinations using the Köppen Geiger Classification (KGC) system, which is constructed upon temperature and precipitation descriptors. Using a well-used Energy Based Model (EBM) thermal index, which permitted the inclusion of additional variables such as radiation and wind patterns, local general urban human thermophysiological threshold frequencies were assessed for each centre.

Subsequently, and focusing upon the urban centre of Ankara, through the continued use of the EBM thermal index, the bottom-up *in-situ* impact of variables, including radiation fluxes with typical urban morphology was assessed. The assessment allowed the determination of both seasonal heat and cold threshold vulnerability within different characteristic urban canyon systems, and their sub-regions across the seven districts of central Ankara. These were mapped across the different districts and then linked with potential opportunities for bioclimatic adaptation possibilities using different typologies of thermal Measure Review Frameworks (MRFs) (Nouri, Costa et al., 2018) to address the identified thermophysiological risk factors in the study.

2 Methodology

This book chapter initiates its methodical analysis by undertaking an encompassing analysis into three of the densest cities within Türkiye. The intention is to start at a more encompassing scale which, due to the country's interchangeability in KGC varies within such urban centres.

As demonstrated in Table 1, the KGC thresholds for both precipitation and temperatures descriptors were presented, for the three major cities in Türkiye that were correlated with selected urban World Meteorological Organisation (WMO) stations; these being: Istanbul (#17,064, 40°54'°N 29°9'°E, 18 m ASL), Izmir (#17,220, 38°26'°N 27°10'°E, 29 m ASL), Ankara (17,130, 39°58'°N 32°51'°E, 886 m ASL). For each hour four climatic variables were processed, these being air temperature (Ta), Relative Humidity (RH), wind speed (at 10 m) (V), and cloud cover (Oct).

Table 1 Descriptive environmental summary of the Köppen Geiger classification system adapted from Peel et al. (2007) in association to three of Türkiye's largest cites

				Specific environmental thresholds			
				Precipitation descriptors		Temperature descriptors	
City	KG class	Colloquial name of sub-classification	General classification descriptors	General description	Climate specification	General description	Climate specification
-	'*Dsb*'	Snow/Cold climate with dry/warm summer	$T_{hot} \leq 21$ °C & $T_{cold} \leq 0$	Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$	Warm Summer	$T_{hot} \leq 21$ °C & $T_{mon10} \geq 4$
Ankara	'*Dsa*'	Snow/Cold climate with dry hot summer	$T_{hot} \leq 21$ °C & $T_{cold} \leq 0$	Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$	Hot Summer	$T_{hot} \geq 22$ °C
Istanbul, Izmir	'*Csa*'	Warm temperate with dry hot summer	$T_{hot} > 10$ °C & $T_{cold} < 18$	Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$	Hot Summer	$T_{hot} \geq 22$ °C

Key – T_{hot} = temperature of the hottest month; T_{cold} = temperature of the coldest month; T_{mon10} = number of months where the temperature is above 10; P_{sdry} = precipitation of the driest month in summer; P_{wdry} = precipitation of the driest month in summer; P_{wwet} = precipitation of the wettest month in winter

Parallel with the temperature and aridity thresholds inherent to the KGCs, the first two variables enabled a similar meteorological assessment. However, and focusing upon the objectives of this book chapter, to effectively understand the climatic impacts upon the biometereological system, V and Oct permitted the significant effects of urban wind dynamics and radiation fluxes. This thus permitted a more effective understanding and approach towards the 'human-centred approach' even they are based upon general urban conditions; the intention was to depart from the initial KGC comprehension with the added encompassing inclusion of Mean Radiant Temperature (MRT) and V considerations.

Resultantly, from the aforementioned stations, hourly recorded Oct values were assessed in combination with the previous climatic variables within the biometereological RayMan Pro Model (Fröhlich et al., 2019; Matzarakis & Fröhlich, 2018; Matzarakis et al., 2010a, 2010b) to obtain MRT estimations for each urban setting. Since the V values were recorded at 10 m by the WMO station, using the methodology defined by Kuttler (2000), the values were subsequently translated to a height of 1.1 m (henceforth $V_{1.1}$) which is defined as the centre of the human body.

Subsequently for the three urban centres, RayMan was utilised to process the Physiologically Equivalent Temperature (PET) (Höppe, 1999; Matzarakis et al., 1999; Mayer & Höppe, 1987). Based upon the work by (Charalampopoulos, 2019; de Freitas & Grigorieva, 2015; Nouri et al., 2017; Potchter et al., 2022; Staiger et al., 2019), the respective EBM thermal index's applicability has been recognised in terms of it effective evaluations of body-atmosphere balance dynamics.

In addition, and as shown in Table 2, the application of the PET also further permitted the correlation against Physiological Stress (PS) grades as originally described by Matzarakis et al. (1999). In parallel with previous methodologies, in the case of Cold Stress (CS), the added PS grades 'beyond' the original 'extreme cold stress' classification were applied based the increment methodology undertaken by Bauche et al. (2013) and Matzarakis (2014). Pertaining to Heat Stress (HS), the expansion methodology was undertaken using the method applied in Nouri, Lopes et al. (2018), where increments of 5 °C were applied beyond the initial original 'extreme heat stress' classification.

As demonstrated in Table 3, based upon similar studies (e.g., Ketterer & Matzarakis, 2014; Matzarakis et al., 2018; Nouri et al., 2023), the study configured different urban morphological settings within the obstacle plugin of RayMan. These resulting Urban Canyon Cases (UCCs) were modelled in respect to different Height-to-Width (H/W) ratios ranging between 0.25 and 3.50.

Within the segment of the chapter that focused upon urban conditions within the specific case of Ankara, the most typical existing Aspect Ratios (ARs) were assessed between the seven districts within the city centre. A focus was made upon the most common morphological characteristics. More specifically, UCCs were required to: (1) be clearly defined canyons with two vertical facades; (2) have clear definitions between pedestrian and vehicular areas; (3) consist of a symmetrical geometric profile; and lastly, (4) have a façade continuity of at least 20 m. In addition to the definitions of the UCCs for each of the ARs, 12 different orientations were simulated

Table 2 Ranges of the thermal index of physiologically equivalent temperature for different grades of physiological stress on human beings

PET* (°C)	PS level	Stress level abbreviation			Existing/added
< −20	Beyond extreme cold stress 3	CS		(CS7)	Added
−20 ~ −10	Beyond extreme cold stress 2			(CS6)	Added
−10 ~ 0	Beyond extreme cold stress 1			(CS5)	Added
0 ~ 4	extreme cold stress			(CS4)	Existing
4 ~ 8	Strong cold stress			(CS3)	Existing
8 ~ 13	Moderate cold stress			(CS2)	Existing
13 ~ 18	Slight cold stress			(CS1)	Existing
18 ~ 23	No Thermal Stress	NTS	NTS_{EXP}	(NTS)	Existing
23 ~ 29	Slight Heat Stress			(HS1)	Existing
29 ~ 35	Moderate Heat Stress	HS		(HS2)	Existing
35 ~ 41	Strong Heat Stress			(HS3)	Existing
41 ~ 46	Extreme Heat Stress			(HS4)	Added
> 46	Beyond Extreme Heat Stress			(HS5)	Added

Sources Adapted from Matzarakis et al. (1999), with expanded cold/heat levels as delineated by (Nouri et al., 2021)

$*^{1}$ Ranges of PS for PET calculation based upon an internal heat production of 80 W, and a heat transfer resistance of the clothing set to a value of 0.9 clo according to Matzarakis and Mayer (1997)

Table 3 Description of utilised Aspect Ratios (ARs) depicting information into their Height, Width, H/W Ratio

H/W ratio	Canyon height (m)	Canyon width (m)
0.25	5	20
0.50	10	20
1.00	20	20
1.50	30	20
2.00	40	20
2.50	50	20
3.00	60	20
3.50	70	20

with increments of 15° to account for the elevated variability of Ankara's urban fabric as well (Fig. 1).

Based on Ankara's consolidated fabric (Fig. 2), numerous recurrent characteristics were utilised to erect the UCCs ARs, including the recurring canyon width of 20 m between the facades (Table 3). In addition, their distribution was based upon categories, those that: (1) presently existed within Ankara's consolidated urban fabric (with ARs between 0.25 and 1.50); and (2) could result from patterns of future urban densification (with AR's between 2.00 and 3.50).

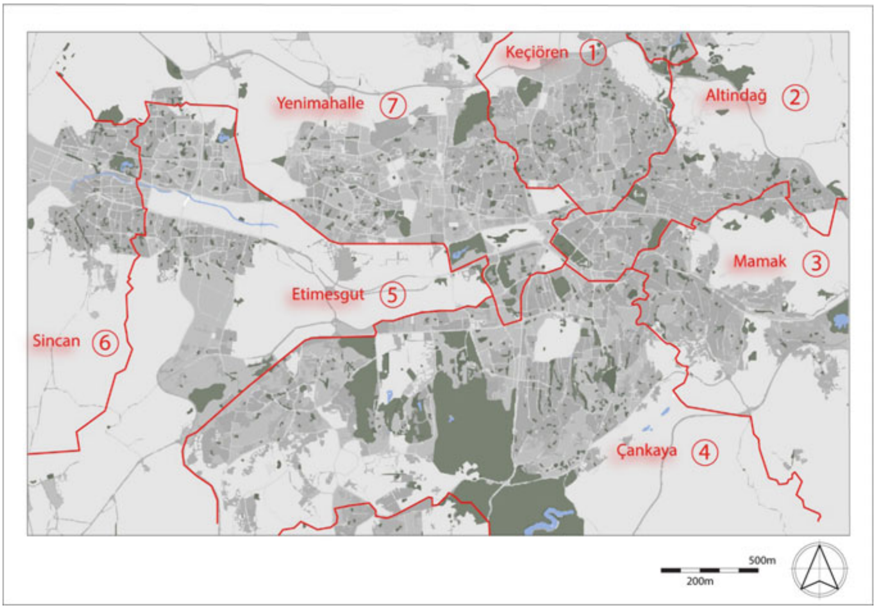

Fig. 1 Map of central Ankara and location of its seven districts

In alignment with previous studies (e.g., Nouri, Charalampopoulos, Afacan et al., 2023, Nouri, Rodriguez-Algecíras et al., 2023; Rodríguez-Algeciras et al., 2021), the constructed UCCs hosted three Reference Points (RPs), i.e.,: (i) two lateral RPs to represent the 'sidewalk area', each 3 m away from the respective facades, represented by the Left Lateral (RP_{LL}), and Right Lateral (RP_{RL}); and, (ii) one central RP (i.e., RP_{C}) to portray the middle of the canyon 10 m away from both canyon façades. Resultantly, each of these three RPs determined distinguished three *in-situ* locations within each canyon, thus presenting the possibility to better differentiate the exposure to urban dynamic radiation fluxes as a result of the winter/summer encompassing solar path.

For the case of Ankara, based upon the hourly processed data retrieved for the summer and winter periods between 2008 and 2020; a frequency window of 10 days was used. For both summer and winter months, given also the increased rate of urban activity, the hours between 12:00 and 15:00 were utilised to determine the frequency and intensity of the calculated CS and HS based upon the retrieved PET and associated PS levels. Moreover, this and in alignment with the studies undertaken by Ketterer and Matzarakis (2014) and Nouri et al. (2023), CS1 (symptomatic of 'slight cold stress') and HS1 (symptomatic 'slight heat stress') were combined with NTS PS grade. As a result, and with the aim of accepting slight variations within the original NTS threshold (hereafter referred to as NTS_{EXP}), the new grade was expanded to encompass PET values ranging between 13.1 °C and 29.0 °C (Table 2).

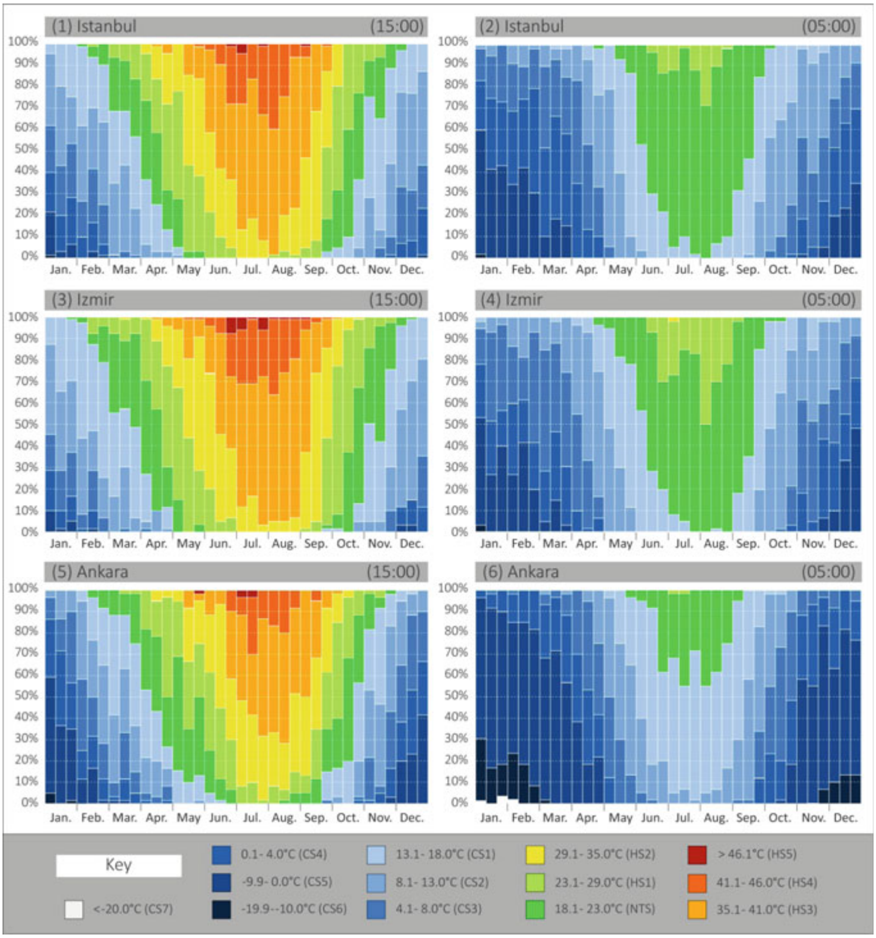

Fig. 2 Frequency distribution of Physiological Stress (PS) grades PS between 2014 and 2019 at 15:00 and 05:00 for the most populated Turkish urban centres, Istanbul, Izmir and Ankara

3 Results and Discussion

3.1 *Comparison of Overall Human Thermophysiological Thresholds*

The comparison of the urban human thermophysiological frequencies between the three major cities of Istanbul, Izmir and Ankara revealed strong dissimilarities both during the summer and winter seasons (Fig. 2). For both CS and HS, it was possible to link the hourly resolution of annual PET between the years of 2014 and 2019 with the divergent thresholds of the KGC of '*Csa*' and that of '*Dsa*'. These initial results were already indicative of how thermophysiological assessments that combined factors such as how radiation fluxes complemented the divergence in the KGCs built solely upon aridity and temperature descriptors.

The largest difference in the case of Ankara could be highlighted by the increased frequency of CS. Even during the hottest hour of the day, the occurrence of CS was substantially higher, with CS5 frequencies varying between 53 and 36% for the month of January. In contrast, such a frequency in Izmir and Istanbul was particularly lower, with a maximum frequency of CS5 only reaching 20% during the first days of the month in Istanbul. The only periods where both Izmir and Istanbul reached comparable frequencies of CS were during the colder hours for the winter months. However, during the same colder period in Ankara, CS5 frequency remained around 70%, with an additional noteworthy frequency of CS6 (between 15 and 28%). While CS reached CS7 (i.e., of PET ranging below −20.0 °C) for a minor frequency of up to 3% at the end of January. Istanbul and Izmir did not present any frequency of CS7, nor significant CS6 vulnerability.

For HS, all cities presented considerable exposure to diurnal heat, with grades varying considerably between HS3 through to HS5 during the summer season. Izmir presented the highest exposure to such grades, including to HS5 (i.e., of PET ranging above 51.0 °C) for noteworthy frequencies of up to 8% during June and July. In the case of HS3/4, between July and August, the combination of both thresholds revealed almost a continuous frequency of over 90%. Just as importantly, from late June to early September, the frequency of HS4 alone remained between 20 and 30%. The frequency of both HS4 and HS5 were similar in Istanbul, albeit with slightly more oscillations. Nonetheless in the case of Ankara, with the exclusion of mid-July which presented a similar HS4 frequency of 30%, the rest of the summer season witnessed lower frequencies, between 10 and 20%. In the case of HS3, Ankara still observed significant frequencies that remained predominantly between 50 and 60% for the same period.

Like CS conditions, the colder hours revealed significant distinctions from HS as well. For most of the summer period, both Izmir and Istanbul presented almost no CS exposure, with frequencies of NTS conditions varying up to 86%. In addition, there was also some degree of HS during the nocturnal period, as revealed particularly for the case of Izmir, with HS1 frequency varying up to 50%. In the case of Ankara, the nocturnal period was particularly different with NTS frequencies rarely surpassing 40%, and moreover, with a more predominant occurrence of CS1 throughout the summer period.

3.2 Frequency of HS in Ankara's Urban Morphological Characteristics

The analysis of HS frequency amongst Ankara's typical morphological characteristics revealed clear trends with regards to processed human thermophysiological in-situ conditions. Firstly, as to be expected, there was a clear downward trend in HS frequency conditions as the AR increased given the reductions in radiation fluxes within the UCCs. However, and as shown in Fig. 3, considering the specification of in-situ locations within the twelve orientations, the reduction of HS during the summer varied this aforementioned trend considerably. With an AR of 0.25, most UCCs started with a HS frequency of between 83.0 and 85.0% (2988 and 3060 min, respectively). At an AR of 0.50 clear disparities could were already found between the urban settings. For example, most of the RP_C of the UCCs revealed a HS frequency of 83.0%, and a large number of $\mathrm{RP}_{\mathrm{LL}}$ witnessed already considerable reductions down to 75.0%, representing a reduction of HS exposure by 8.0% (equating to 288 min).

It was also verified that the abovementioned summer HS variability took place within the same orientations as well. An example of this could be withdrawn from the UCCs with an orientation of 90°, where the $\mathrm{RP}_{\mathrm{RL}}$ continuously remained one of the most vulnerable to HS across all ARs. On the hand, and still at an orientation of 90°, the $\mathrm{RP}_{\mathrm{LL}}$ almost continuously revealed the lowest exposure to such thermophysiological stress. With regards to the RP_{C}s, in the case of orientations between 15.0° and 75.0°, it was possible to identify that their comparative vulnerability shifted as

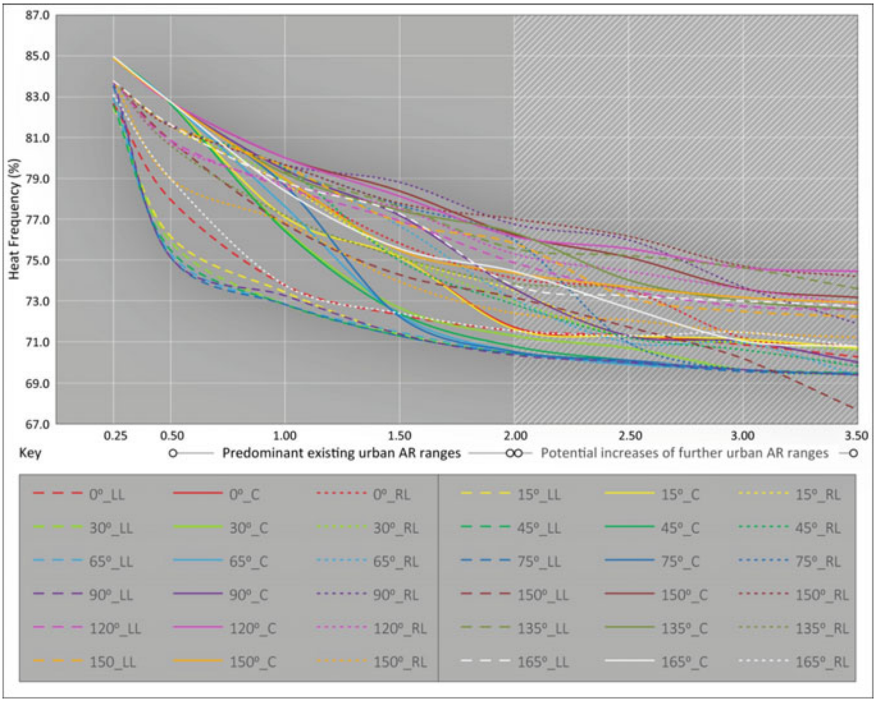

Fig. 3 Frequency distribution Heat Stress (HS) for central Ankara within existing and projected Urban Canyon Cases (UCCs) and canyon Reference Points (RPs) (Left Lateral [LL], Central [C], and Right Lateral [RL]) in association to each orientation with an average hourly resolution between 12:00 and 15:00 for the years 2008–2020 for the summer period

the ARs increased. In lower ARs, starting from 85.0% (3060 min) they presented the in-situ conditions with highest exposure to HS. By AR 3.50, these central areas of the respective orientations were those with some of the lowest exposures to HS, with frequencies varying around 70.0% (2520 min).

These disclosed results demonstrated three key factors with regards to the relationship with UCCs and HS vulnerability during the summer using the PET index, namely: (i) while ARs presented a crucial means to downscale the understanding of in-situ conditions pertaining to human thermophysiological stress intensity and frequency, they do not provide the entire picture when considering factors such as radiation fluxes and exposure; (ii) overall frequencies to HS were high during the summer, but the determined variations in frequencies also presented considerable differences in terms of diurnal duration, particularly considering that some of the largest dissimilarities took place within the same UCCs, with 20 m in width between facades; (iii) similar to the previous point, with a focus upon thermal adaptation processes, it moreover provided a further spatial understanding where in-situ interventions could take place within the UCCs themselves; and finally, (iv) how the effects of further central urban densification patterns could modify present HS levels.

3.3 Seasonal Division of Human Thermophysiological Stress Frequency

In addition to the *in-situ* morphological assessments which focused upon the summer, to better understand the inherent dynamism with regards to the different summer months, HS averages (of all 12 orientations [henceforth expressed as $\overline{\text{HS}}$]) for each AR was conducted. As shown in Fig. 4, although June witnesses the highest axial tilt towards the sun for the Northern hemisphere, it was by far the month with lower quantity of HS frequency, across all ARs. Even in AR 0.25 where the building facades were only 5 m in height (Table 3), the $\overline{\text{HS}}$ frequency was of 63.9%, which decreased to 43.0% in the case of AR 3.50. Such trends were considerably less accentuated for the months of July, August and overall summer which can be related with the influence of other variables such as peak summer Ta values. For the case of August which always surpassed $\overline{\text{HS}}$ frequency for the whole summer season, the decrease in $\overline{\text{HS}}$ frequency between an AR of 0.25 and 3.50 was of 7.9%, the lowest between all months.

These results presented another crucial aspect and/or perspective to approaching human thermophysiological thresholds via the applied EBM index. By dividing the summer period into separate months, it was possible to identify large variations of $\overline{\text{HS}}$ exposure levels, which would need to be considered in the design/erection of any permanent *in-situ* adaptation measures to address summer heat vulnerability. Naturally, this is coupled with the essential recognition that such measures would also have to consider their impact during winter conditions. In the case of Ankara, this

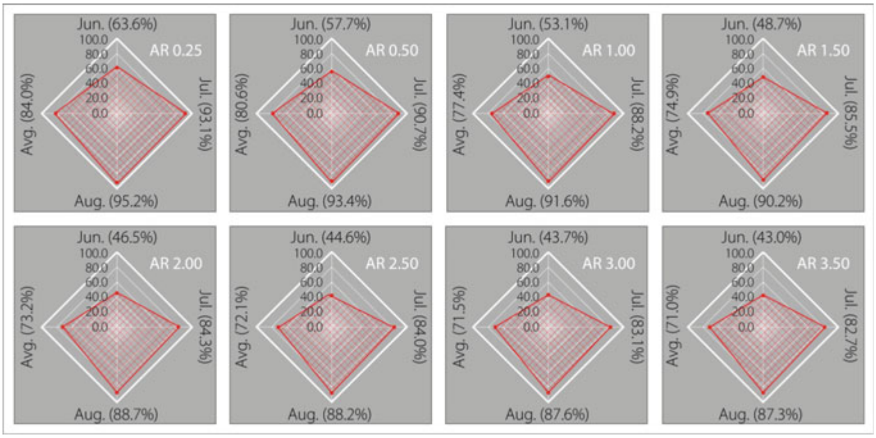

Fig. 4 Average frequency distribution Heat Stress ($\overline{\text{HS}}$) for central Ankara during different summer months based upon *in-situ* averages within existing and projected Urban Canyon Cases (UCCs) in the divergent Aspect Ratios (ARs) at an average hourly resolution between 12:00 and 15:00 for the years 2008–2020

is particularly significant given the previously identified oscillation between summer and winter thermophysiological stress conditions.

Due to limiting the scope size of the chapter, the frequency distribution of CS was not assessed along with the HS analysis. However, given the importance of the results disclosed in Fig. 4, the same methodical assessment was undertaken for the winter months. The inclusion of such results emphasised the required avoidance of 'maladaptation' occurrences by moreover recognising urban $\overline{\text{CS}}$ vulnerabilities as well.

As demonstrated in Fig. 5, it was possible to determine that the month with the highest $\overline{\text{CS}}$ frequency, which by a large margin, was January that mostly remained at above 90%. These results moreover were in alignment with the results presented for the identified overall urban thermophysiological conditions during the three 10-day temporal window for January as presented in Fig. 2 (5/6). Unlike in the case of $\overline{\text{HS}}$, $\overline{\text{CS}}$ altered less between AR 0.25 and 3.50. The reason for this can be attributed to the decreased capacity of radiation in cold weather given other variables such as increased $V_{1.1}$ and lower Ta values. As stated, the overall frequency $\overline{\text{CS}}$ distribution also proved to be noticeably more similar between the different ARs, however in the case of the months with highest amount of thermophysiological stress (i.e., $\overline{\text{CS}}$); ARs $\geq$ 2.00 (representing UCCs associated to future potential urban densification patterns, the frequencies remained almost identical.

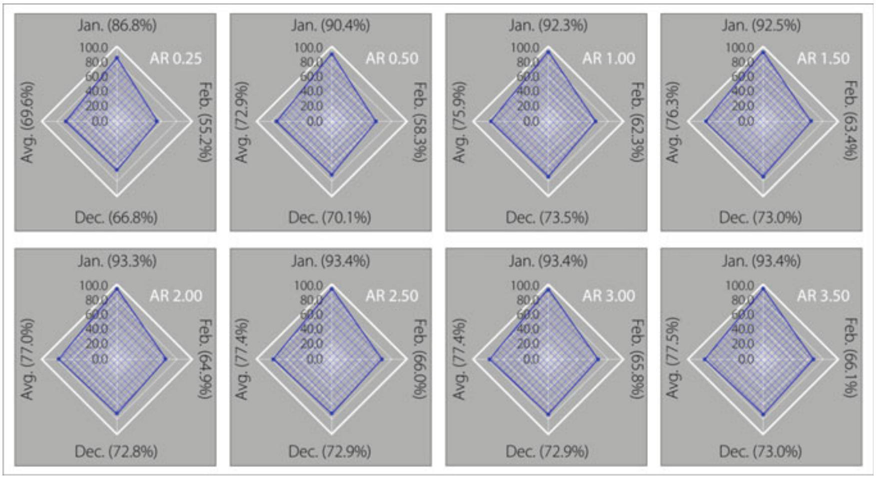

Fig. 5 Average frequency distribution Cold Stress (CS) for central Ankara during different winter months based upon *in-situ* averages within existing and projected Urban Canyon Cases (UCCs) in the divergent Aspect Ratios (ARs) at an average hourly resolution between 12:00 and 15:00 for the years 2008–2020

3.4 District Vulnerability Mapping with Morphological Characteristics

As shown in Fig. 6, based upon mapping the typical morphological characteristics throughout the seven urban districts, it was possible to link the identified *in-situ* human thermophysiological conditions at a neighbourhood scale within central Ankara. The produced drawings revealed a more detailed mapping of both UCC areas, and the canyons themselves, including their encompassing orientation.

Containing a total of 1348 relevant canyons based upon the disclosed study selection criterion, the southern Keçiören district, presented the highest number of assessed canyons. Most of the canyons either had an AR of 0.80 (with 637 canyons) or 0.60 (with 438 canyons), with a smaller occurrence of 1.00 (with 273 streets). It moreover was one of the areas with the highest amount of canyon orientations, yet with a predominance oscillating between 90° and 105°.

The south-western Altındağ district area accommodated one of smallest quantities of relevant canyons in the study with a total of 630 assessed canyons. It consisted of several different ARs, these being prominently, 0.80 (with 461 canyons), 0.60 (with 123 canyons), 1.00 (with 46 canyons), and lastly, a restricted number of 1.20 cases (with 12 canyons). The general range in canyon orientation resembled the case of southern Keçiören.

Within the area of western Mamak, the predominant AR typology was 0.80, with a total of 765 canyons (out of a total of 862). While this district represented another

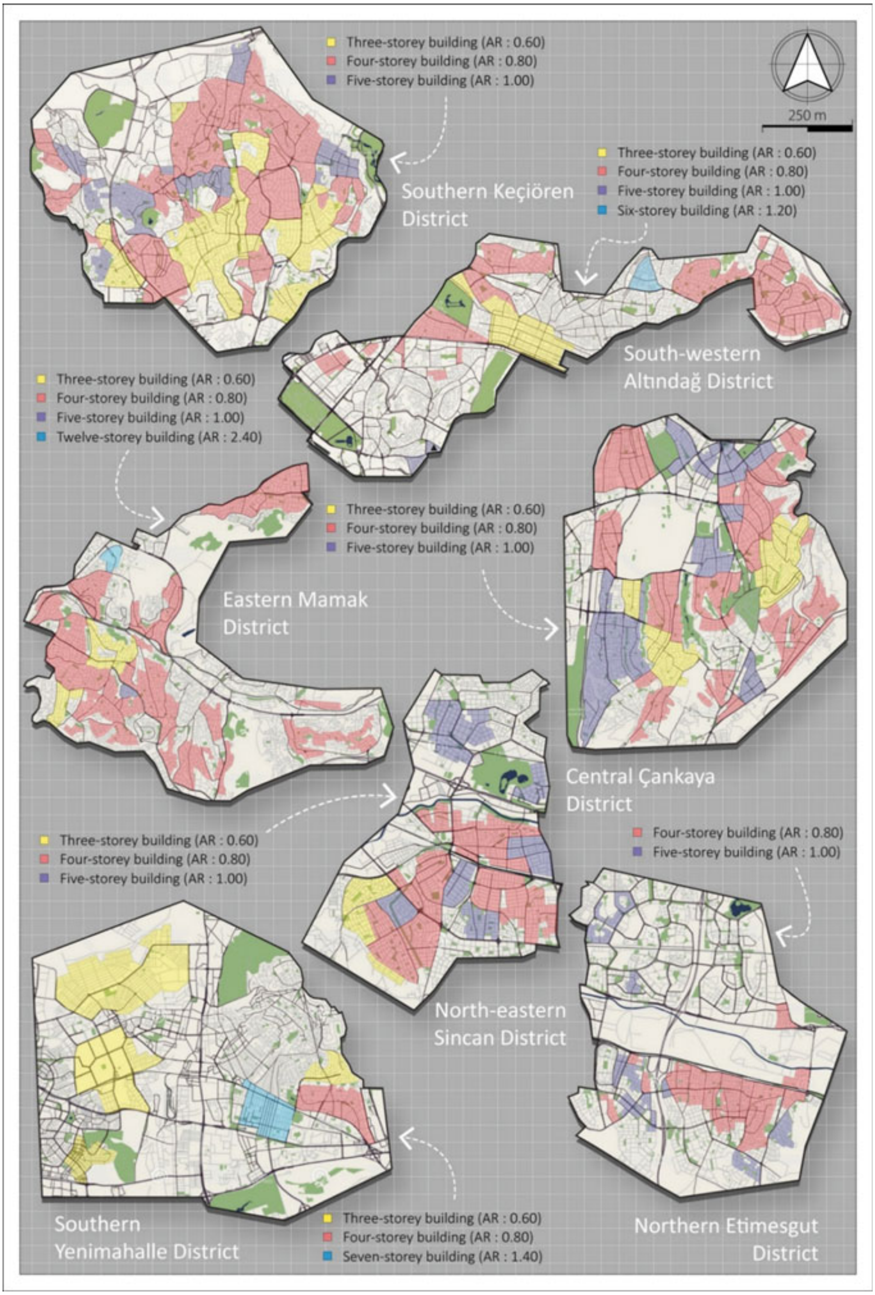

Fig. 6 Mapping of the different Urban Canyon Cases (UCCs) and Aspect Ratios (ARs) across the seven districts within Ankara's urban centre with overlapped street locations/orientations

example of notable oscillation in orientations (including intermediate ones), there was still a notably tendency towards those equal or adjacent to 90°.

The central area of Çankaya presented a more balanced distribution amid its comparatively higher number of 1202 canyons, with the three ARs, 0.60 (with 225 canyons), 0.80 (with 604 canyons), and 1.00 (with 373 canyons). As was the case for Mamak, this district also had a similar propensity towards orientations close or equal 90°.

The northern Etimesgut district presented the lowest amount canyons, with a total of 582 streets. There were only two types of ARs within the area which oscillated between 0.80 (with 386 canyons) and 1.00 (with 196 canyons). While there was a noteworthy number of canyons with an orientation between 0° and 15° (ranging up to 62 streets) in the case of 0.80, the canyon orientations with the highest frequency of streets were again at 90° and at 105°.

In the north-eastern area of the Sincan district there was a total of 793 streets, and a higher fluctuation in orientations. The orientations of 0° and 90° continued to present the largest number canyons (particularly in the case of AR 0.80, with 81 and 78 streets respectively). Nevertheless, given the areas total number of canyons, including 415 of those with an AR of 0.80, Sincan also hosted a considerable amount of canyons with different orientations, including at 60° and 150°.

Within southern Yenimahalle, this was the district with the lowest number of assessed canyons. The predominant AR was 0.60, with restricted areas reaching 0.80 and 1.40. Regardless of this lower canyon amount (with a total of 604 streets, of which 461 had an AR of 0.60), there was a significant variation in orientations, in addition to the recurrent 90° (with 52 canyons) and 0° (also with 52 canyons) between most districts.

3.5 Opportunities for **In-Situ** *Bioclimatic Interventions Based upon MRF Typologies*

3.5.1 'Green' MRF—Urban Vegetation

While there are a lot of studies that discuss the cooling potentiality resultant of urban vegetation within the urban fabric, an emphasis was made to highlight those which utilised an EBM thermal index to evaluate potential reductions in indices such as PET. These studies also highlight the crucial effects of radiation fluxes within the studied *in-situ* setting. Given that this book chapter was focused upon the determined UCCs commonly found in Ankara, studies based upon slightly larger scales, (e.g., Park Cooling Islands (PCIs)) were not considered to the same extent. This being said, the valuable lessons, including those highlighted in prominent review studies, regardless of their age (e.g., Bowler et al., 2010; Givoni, 1991; Nouri, Costa et al., 2018; Santamouris et al., 2017) should not be overlooked.

Given the already extended scope of this chapter, the objective of this final segment was not to provide an extensive analysis of the existing literature, nor undertake any type of further microclimatic assessment. Instead, as with the other MRF typologies, the aim was to highlight the potential of urban vegetation under pertinent morphological settings.

As revealed in the prominent early studies before the turn of the century (e.g., Brown & Cherkezoff, 1989; Brown & Gillespie, 1995; McPherson, 1984), different *in-situ* tree species result in considerably dissimilar levels of radiation permeation due to their leaf/twig density and foliage development. As also identified in early bioclimatic studies, different planting layouts also symbiotically interrelated with the characteristics of the individual tree. Furthermore, these can be an effective means to influences outdoor comfort levels due to radiation offsetting (e.g., Abreu-Harbich et al., 2014; Almeida, 2006; Bartholomei & Labaki, 2003; Brown & Gillespie, 1990; Erell et al., 2011; Hwang et al., 2011; Shashua-Bar et al., 2010; Streiling & Matzarakis, 2003; Torre, 1999; Viñas et al., 1995).

Slightly shorter than the diurnal window set in this study, concomitant with other studies, Tsilini et al. (2014) highlighted that the hours which revealed the greatest variations as a result of *in-situ* vegetation were between 12:00 and 15:00. Following this line of reasoning, any implementation of vegetation to reduce HS in Ankara would have a direct impact upon the overall frequencies disclosed in this study. Many studies moreover determined elevated reductions in PET as a result of radiation attenuation, with smaller reductions in Ta given its rapid diffusion into the encircling atmosphere (Abreu-Harbich and Labaki, 2010; Abreu-Harbich et al., 2014; Kong et al., 2017; Martins et al., 2016; Morakinyo et al., 2017; Nouri & Costa, 2017a; Nouri, Fröhlich et al., 2018; Perini & Magliocco, 2014; Wang et al., 2016). Based on most of these aforementioned studies, while Ta oscillated to a maximum of ~ −2.5° for *in-situ* reductions, ~ −7.6° for PCI reductions; PET presented maximum reductions of ~ −16.0° for *in-situ*, and ~ −24.0° for PCI reductions.

As stated in this chapter, geographic location and climatic context are imperative factors for any bioclimatic measure, particularly at such a microscale (Matzarakis, 2021; Matzarakis et al., 2018). For this reason, the specific variables themselves are symbolic on their own, as they can change considerably when considered for the case of Ankara. However, for urban designers/planners, architects and other local based professions, further bioclimatic lessons can be extracted, these being the:

- Continued intrinsic association with radiation, whereby the full extension of their impact at the pedestrian level must be strongly associated to the divergent impacts upon annual radiation levels, frequency, and seasonal periodicity. Within an annual perspective, this includes considering the winter seasons in order not to cause the trapping of otherwise desired radiation.
- Correct placement of thermal sensitive adaptive measures within a specific UCC and, more specifically, their inner regions to avoid occurrences of maladaptation. Such a bottom-up centred upon the human biometereological system and local *in-situ* characteristics relays entirely to the ‘human-centred approach’. One which includes the depiction further detailed breakdown of UCCs into different RPs, each

with potentially different conditions to one another, including within a modest canyon span of 20 m.

- Careful consideration of the correct tree species, not only between deciduous and evergreen, but just as significantly, into the species that lose their foliation at the suitable time of the year to maximise the microclimatic *in-situ* contribution to a given location (Almeida, 2006; Nouri, Fröhlich et al., 2018; Viñas et al., 1995). Such awareness also includes the comprehension of both their growth patterns/requirements, and how these can directly: (i) modify their impact over time (Picot, 2004); and, (ii) other associated, yet meaningful, vegetative pros-and-cons impacts upon the local public realm (Soares et al., 2011).

Within Ankara's frequently occurring districts with high numbers of UCCs and lower ARs (such as 0.60 and/or 0.80) as exemplified by southern Keçiören, western Mamak, central Çankaya, north-eastern Sincan, there was a strong opportunity to consider vegetation solutions, particularly within most RP_C and RP_{RL} areas. Nevertheless, and just as importantly, as already stated, such green measures would require to be cross-examined by local actors against CS frequency during the winter, where radiation would improve *in-situ* human thermophysiological conditions, particularly within ARs up to 1.00.

3.5.2 'Sun' MRF—Shelter Canopies

As revealed in this chapter, radiation fluxes changed dramatically based not only on AR, but just as significantly, due to the orientation, and the inner areas of a respective UCC. In climate sensitive planning and design terms, and when considering measures such as shading structures within the 'Sun' MRF, another crucial factor must be considered for such bottom-up approaches. While Ta under a shading canopy may be identical (or even slightly hotter depending on other variables, such as $V_{1.1}$) to an area fully exposed to the sun, MRT values will be significantly different. Invariably this will have strong influences upon thermal indices of an EBM nature, including in the case of PET index.

As discussed in the existing literature, like the case of vegetative tree crowns, the resulting MRT underneath a canopy and/or structure can be significantly lower. The implication of this directly results in the reduction of associated PS grades upon pedestrians (Nouri, Costa et al., 2018). Invariably, the opposite is also true, whereby a misplaced structure might provide effective attenuation for HS during the hotter months yet may also induce higher CS frequency due to the reduction in required/desired MRT levels during colder seasons and/or months. Such examples of bioclimatic maladaptation can be serious within the consolidated fabrics exposed to cold winters, and limited opportunities for the winter solstice to permeate the public realm. Further associating such concerns to the case of Ankara, its continued rapid and mal-regulated densification patterns which will lead both to the proliferation of the urban edge, but the very density within the city centre (Karaca et al., 1995; Nouri et al., 2021; Yuksel & Yilmaz, 2008). Within this chapter, this occurrence linked with the patterns of CS in ARs 1.00 through to 3.50 which almost remained identical between orientations 30° through to 120°. Moreover, this was further highlighted when considering oscillations within the colder season itself, as exemplified by the retrieved monthly $\overline{\text{CS}}$ frequencies in the study.

Given the UCC characteristics found across Ankara's identified districts, and within concrete measure solutions, a particular emphasis can be upon Ephemeral Thermal Comfort Solutions (ETCS) (Nouri, 2015; Nouri, Costa et al., 2018). These flexible types of solutions are those that can provide short-term solutions during months of increased HS without the risk of reducing thermal comfort during the winter. In addition, given the identified oscillation within the seasons themselves (e.g., the identified lower frequencies of $\overline{\text{HS}}$ during the month of June during the summer period), such reflections could present beneficial results for the same season as well. More encompassingly, and given the composition of the ARs, such measure typologies could present numerous opportunities. Examples of these can be found frequently within urban centres as exemplified by: (i) the 'Umbrella Sky Project' in Águeda in canyons with an AR of 1.30; (ii) Calle del Arenal in Madrid within canyons with an AR of 1.10; and (iii) Calle del Sierpes in Seville within canyons with an AR of ~ 3.00.

To date, the reductions of human thermophysiological thresholds have not been undertaken for these predominantly design orientated solutions, however their erection have resulted in many years of experience within urban centres with high frequencies of HS with yet the pursuit of radiation during the winter months to reduce *in-situ* CS. As a result, similar solutions can be found in different cities, which did not originate from a bioclimatic project with a rooted understanding of the actual quantitative effects upon human thermophysiological thresholds. This being said, amid the limited studies, a few have already started to quantify such reductions during the summer period as presented by: (i) Kántor et al. (2018), who through the use of nylon sun sails in Pécs, Hungry within an AR of 1.70, induced maximum MRT/PET reductions of −27.0 °C and −13.0 °C, respectively; and (ii) Nouri and Costa (2017a) and Nouri, Lopes et al. (2018), who also through the use of nylon sun sails in Lisbon within an AR of 0.20, revealed maximum projected MRT/PET reductions of −20.0 °C and −9.9 °C, respectively.

Invariably, such reductions in HS would vary in the specific context of Ankara, and a case-study should be considered based on the assessment of local quantitative reductions in thermophysiological stress grades. Nonetheless, the methodology of approaching such human biometereological thresholds through frequency distribution in this chapter enabled the consideration of how similar ETCS measures could reduce HS frequency: (i) in recurrent ARs such as 0.60 and 0.80 in districts such as southern Keçiören, western Mamak, central Çankaya, north-eastern Sincan and southern Yenimahalle; and, (ii) in relevant RPs for most ARs at particular orientations, as exemplified by the case of RP_{RL} in orientations 0° through to 90°, and RP_{LL} orientations 135° to 165° (Fig. 3).

3.5.3 ‘Surface’ MRF—Materiality

The major architectural typology throughout the different districts were that of medium–low-rise residential buildings constructed out of coated brick walls (many of which representing remaining out-dated thermal construction requirements (Nouri, Çalışkan et al., 2022), with a central asphalt road in the middle (Nouri et al., 2023). It is well recognised by the existing literature that when considering the urban energy balance (as detailed by Oke, 2016; Oke et al., 2017), urban materials such as traditional concrete and asphalt perform very poorly, and strongly associated to UHI patterns (Nwakaire et al., 2020; Santamouris, 2014, 2016).

For this reason, even early approaches have already been well discussed (e.g., in Fintikakis et al., 2011; Gaitani et al., 2011; Kyriakodis et al., 2016; Santamouris, Gaitani et al., 2012; Santamouris, Xirafi et al. 2012), including: (i) increasing reflectivity and emissivity values by changing the composition, aggregate, texture and colour; and, (ii) decreasing the amount of radiation that materials receive as a result of limiting the amount of energy reaching surface/pavement solutions in the first place. As presented in the exemplified studies, the modification of such traditional materials (including traditional concrete and asphalt typologies) in ARs ranging from 0.15 to 0.60 rendered reductions of surface temperatures between 4.5 °C and 11.0 °C. These results were obtained via the obtention of new albedo levels (which did not always require the implementation of lighter coloured surfaces), that ranged between 0.60 and 0.70.

While these values should be considered indicative only and require *in-situ* studies to hold evocative meaning, they provide examples that could be explored in many of the UCCs within Ankara. Such opportunities were applicable both for the lower ARs with higher HS frequencies, but in addition, the more susceptible RPs within mid-range ARs. As already suggested, such a measure typology would invariably require to be approached in combination with other typologies to effectively reduce the amount of radiation when required in the vulnerable *in-situ* settings.

3.5.4 ‘Blue’ MRF—Misting Systems

With regards to the ‘Blue’ MRF, given the identified typology of the ARs found in the city centre, and emphasis was attributed more towards the capacity of misting systems to potentiality reduce human thermophysiological thresholds. In addition, the focus upon misting systems also relayed back towards ETCS that could potentially provide a means to reduce summer HS without counteractively affecting winter CS. When conceiving the specific case of Ankara, given its hot yet dry summers based upon its KGC (Table 1), a fertile ground of opportunity can be conceived for this type of *in-situ* measure.

More concretely, this launches the opportunity to look at concrete ETCS based thermal sensitive measures which can reduce encircling Ta levels by manipulating RH without the reduced risk of exacerbating encircling atmospheric moisture. Through effective thermal sensitive design rationales (that moreover must consider dynamic

$V_{1.1}$ patterns and MRT fluxes) this can be launched within more problematic UCCs and, just as importantly, within their inner regions. These design rationales must thus consider factors such as appropriate water pressure, nozzle type/height, and functioning periods (Nouri & Costa, 2017b; Nouri, Costa et al., 2018; Nouri, Lopes et al.2018; Su et al., 2022).

Based upon the early Japanese teachings of '*Uchimizu*' which entailed the controlled wetting of surfaces to reduce encircling urban HS and air-conditioning requirements, this section shall emphasis upon engineering projects that reduce Ta through the controlled augmentation of RH. It was important to note that such projects were mostly applied within a KGC of '*Cfa*', thus the comparatively lower RH levels during the summer of Ankara permitted more possibilities without the risk of exacerbating acceptable atmospheric moisture levels. Within such studies, noteworthy explorations were undertaken, including into 'Dry-Mist' systems with maximum reductions of Ta ranging between −0.8 °C and −6.0 °C through the use of different pump pressures, type and/or height, and functioning periods (Farnham et al., 2011; Ishii et al., 2008, 2009; Yamada et al., 2008; Yoon et al., 2008). In the case of Lisbon, and also using the PET, it was found that the use of such systems could render reductions of up to −4.7 °C during the summer period through the incorporation of such mechanisms within the surrounding tree crowns on the lateral side of a larger UCC (Nouri & Costa, 2017a). In one of the most recent field studies, Su et al. (2022) undertook a similar assessment within Xi'an China who also found reductions in MRT between 9.7 °C and 31.5 °C depending on nozzle configuration (including height) during the summer months.

There are of course other types of bioclimatic measures, including those that have a stronger 'architectural/design perspective', and moreover presented some of the first 'contemporary' constructed solutions that linked mist with total and/or partial water bodies (Alvarez et al., 1991; Velazquez et al., 1992). However, as stated, given the more narrow composition of the predominantly residential UCCs analysed in this chapter, an emphasis was attributed to the first group, where HS: (i) could be reduced within specific RPs within mid-range ARs, including in generally more susceptible orientations; and, (ii) interlinked with other aforementioned bioclimatic measures in lower ARs, including within *in-situ* contexts with higher footfall, with high exposure to HS, where the design of the public realm can most benefit from such ETCSs. In association, both perspectives can be interlinked with Ankara's districts with a number of lower ARs (e.g., southern Keçiören, western Mamak, and southern Yenimahalle), and with higher UCCs numbers altogether (e.g., in southern Keçiören, and central Çankaya).

4 Concluding Remarks

Ankara, one of the most densely populated cities in Türkiye, presented numerous bioclimatic *in-situ* lessons for densifying urban centres that are also already witnessing the clear and growing effects of climate change. The capital city serves as a relevant case study to learn from the: (i) augmented exposure to both annual cold stress and heat stress in comparison other national urban centres, where winter conditions serve as a unwavering cue that adaptive interventions must continually contemplate relationships with local dynamic annual/seasonal/seasonal radiation fluxes; (ii) typification of an urban context that is still rapidly densifying, yet witnesses limited urban bioclimatic regulation and/or planning; (iii) future risks associated to its encompassing geographic and topographical attributes that render the area to be particularly prone to further augmentations of both the frequency and intensity of local extreme events as a result of future climate aggravations; and (iv) encompassing exposure to heat stress as a result of its predominantly low-to-mid ranged aspects ratios, and vulnerable canyon orientations regardless of their aspect ratio.

These lessons discussed in this book chapter resulted from scrutiny of the symbiotic relationship between local radiation fluxes and typical morphological characteristics. The results emphasised the importance of climatic bottom-up and interdisciplinary approaches, and the inclusion of energy-based model thermal indices that permitted the better understanding of climatic stimuli upon the human biometereological system. Such an approach was based upon strengthening the value of the ‘human-centred approach’, that without diluting the crucial role of more climatic top-down perspectives/assessments, enforced the need to assess/modify the symbiotic relationship between the urban climate with that of the human being.

For this reason, commencing from a more regional assessment of overall human thermophysiological between Turkish centres, the specificity of Ankara’s comparatively diverse exposure to annual cold and heat stress, were also downscaled through the assessment of its existing and future potential morphological patterns. Ultimately such a methodology permitted typically found urban canyons to be explored in more detail by going beyond aspect ratio considerations—and moreover raise synoptic potentialities for specific *in-situ* measure review frameworks typologies across Ankara’s different central districts.

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Chapter 12
Comparison of Thermal Indices in Urban Environments with SkyHelios Model

Marcel Gangwisch and Andreas Matzarakis

Abstract Global climate change and its thermal implications on cities makes it necessary to react with long-term climate-adaptive urban planning. This should be part of heat action plans to be implemented by municipalities, to minimize future risks of overheated city districts on the city dwellers and especially on risk and vulnerable groups. The evaluation of the thermal impact, based on thermal indices (depicting human thermoregulation) is most important in order to allow for a safe and risk-minimized but also human-adapted urban planning. The assessment of thermal impacts can be achieved using numerical urban microscale models, which are suitable to analyse the human thermal outdoor conditions of future building- and local climate-scenarios. This chapter aims to demonstrate the applicability of the urban microscale model SkyHelios and thermal indices to an urban district in Freiburg, Germany. The findings demonstrate the thermal vulnerabilities, strengths and similarities of the indices and provide additional information for future action.

Keywords Thermal indices · Urban microscale modelling · Heat action plans · Human outdoor thermal comfort

1 Introduction

The risks to cities and urban environments from heatwaves and thermal discomfort will worsen by 2100 due to global climate change and further urbanisation (Dodman et al., 2022; World Health Organization, 2021). Vulnerable and risk groups of people (e.g., the elderly, the sick, children, and the poor) are particularly affected. Further urbanization and the aging of society additionally increase this risk (United Nations, 2015; United Nations et al., 2019). The risk is not only a challenge in the health sector

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with an increased mortality rate or hospital admissions, but also in the productivity of society in a wide variety of business areas (Flouris et al., 2018; Matzarakis, 2021). After all, it is also about the simple things like the quality of life, the popularity of the city, or the well-being of the citizen (Gehl, 2010). Therefore, we have to ask ourselves how we want to design our cities and especially how we want to live in our cities (Matzarakis, 2022).

To reduce this risk for the society, the city and its inhabitants, it is necessary to identify, determine, quantify the risk, define appropriate (short- and long-term) actions and finally implement them. The actions have to be quantified according to the recommendations for heat action plans and monitored in the long term (Matthies et al., 2008; Matzarakis & Nouri, 2022).

This work is dedicated to the quantification of thermal risk and perception. Both can be assessed by thermal indices (e.g., Physiologically Equivalent Temperature, Perceived Temperature, and Universal Thermal Climate Index). These indices map human metabolism, behaviour, and the interaction of ambient, meteorological conditions differently on the human body. Most thermal indices quantify thermal sensation via an equivalent temperature, which often has the physical unit "°C". Usually, physical units (e.g., SI units) provide comparability and standardization. However, thermal indices (due to different implementations, approaches, backgrounds, theories, and complexities) are only directly comparable to each other to a limited extent (VDI, 2021).

The thermal indices, which are based on a complete human heat balance (PET, PT) were correlated to UTCI (Blazejczyk et al., 2012). But these indices also provide varying temperature thresholds for the same degree of thermal sensation (Blazejczyk et al., 2012). At the same time, these thresholds for thermal sensation would need to be adjusted to a particular region (tropics, arctic and mid-latitudes) and to season because of (temporal and cultural) acclimatisation (Potchter et al., 2018). A direct comparison of PET, PT and UTCI as conducted by (Blazejczyk et al., 2012) is difficult, because of different underlying technical implementations in the urban microscale models. Thus, the models differ in the implementation of the mean radiant temperature, as well as in the resolution of the meteorological variables, which in turn are needed as input for the thermal indices.

Measurements have been normalized in the past for urban heat island analysis (Dobrovolný & Krahula, 2015; Unger et al., 2010), in order to consider physical quantities independently of their respective unit and to relate them independently of their magnitude.

In this study, we apply a novel and different approach to counter the direct comparability of thermal indices. Spatial min–max normalisation of the thermal indices allows the direct comparison of PET, PT and UTCI, because of the independency of the fundamental underlying technical implementation and physical unit. The normalisation was applied to show the differences of the thermal indices among each other, and to show the possibilities of the SkyHelios model. A linear regression analysis reveals the correlations between the individual indices on a normalised scale. At the same time, the spatial analysis shows the differences of thermal indices in areas with modified wind speed and shade based on modelling results of the urban microscale model SkyHelios.

2 Background Knowledge

2.1 Thermal Indices

There are a large number of thermal indices in the literature. Each index has its own application and properties, so it is most important to know the exact background and implementation of each index to understand the index. Typically, a thermal index represents the thermal sensation of a standardised reference person for given meteorological parameter. Often this person is male, 80 kg and moves at a slow pace (Fig. 1). Thermal indices require the basic meteorological conditions that have an impact on people's thermal sensation (air temperature, relative humidity or vapour pressure, radiation and wind speed) as input parameters. Thermal sensation is then given as the indoor air temperature, which would lead to the same thermal sensation as the meteorological outdoor conditions (Staiger et al., 2019).

The most common indices (Staiger et al., 2019) are Physiologically Equivalent Temperature (PET) (Höppe, 1999; Matzarakis et al., 1999), modified PET (mPET) (Chen & Matzarakis, 2018), Predicted Mean Vote (PMV), Standard Effective Temperature* (SET*) (Gagge et al., 1986), Universal Thermal Climate Index (UTCI) (Bröde et al., 2012; Havenith et al., 2012; Jendritzky et al., 2012), and Perceived Temperature (PT) (Staiger et al., 2012; VDI, 2021). PT is the basis for a complete heat model (Klima-Michel-model) which is utilized by the German Meteorological Service, DWD, for the national Heat-Health Warning System (Jendritzky, 1990; Matzarakis et al., 2020).

The aforementioned thermal indices vary mainly in the complexity of the underlying endogenous processes (i.e., human thermoregulation) and the implemented clothing models. E.g., mPET and UTCI incorporate an automatic adaptation of the clothing. In addition, thermal indices differ in interpretation and linking of the index to thermal sensation. The categories for thermal stress vary between the indices (e.g., UTCI and PET).

2.2 Modelling of Urban Environments

In urban regions, the morphology (Green, Grey and Blue Infrastructure) modify the meteorological conditions, so that the thermal sensation is altered. The Urban Heat Island (UHI) is formed by alteration of thermal properties of surfaces within the city.

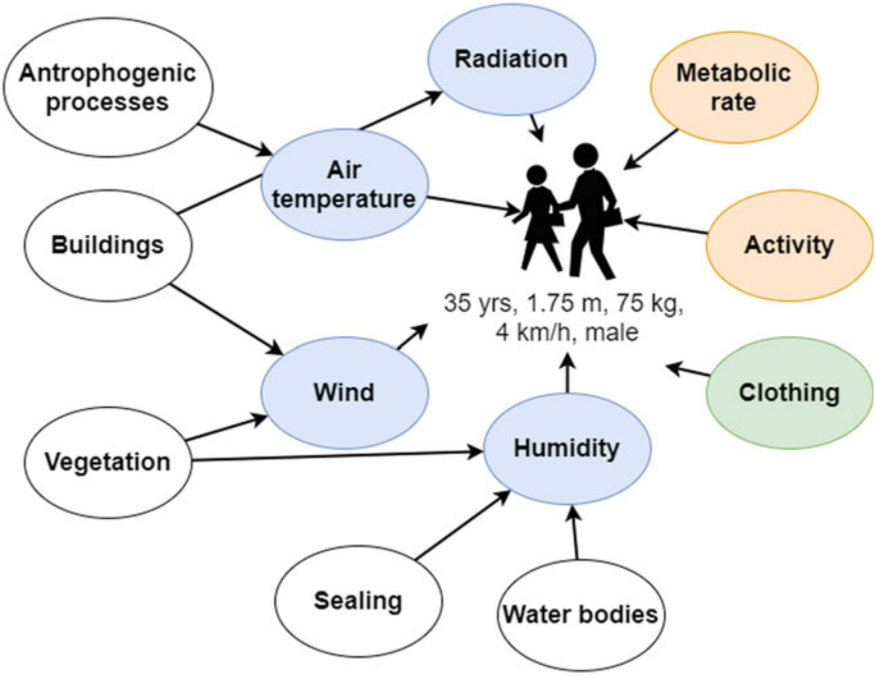


Fig. 1 Meteorological variables modify human thermal comfort and can be summarised in a comprehensive way to thermal indices. These indices rely on meteorological conditions as well as behaviour and clothing. Meteorological conditions are modified by urban morphological surroundings

The UHI can be defined by an increased air temperature in the urban area in contrast to the surrounding, rural areas.

Computer programs and algorithms can be applied to simulate thermal sensation in urban environments. Simple models can calculate thermal indices by taking the meteorological parameters as given. These models are steady-state models and include the processes of the human body (e.g., sweat rate or metabolism in general) (VDI, 2021).

On the other hand, there are statistical and process-based models that can calculate the meteorological outdoor conditions in the city and subsequently determine thermal sensation by thermal indices. These models can be separated by their spatial and temporal resolution into urban micro- and mesoscale models.

There are requirements to determine thermal comfort from a wide variety of sectors. This finds appeal in the indoor-design and design of buildings, from neighbourhoods to larger cities.

For individual buildings, thermal comfort is often calculated in the area of computationally aided design (CAD) for an environmental friendly design (Rhinoceros, Ladybug and Grasshopper) (Roudsari et al., 2013). The most accurate results are obtained with the computational fluid dynamics methods (CFD) used in the models like OpenLB and OpenFOAM on the microscale (Siodlaczek et al., 2021). However, these methods are very complex, time-consuming and expensive. Therefore, other models try to represent the urban atmosphere and its processes in a simplified, parametrized way.

For example, the urban climate model PALM-4U can be executed in Reynolds-averaged Navier Stokes (RANS) mode in addition to the complex Large Eddy Simulation (LES) mode to reduce complexity (Fröhlich & Matzarakis, 2020; Maronga et al., 2019).

In Muklimo_3, on the other hand, the spatial resolution is reduced and the buildings are considered as a porous medium (Sievers & Deutscher Wetterdienst, 2012, 2016).

2.3 Microscale Modelling in SkyHelios

SkyHelios is a freely available urban microscale model (Fröhlich & Matzarakis, 2018; Matzarakis & Gangwisch, 2020; Matzarakis & Matuschek, 2011; Matzarakis et al., 2021). It utilizes three-dimensional geodata to generate a virtual scene (see main user interface of SkyHelios [Fig. 2]). The virtual scene enables SkyHelios to conduct complex computations in this three-dimensional domain by a graphics computing engine (managed OGRE) on the Graphics Processing Unit (GPU). With the aid of the graphics engine, mainly radiation-based calculations (e.g., shading, sunshine duration) can be conducted. SkyHelios was developed to overcome the limitations of classic numerical process-based models by applying highly parallelised algorithms on parallel hardware.

For human-biometeorological analyses, it is especially important to determine the long and short wave radiation fluxes. These can be summarised to the mean radiant temperature (T_{mrt}). SkyHelios offers the simple possibility to calculate spatially resolved Sky View Factor (SVF). Since the scenery is generated from vector data, the spatial resolution of the calculation can be defined by the user. Thus, also the considered reference height for the calculation of the SVF as well as the desired parameters can be defined. Meanwhile, other functions and products are available within SkyHelios, such as aerodynamic roughness length and diagnostic wind speed and direction (Fröhlich, 2017; Ketterer et al., 2017). Currently SkyHelios is not yet able to calculate the air temperature and humidity spatially resolved. The user determines these for the entire study area.

SkyHelios is only one model among others from the domain of urban microscale models, which is capable of calculating human outdoor thermal comfort (Table 1).

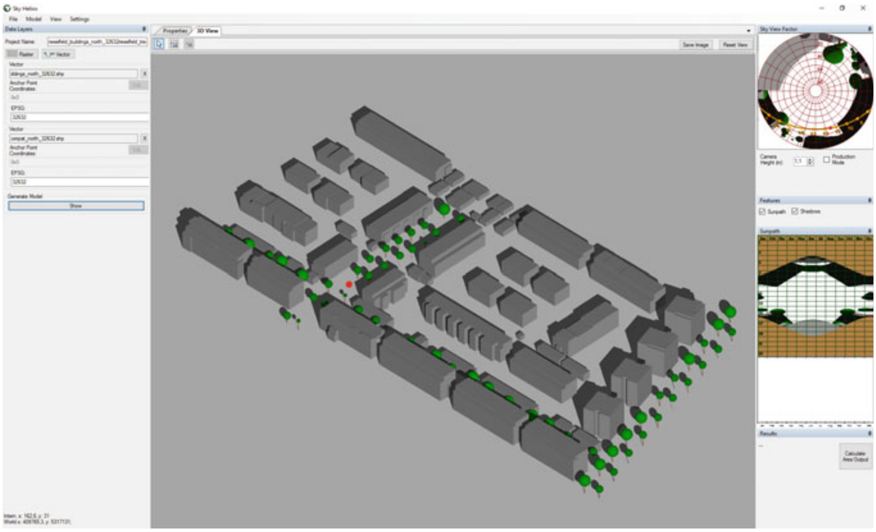


Fig. 2 SkyHelios main window with its 3D-scene in the center, Sky View Factor in the top right and list of input layers in the left. The shown scene is located in the north of Rieselfeld and is based on LOD1 data and tree cadaster data of the municipality of Freiburg (Sect. 3.1)

3 Data and Methods

In this study, we want to compare the spatial patterns of three different thermal indices (PET, PT, and UTCI) for human thermal outdoor conditions. The first step is to calculate the thermal indices for a predefined standardised day with standardised meteorological conditions spatially resolved for the study area (Table 2). This standardization serves as benchmark for the subsequent analysis. Subsequently, the thermal indices are normalised, i.e. mathematically mapped to the value range [0,1]. Finally, the hourly-normalised datasets are spatially aggregated, resulting in one raster dataset per index. The three created raster data sets are compared with each other and statistically analysed. The whole process is depicted in Fig. 3.

3.1 Rieselfeld in Freiburg

Freiburg is located in the warm Upper Rhine Valley in Germany. The city centre is located at 47.9°N, and 7.8°E at about 278 m above mean sea level. In 2021, 231,848 inhabitants lived in an area of 153.0 km^2 (1515 inhabitants/km^2) (Statistisches Landesamt Baden-Württemberg, 2020). Out of these, 9459 people live in district *Rieselfeld* (Stadt Freiburg im Breisgau, 2022). High heat stress in the Upper Rhine Valley reflects various climatic particularities, some of which caused by topography. These result in warm, humid air, high irradiation combined with low wind speeds,

Table 1 Classification of the SkyHelios model and comparison with other urban microscale models

Model	type	Spatial scale	I/O	OS	Speciality	Field of application
SkyHelios	Stand-alone, Steady state	Micro	OGR/GDAL	Win	Sky View Factor, Area of Interest	Urban climate studies, Thermal Comfort, Adaptation
RayMan	Stand-alone, Steady state	Micro	Obstacle	Win	Sky View Factor, Point of Interest	Urban climate studies, Thermal Comfort, Adaptation
ENVI-met	Stand-alone, Steady state	Micro	Area Input File	Win	Comprehensive tool; with different surfaces and tree species	Urban climate studies, Thermal Comfort, Adaptation
Ladybug/Grasshopper	Rhino-Plugin, CAD	Micro	Open-NURBS	Win/Mac	Architectural design	Architectural outdoor comfort studies, Evaluation of urban design
UMEP/SOLWEIG	QGIS-Plugin	Micro	GDAL	Win/Linux/Mac	Mean radiant temperature	Spatial variation of 3D radiation fluxes
MUKLIMO_3	Fluid dynamics	Micro/Local	Fortran-NAMELIST	Linux/Unix	Fluid dynamics and thermodynamics	Urban climate studies on HPC, Process-based, physical model
PALM-4U	Fluid dynamics	Micro/Local	NetCFD	Linux/Unix	LES and RANS mode Thermodynamics and Chemistry	Urban climate studies on HPC Process-based, physical model, Dispersion

Table 2 Meteorological input parameters for simulations in SkyHelios describing an ideal day for benchmark testing

Day	01.08.2022
Time	00:00–24:00 LST
Air temperature (T_a)	30 °C
Relative humidity (RH)	50%
Vapour pressure (VP)	21.1 hPa
Cloud cover (CC)	0
Wind velocity (v)	$1\ \text{m} \cdot \text{s}^{-1}$
Wind direction (WD)	265°

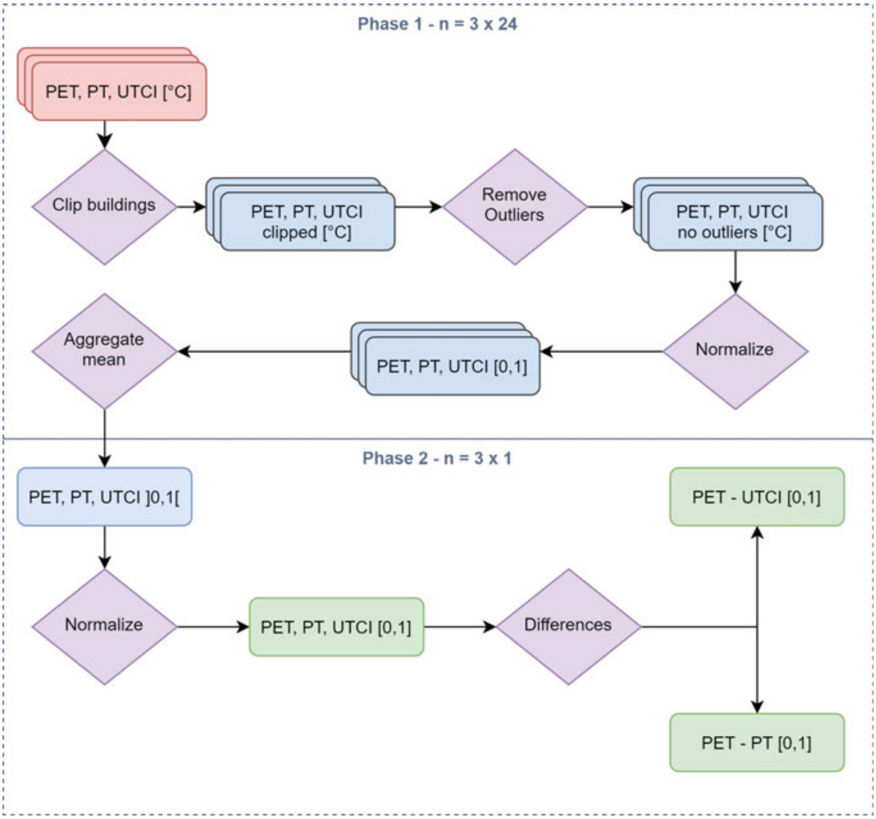


Fig. 3 Workflow of this study to normalise and spatially compare different thermal indices (PET, PT and UTCI). Comparison of indices is conducted for a typical hot day (1st of August) based on standardised meteorological variables (Table 2) and for a standardised person (Table 3). The initial calculation of the indices is conducted in SkyHelios; subsequent analysis is performed by Quantum GIS

Fig. 4 District of Freiburg in the southwest of Germany. The district was planned independently from the main city and is therefore particularly well suited for urban climatological studies (*Source* Photo taken by Erich Meyer and used with permission)

reflecting the Köppen-Geiger class Cfb for warm temperate, fully humid with warm summer (Rubel & Kottek, 2010).

The municipality of Freiburg provided a Level of Detail 1 (LoD1) dataset in the CityGML format (Gröger et al., 2012) for the urban district Rieselfeld in the western part of Freiburg (Fig. 4). The Rieselfeld is very well suited for microscale, urban climatological studies, since the building and tree cadastre is of high quality and the district was independently planned and implemented from the main city.

3.2 Calculation of Thermal Indices

Based on SkyHelios, the thermal indices PET, PT and UTCI were spatially estimated for Freiburg's district Rieselfeld. The thermal indices were calculated for a hypothetical, standardised day. The conditions correspond to a hot summer day and serve as a typical day for benchmark testing with fixed boundary conditions. The meteorological outdoor conditions were set as shown in Table 2. The boundary conditions are the same for all time steps. The meteorological boundary conditions remained constant, only the time of interest was changed on hourly basis so that the simulation varied the radiation fluxes and thus T_{mrt}.

Table 3 Additional default input parameters for simulations in SkyHelios to describe the human body, personal behavior and clothing

Height	1.75 m
Weight	75.0 kg
Age	35 years
Sex	Male
Clothing	0.9
Activity	80 W

Other parameters for persons' behaviour, humans' metabolism as well as clothing were set as shown in Table 3.

The calculation was performed with a temporal resolution of one hour and a spatial resolution of one meter. All parameters were calculated for the height of 1.1 m, which is the average height of a standing person's gravity centre in Europe.

3.3 Normalisation of Thermal Indices

All thermal indices use a different scale to map the reference temperature of the index to the thermal sensation. For this reason, we apply a spatial min–max normalisation for each time step to spatially compare the thermal indices. This processing is done with Geographic Information Systems (GIS): Quantum GIS (QGIS) and SAGA GIS (Conrad et al., 2015). The min–max normalisation was calculated in accordance to Eq. (1).

$$p_{norm} = \frac{p - \min(p)}{\max(p) - \min(p)} \tag{1}$$

After normalising each time step for each thermal index, the individual time steps of each index were aggregated so that a normalised averaged gridded dataset per index was obtained. The averaged gridded dataset per index is normalised once again. The normalised indices are named after the original designation. Thus, nPET, nPT, nUTCI stands for the normalised version of PET, PT and UTCI, respectively.

4 Results: Pattern and Differences of Normalised Thermal Indices

The normalised thermal indices show spatially similar patterns for PET, PT and UTCI (Figs. 5, 6 and 7). The spatial analysis reveals that all indices show a similar pattern with decreased heat stress in the shade of buildings and trees as well as in areas with high wind speed. In shaded areas, the normalised values of the thermal indices are generally lower than in open areas. However, the areas that are characterised by a change in the wind field are particularly prominent. The spatial influence of the buildings and the trees is clearly visible. The hourly averaging of the individual indices shows the influence of the buildings on the northern side, since the influence of the shadow cast over the diurnal cycle is most pronounced here. The linear regression analysis shows great similarity between all three indices. The regression lines are close to the identity lines. All indices agree for higher values but differ on the lower part of the scale between 0 and 1 (Figs. 8, 9, and 10). UTCI shows systematically larger values and PT systematically smaller than PET.

nPT (mean: 0.79, sd: 0.19) shows the greatest contrast between low and high values, compared to nPET (mean: 0.83, sd: 0.16) and nUTCI (mean: 0.85, sd: 0.13). nUTCI shows the lowest contrast and thus has the most homogeneous spatial pattern and is less influenced by shading and wind.

The differences between the individual indices are particularly evident in the spatial difference images (nPET–nUTCI and nPET–nPT), which indicate precisely the areas with low and high wind speeds (recirculation and stagnation zones) as well as shaded areas (Figs. 11 and 12).

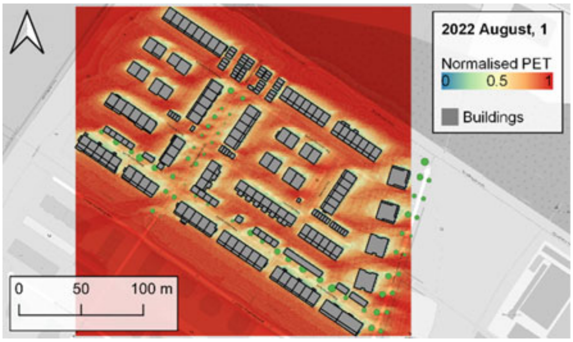


Fig. 5 Averaged and normalised PET for 1st of August in 2022 showing the effect of shading and wind. The data originates from hourly output of absolute PET values by SkyHelios

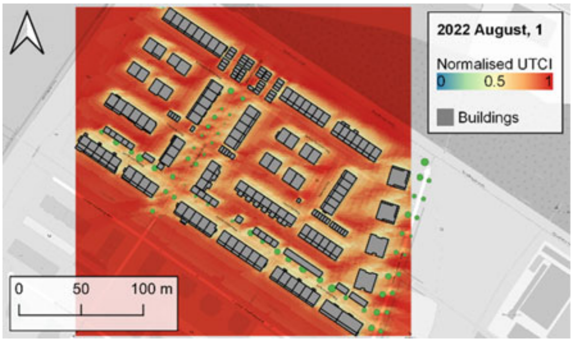


Fig. 6 Normalised UTCI for 1st of August in 2022 showing the effect of shading and wind. The data originates from hourly output of absolute UTCI values by SkyHelios

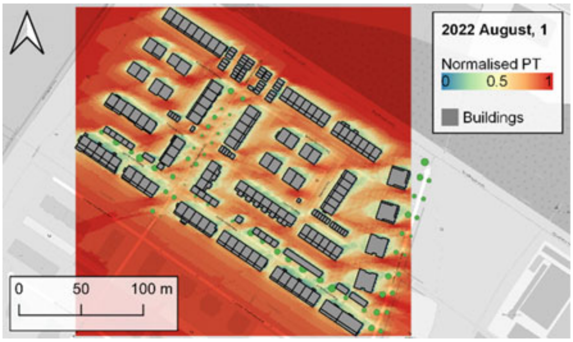


Fig. 7 Normalised PT for 1st of August in 2022 showing the effect of shading and wind. The data originates from hourly output of absolute PT values by SkyHelios

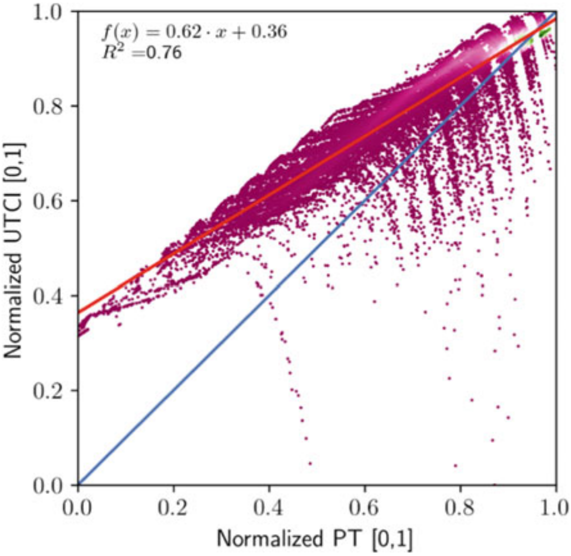


Fig. 8 Comparison of normalised PT and UTCI. A linear regression analysis shows the link between both indices (red) in comparison to the identity line (blue). nPET and nUTCI differ especially for low values of nPT but align for greater values

5 Discussion and Conclusion

The thermal indices were calculated within the same micro-scale model SkyHelios. Errors in the implementation of the individual indices or in the calculation of the meteorological conditions cannot be excluded. In particular, SkyHelios currently does not include a spatial calculation of air temperature and humidity, therefore the results or the thermal indices must also be compared to other models. Comparing the thermal indices across multiple models could reveal errors in the implementation of the models itself. In the future, it would certainly be very exciting to perform a spatial comparison under standardised boundary conditions of different, micro-scale models. In this way, not only the thermal indices could be compared with each other,

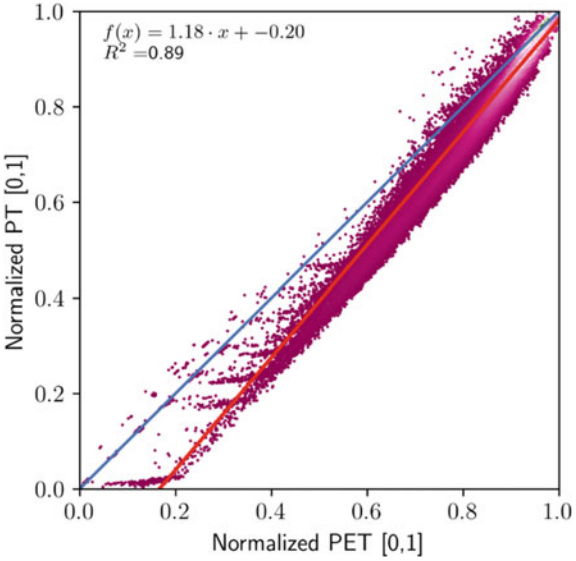


Fig. 9 Comparison of normalised PET and PT. A linear regression analysis shows the link between both indices (red) in comparison to the identity line (blue). nPET and nPT differ especially for low values of nPET but align for greater values

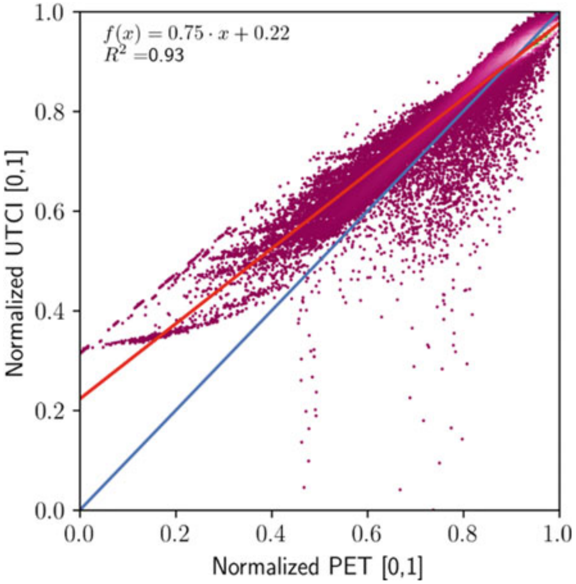


Fig. 10 Comparison of normalised PET and UTCI. A linear regression analysis shows the link between both indices (red) in comparison to the identity line (blue). nPET and nUTCI differ especially for low values of nPET but align for greater values

but also the technical implementations of the individual indices in the respective models (e.g., SkyHelios, ENVI-met, and Palm-4U).

The thermal indices were benchmarked for one specific test scenario, which is typical for a heat wave (autochthonous weather conditions with high air temperature, low wind speed, and clear sky conditions) in Western Europe. Other test cases with

Fig. 11 Spatial difference of normalised PET and normalised UTCI for 1st of August in 2022. Differences with greatest magnitude are in the area of shade and in stagnation and recirculation zones of wind. The data originates from hourly output of absolute PET values by SkyHelios

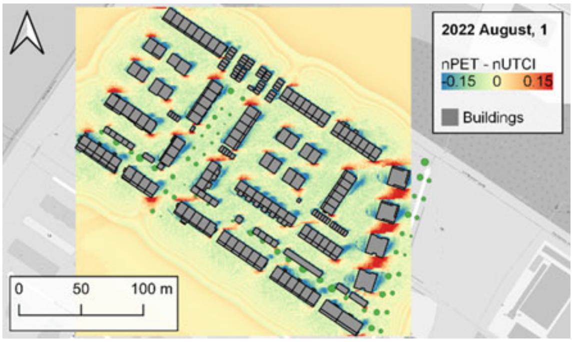
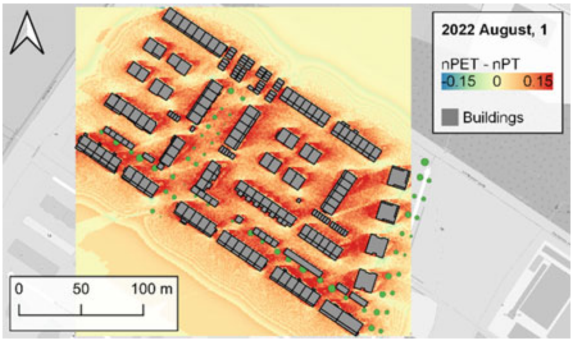


Fig. 12 Spatial difference of normalised PET and normalised PT for 1st of August in 2022. Differences with greatest magnitude are in the area of shade and in stagnation and recirculation zones of wind. nPET is of lower magnitude compared to nPT. The data originates from hourly output of absolute PET values by SkyHelios



higher wind speed, humid air or sultry conditions could be considered and should be tested, as e.g., the influence of humidity on PET is limited (Blazejczyk et al., 2012). All indices show great agreement in the warm areas, but vary especially in the cold regions of the study area. This means that the influence of the cooling factors (e.g., shading and wind speed), because of the clothing mechanisms, have different impact on the thermal indices.

SkyHelios is a steady-state model, i.e., for a given time, the areal thermal indices are calculated under the given boundary conditions. This reduces the complexity of the model, but at the same time it is not as accurate as a dynamic model, which, for example, takes into account the heat storage capacity of buildings or the inertia of the human body to adapt to meteorological conditions.

A major challenge is still the integration and linking of building models with GIS systems. For example, despite the Geodata Abstraction Library (GDAL), architectural data (CAD data) are often not georeferenced, so that they cannot be easily integrated into microscale models.

Normalisation of thermal indices enables spatial comparison of indices independent of prevailing absolute meteorological conditions. This makes it possible to compare different situations within a city and also between several cities of different latitude. This method is not only applicable to Rieselfeld in Freiburg, but rather transferable and applicable to various situations. The min–max normalization is directly dependent on the min/max values and is only suitable if the data is evenly distributed. Instead of min–max normalization, Z-score normalization should also be considered in future research.

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Part III
Policies

Chapter 13
Urbanisation and Urban Heat Island in a Mekong Delta City: From Monitoring to Dominant Factors

Phan Kieu Diem, Nguyen Kieu Diem, Can Trong Nguyen, and Nguyen Thi Hong Diep

Abstract Urbanisation is an indispensable process along with socio-economic development. However, this is also the root of various challenges in urban areas from social to environmental and microclimate changes such as urban heat islands (UHI). This book chapter showcases a case study regarding rapid urbanisation, dynamic of surface urban heat island (SUHI), and controlling factors of UHI in Can Tho city—a regional newly developing city in the Vietnamese Mekong Delta since 2005. Using an integrated methodology framework of earth observation analyses and Analytic Hierarchy Process (AHP), we assessed the urbanisation trends based on urban density and annual growth rate (AGR). The deterioration of SUHI was analysed using land surface temperature (LST) retrieved from Landsat thermal infrared band. AHP is a social approach via expert interviews to identify the key elements and their contribution weights to UHI under the local conditions. It revealed that urban areas have continuously expanded outwards since 2005 towards the Western and main roads along the Bassac river. The AGR is about 0.73%/year over the period of 2005–2019. In particular, the city center has experienced a relatively high rate of urbanisation compared to other areas (i.e., 3.98–5.04% versus 0.5%/year). LST increased significantly and the growth of SUHI was more moderate in terms of intensity and spatial patterns. SUHI is frequently observed in industrial zones and densely populated areas. Urban sprawl was found to significantly stimulate the variations of SUHI intensity. Regarding to the driving factors of UHI, five (05) main factors including nature, society, infrastructure, policy and environment are found contributing to form of UHI at this specific area. In which, the natural factors including coverage ratio of vegetation and water surface are the most contributors to UHI. The key analytical

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factors from AHP are likely to be prioritised elements, which should be mainstreamed into urban planning to mitigate UHI towards a cooling city.

Keywords Analytic Hierarchy Process (AHP) · Can Tho city · Land surface temperature · Surface urban heat island · Urbanisation

1 Introduction

Can Tho city is an important regional and national city in Southern Vietnam as it is located in the "heart" of the Vietnamese Mekong delta—a critical economic region in the Southwest of the country. It was established in 2004 based on the division of Can Tho province into Can Tho city and Hau Giang province. With massive investments over the past decades, Can Tho city owns key elements for development and becomes a rapidly developing city compared to the other five national municipalities. It has made drastic transformations in population and urban areas. For example, it has witnessed a population growth of 564 thousand over ten years from 2005 to 2015, in which urban residents increased by 2.6% (UNs, 2015). Urban areas have also expanded speedily, especially from 2005 onwards (Diep et al., 2021; Son & Thanh, 2018). In 2009, the city was upgraded from Class-2 city to Class-1 city due to its significant growth.

Rapid urbanisation creates favourable conditions for attracting more investment capital and general development motivations. However, it also raises many issues that need to be efficiently solved such as investment policy, land budget, land use transformation and planning, environmental degradation, microclimate change, and career transition due to changes in economic structures (Can et al., 2021; Nguyen et al., 2022). Among these alterations, urban microclimate change is one of the most concern issues since it influences human health and well-being of urban residents. It is induced by rapid urbanisation since urbanisation extensively removes natural surfaces and uses more heat retention materials. Urbanisation also reduces heat evaporative and transformative rates, modifies local climate, airflow and atmosphere.

Urban heat island can be understood as a phenomenon that at the same time, the average temperature in urban development areas with many man-made structures is higher than in rural areas with natural surroundings (Oke, 1982). Urban heat islands are often characterised by built-up areas with most surface materials such as metal roofs, paved roads, concreted structures with low reflection and high absorption of solar energy (Smith et al., 2011). The changes of surface properties and anthropogenic heat sources from human activities along with the urban expansion and industrialisation are jointly contributing to form UHI (Li et al., 2021; Raj et al., 2020).

UHI is one of the main concerns in urban areas due to its negative impacts on human health, energy consumption, and environmental pollution. A number of studies revealed the increased risk of heat-related mortality and morbidity, which mostly affected due to the land surface temperature variations (Benmarhnia et al, 2016; Longden, 2019). In addition, the increase in UHI leads to an increase in energy consumption due to the high demand for cooling during the extreme heat events (Can et al., 2020). UHI also affects the air and water quality and greenhouse gases emissions (Li et al., 2018).

There are several efforts to control and mitigate UHI. It is apparent that UHI is the main consequence of urban development. Yet, UHI is actually controlled jointly by many factors. Therefore, the current strategies intervening a few elements may lead to inefficient mitigation UHI. Enhancing understanding of controlling drivers of UHI will definitely improve the efficiency of solutions for mitigation and adaptation strategy toward greener and low carbon cities in the future, as a basis for urban development planning and orientation of the region. Besides, it also provides a good example for urban planning in similar new developing cities.

2 Rapid Urbanisation in a Just-Established City of a National Municipality

2.1 Evidence of Urban Expansion Through Earth Observation Data

The observation of normalised difference built-up index (NDBI) presents the index accumulation over the past twenty years. The high values regions are the former and unchanged urban areas over time, while the regions with lower values belong to newly developing areas and non-urban areas when it approaches minimum values of NDBI. The expanded urban areas tend to sprawl from the urban core outwards to vicinities and along the transportation system with high urban areas mainly concentrated in Ninh Kieu and Thot Not districts (Fig. 1).

A change detection analysis using land use/cover (LUC) maps was adopted to explore land use/cover changes (LUCC) and urbanisation dynamics. Specifically, LUC maps were obtained from the object-based classification using Landsat spectral bands. There were drastic shifts in LUC over the past 14 years toward urbanisation (2005–2019). LUC has converted from pure agriculture to an economy that less depends on agricultural production. In 2005, about 93.91% of the city's area was covered by green spaces. The green space proportion gradually decreased to 83.31% with more than 10% shared by paddy fields and annual crops in 2019. At the same time, the built-up areas have expanded by 146.63 km^2 to gain urban proportion from 2.16 to 12.34%.

The urban areas are also distributed along the roads and rivers as tree branch form. Specifically, it has experienced dynamic urbanisation along the Bassac River in Cai Rang, Ninh Kieu, Binh Thuy, O Mon, and Thot Not districts. It also inherits the characteristics of urban expansion as in other flat plain deltas that urban areas dominate vicinities under extension form. This expansion has clearly been observed in Ninh Kieu and Thot Not districts, where are both the two urban cores and gateways

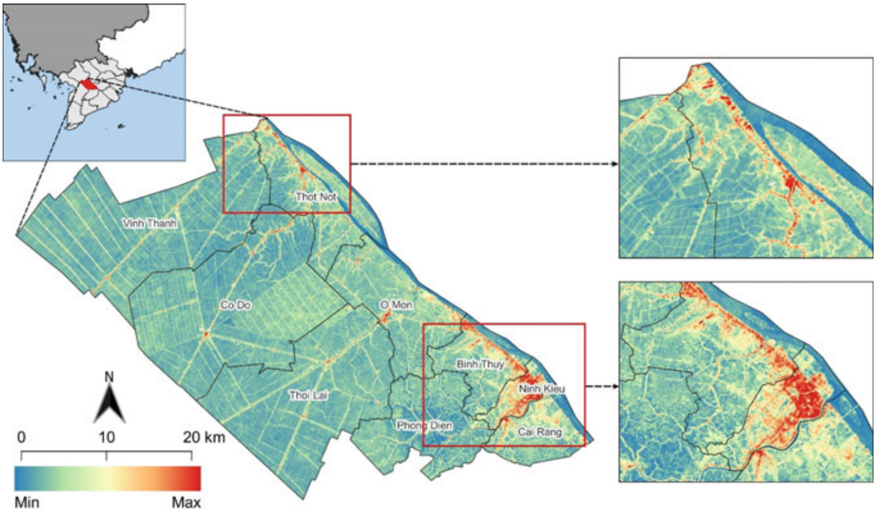

Fig. 1 Accumulative landsat-based NDBI from 2000 to 2020 in the entire Can Tho city and zoom-in areas in two primary urban cores in Ninh Kieu and Thot Not districts

connecting provinces in the Ca Mau peninsula and other parts on the West side (Fig. 2).

The urbanisation at subdistrict level was analysed by two criteria including urban density and annual growth rate (Can et al., 2021). Urban density measures the relative rate of urban area against the total area of each administrative unit. Besides, the annual growth rate (AGR) reveals the average urbanisation speed yearly. Natural break (Jenks) presents urban density and AGR at five levels corresponding to Low/Relatively low/Medium/High/Very high. It indicates that most subdistricts had low and relatively low urban density at the beginning (<8.26%). The high and very high urban density subdistricts were in the city center of Nink Kieu. At the end of the period, there were significant improvements in urban density. The high and very high urban density regions (>32.34%) expanded and occupied almost Ninh Kieu, Binh Thuy, and Cai Rang districts. The neighboring counties and the town of districts (e.g., Vinh Thanh, Co Do, Thoi Lai) had medium urban density, while rural counties in the transition zone have improved their density from low to medium–low levels (Fig. 3).

It is in line with social evidence that earth observation data also reveals the dynamic of urbanisation in terms of AGR. The subdistricts have a relatively high urbanisation speed, higher than 0.75%/year except for the slow regions in immense paddy fields in the South and Southwest of the province. An Khanh (Ninh Kieu district) is the most dynamic county within this period, with AGR = 5.04%/year. High urbanisation regions are in town of Thot Not district (3 subdistricts) and An Binh and Hung Loi (Ninh Kieu district). The contiguous areas of Ninh Kieu in An Thoi (Binh Thuy district) and Hung Thanh, Ba Lang, Phu Thu (Cai Rang district) are also relatively

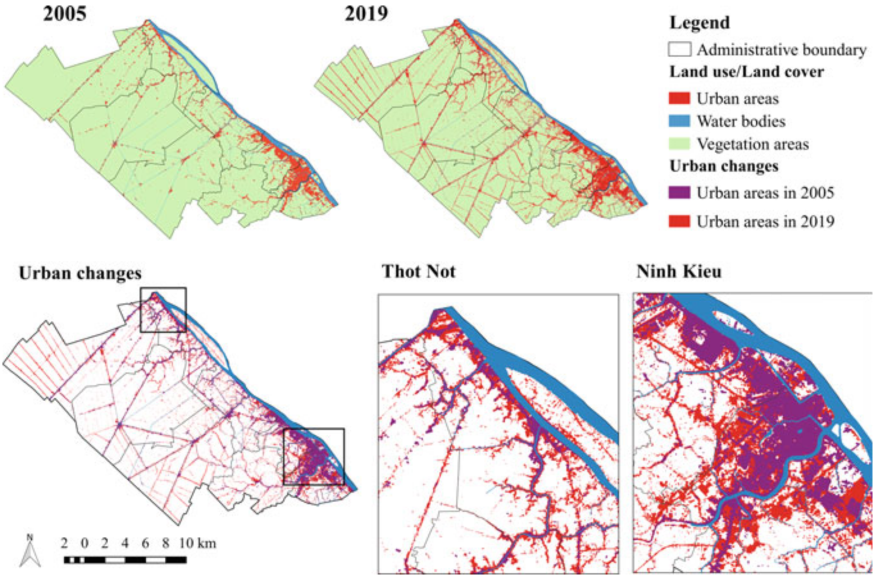

Fig. 2 Land use/cover changes from 2005 to 2019, urban changes, and fragmented maps show two primary urban cores in Ninh Kieu and Thot Not districts

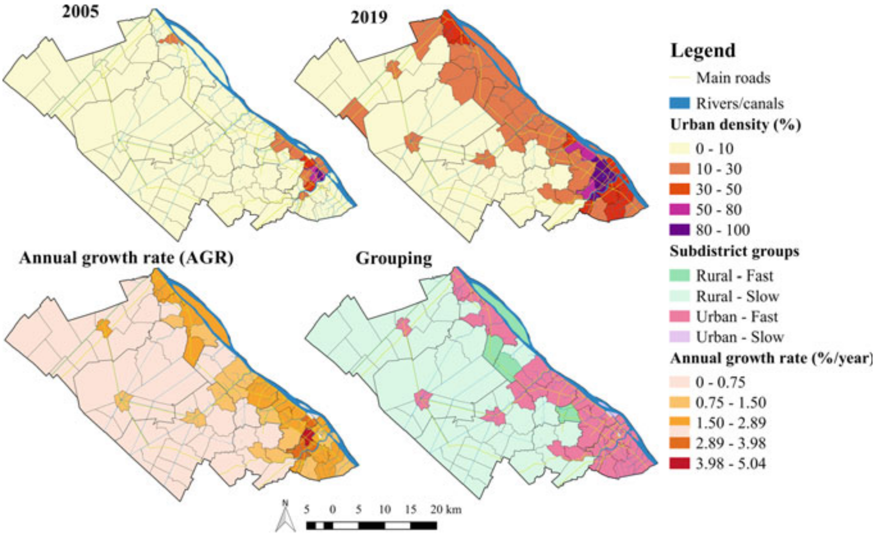

Fig. 3 Urban density over subdistricts in 2005 and 2019, annual growth rate over the period, and subdistrict groups based on urban density and AGR

dynamic (AGR = 1.5–3.98%/year). Besides, the development in peri-urban and district centers also deserves to be considered with medium and relatively low speed.

2.2 A Conventional Framework for Urbanisation Assessment

Subdistricts were considered by a conventional grouping method, which differentiates using median values of urban density and AGR as a proxy standard (Can et al., 2021). A county with an urban density higher than the median value is an urban county. A county has an AGR value higher than the median value assigned to be a fast urbanisation county and vice versa. This method generates four groups based on two-dimensional data. It reveals four unique groups with different concerns. A group of urban subdistricts with a high urbanisation rate (orange shade), where it should have efficient solutions to address common urban problems such as infrastructure overload, environmental pollution, clean water, and sanitation. Besides, rural counties with fast urbanisation have experienced the most dynamic processes when transforming from rural to urban areas. It should have a long-term vision and strategies to develop the city and ensure consistency of infrastructures. On the other hand, urban subdistricts with low urbanisation are city centers with the city seeming to be highly concentrated and saturated. Urban morphology and spatial planning should be taken into account as they will significantly contribute to stimulating urban microclimate (e.g., urban heat islands, thermal discomfort) and ultimately impact on human well-being.

3 Deterioration of Urban Thermal Environment

3.1 Spatial Distribution of Land Surface Temperatures

Landsat thermal infrared band is the main data source for retrieving land surface temperature (LST). It was obtained by converting brightness temperature and then calibrating by NDVI-based land surface emissivity (Son & Thanh, 2018; Van De Griend & Owe, 1993). LST was reclassified into seven groups from low to high based on average value and standard deviation for peer comparison (Zhang et al., 2017).

The distribution of LST shows that most of the high and very high surface temperatures were located in the central areas such as Ninh Kieu, Binh Thuy, Cai Rang districts. The surface temperature in 2019 elevated significantly compared to those in 2005, especially in sub-central districts of O Mon and Thot Not districts. In contrast, the temperature remained relatively lower than average value in the rural areas cultivating rice farming, annual crops, and agricultural crops. Notably, the dense

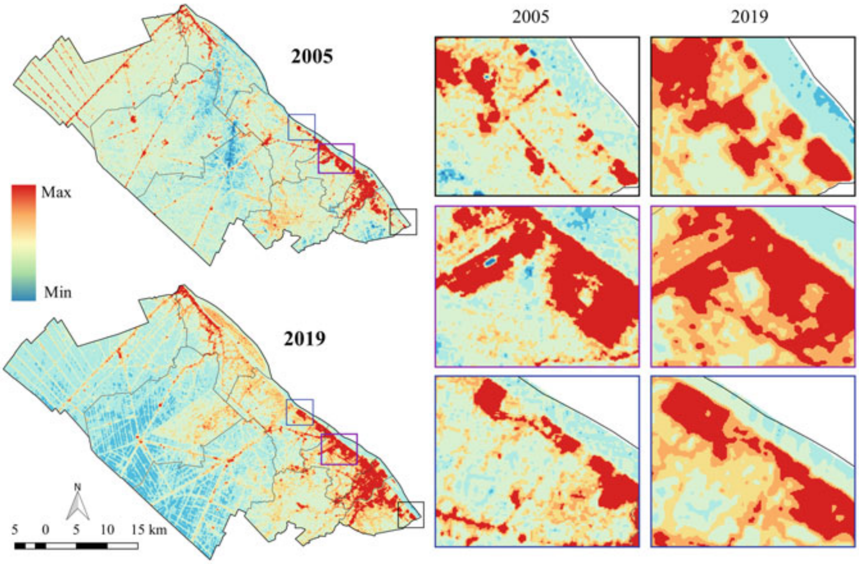

Fig. 4 Land surface temperature in 2005 and 2019 and comparison at zoom-in locations, whereas a, b, c present for first, second and third locations of LST variation between 2005 and 2019

construction and areas with high concentration of impervious surfaces, such as industrial zones of Binh Thuy and Cai Rang, thermal power plants and airport at O Mon district, where always experienced high LST of higher than 28.5 °C (Fig. 4). The areas with high-density population, built-up and less vegetation were found corresponding to higher surface temperatures over the years. The percentage of impervious surfaces and its expansion during urbanisation are closely associated with the increase in LST.

3.2 Formation of Surface Urban Heat Island Over the Past Decade

Surface urban heat island (SUHI) is determined when the surface temperature at any location greater than the average temperature of the entire considered area (Ya et al., 2010).

$$\mathrm{LST} > \mathrm{T_{mean}} + 0.5 \times \mathrm{S_d}$$

where $\mathrm{T_{mean}}$ is the average land surface temperature; $\mathrm{S_d}$ is the standard deviation.

Surface urban heat island magnitude ($\mathrm{I_{SUHI}}$) is estimated based on the difference in the average surface temperature of the urban area ($\mathrm{LST_{urban}}$) compared to the non-urban area ($\mathrm{LST_{non\text{-}urban}}$), whereas the non-urban defined as the eliminating of urban areas.

$$I_{SUHI} = LST_{urban} - LST_{non\text{ - }urban}$$

Surface urban heat island tended to aggravate over time both in terms of dominated areas and heat threshold. In 2005, there was about 17.37% of Can Tho city occurred SUHI. It then expanded up to 24.18% of total areas in 2019 (Fig. 5). SUHI distributed mainly in Ninh Kieu district, residential areas along the 1A national highway in Cai Rang district, the 91 national highway connecting Ninh Kieu District, Binh Thuy and the center of O Mon, Thot Noi, Phong Dien Town, Co Do, Thoi Lai, Vinh Thanh and Thanh An Town (Fig. 5). SUHI intensity has also witnessed dramatical elevation. If the SUHI intensity of higher 6 °C is set up as an extreme proxy, SUHI severity was recognised its encroachment throughout the time. For instance, the highest SUHI in year 2005 was estimated at 6.28 °C and the areas with SUHI higher than 6 °C was only about 27 ha. These values were increased to 8.96 °C and occupied about 87 ha in the year of 2019. The areas with high SUHI intensity also distributed at industrial zones, e.g., Hung Phu 2 Industrial Park, Viet Nhat Industrial Park, and Cai Cui Port, O Mon Thermal Power Plant, Can Tho International Airport, where the temperature is always higher than the surrounding areas about 1–2 °C.

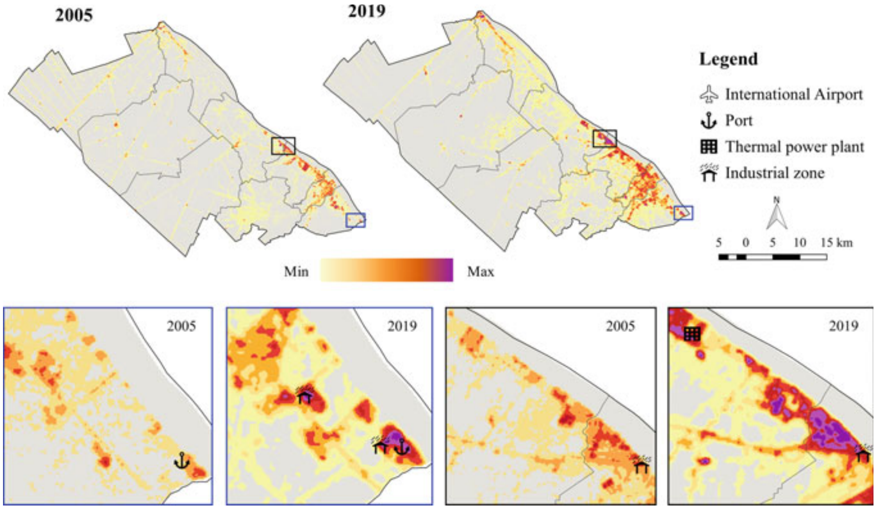

Fig. 5 Development of surface urban heat island and its spatial distribution over time at typical sites

3.3 *Significant Hotspots in Surface Urban Heat Island Formation Along with Urban Development*

The significantly meaningful hotspots have experienced changes in urban thermal environment, where urban dwellers are supposed to face thermal severity. The hotspots were detected by calculating Getis-Ord Gi* statistical value for each object in the data layer. Specifically, probability (p-value) and standard deviation (z-score) are the criterion to identify a certain region belonging to hot or cold regions of SUHI. This tool works by looking at each feature within the context of neighboring features. A feature with a high value of SUHI is interesting but may not be a statistically significant hot spot. To be a statistically significant hot spot, a feature need to have a high SUHI value and be surrounded by high SUHI values as well. The local sum for a feature and its neighbors is compared proportionally to the sum of all features; when the local sum is very different from the expected local sum, and when that difference is too large to be the result of random chance, a statistically significant z-score results.

P-values and z-scores were estimated the aggregation significance (90%, 95% and 99%) for hotspots as well as coldspots. Aggregation is considered to be statistically significant when z-scores are higher than 1.65 (confidence level of 90%), higher than 1.96 (confidence level of 95%), higher than 2.58 (confidence level of 99%) for hot spot areas, or lower than −1.65 for cold spot areas. Otherwise, the result will be responded to a random spatial distribution (Getis & Ord, 1992; Rossi & Becker, 2019). Thus, in this research, the hotspots of SUHI with a significance level of higher 90% representing a high concentration of SUHI, which distributed mainly into three isolated zones (Fig. 6). Zone I has the highest SUHI intensity in the city center of Ninh Kieu, Cai Rang, and Binh Thuy districts with the dense concentration of population and industrial zones. Zone II has the moderate SUHI intensity, distributed in the center of Thot Not district. Plus, Zone III owns a relatively low SUHI intensity in the center O Mon district.

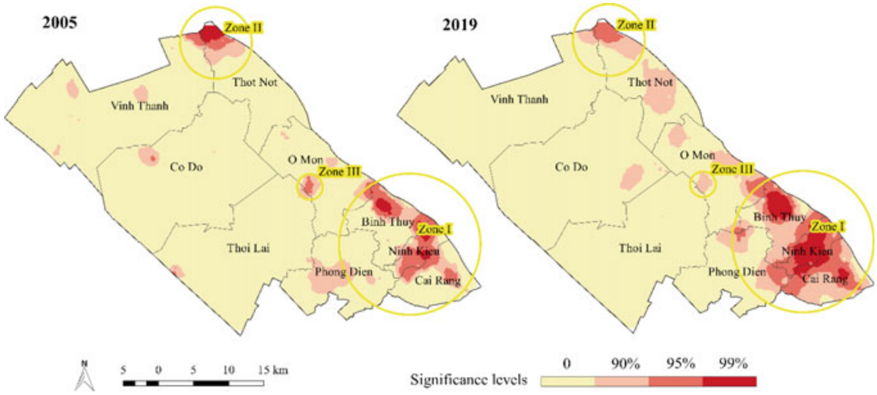

Fig. 6 Surface urban heat island clusters in 2005 and 2019 (The zone 1, 2, and 3 present the specific highlight locations of UHI clusters)

SUHI is highly correlated with the ratio of urban areas (positive) and the ratio of vegetation areas (negative) ($|r| > 0.9$). It also has a relatively high relationship with LST ($r = 0.72$). The urbanisation leads to vegetation reduction and urban expansion, which strongly contribute to exacerbate SUHI intensity. It implies a promising solution to mitigate SUHI in urban areas by enhance cool surfaces such as green spaces and water bodies within the city.

In terms of earth observation for urban theme, further studies need to be taken into consideration to overcome the uncertainty in urban extraction, the different remote sensed indices may need to apply for distinguish bare land and small parcel of impervious areas. Besides, LST analysis need to be considered by cloud issues and temporal resolution in further applications.

4 Key Controlling Factors of UHI

Analytic Hierarchy Process (AHP) was conducted through expert interviews to detect the key elements and their contribution weights to UHI under local conditions. A list of key elements (principal factors and sub-factors) was formed based on the literature review and first round interview. The elements rated by about 50% of experts as unimportant will be removed in second interview. The relative importance of the key elements was rated in nine importance scales, from absolutely less important (1/9), very less important (1/7), less important (1/5), somewhat less important (1/3), equal important (1), somewhat more important (3), much more important (5), very much more important (7), and absolutely more important (9). Nine experts were interviewed, who are considered as to have expertise in their fields related to environmental resources, economy, society, and policy to figure out different aspects of UHI. The weight of each elements was then estimated using the pairwise comparison matrix (Saaty, 1980). The Consistency Ratio (CR) is an indicator to evaluate the consistence of expert's opinions, which was obtained as follows fomular (Samo & Anka, 2009):

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI}$$

where: RI is a random index; CI is a consistency index measuring the consistent deviation (Saaty, 1977, 1980). According to AHP approach, as explaintation in text, the expert's opinion with $\mathrm{CR} < 10\%$ were selected as it is relatively consistent. In contrast, if $\mathrm{CR} > 10\%$, the assessment are inconsistent, there are a need to be re-checked and conduct the interview again. This study, the only CR met requirements of consistence are further processed. The bold values in Table 1 showed the highest weight in the sub-factors. Accordingly, the importance levels of five groups, principal factors, and 23 sub-factors were analysed and presented in Table 1.

Among principal factors, nature is the most important contributor to UHI ($W_N = 0.493$). It is then followed by society ($W_s = 0.211$), infrastructure ($W_I = 0.116$), environment ($W_E = 0.101$) and policy ($W_P = 0.081$). In essence, the nature of surface

Table 1 Weights of key elements obtained by AHP

Principal factor	Weight of principal factors (W_1)	Sub-factors	Weight of sub-factors (W_2)	Overall weight ($W = W_1 \times W_2$)
Nature (N)	**0.493**	**N1. Ratio of water surfaces**	**0.368**	**0.181**
		N2. Vegetation areas	0.202	0.100
		N3. Weather, climate	0.152	0.075
		N4. Solar radiation	0.113	0.056
		N5. Urban form (sky view)	0.080	0.040
		N6. Climate changes	0.052	0.026
		N7. Ratio of cool surfaces	0.032	0.016
Society (S)	0.211	**S1. Urbanisation**	**0.411**	**0.087**
		S2. Population density	0.237	0.050
		S3. Traffic at transit station and intersection	0.149	0.031
		S4. Bussiness activities	0.117	0.025
		S5. Lifestyle	0.086	0.018
Infrastructure (I)	0.116	**I1. Urban design**	**0.512**	**0.059**
		I2. Building materials	0.175	0.020
		I3. Concrete pavement	0.130	0.015
		I4. Urban structures	0.101	0.012
		I5. Direction of buildings	0.082	0.009
Policy (P)	0.081	**P1. Urban planning**	**0.640**	**0.052**
		P2. Urban design orientation	0.175	0.014
		P3. Architectural planning policy	0.107	0.008
		P4. Policy for rural construction	0.078	0.006
Environment (E)	0.101	**E1. Environmental factors, air pollution**	**0.865**	**0.087**
		E2. Solid waste disposal	0.135	0.014

characteristics mainly defines and contributes to UHI significantly compared to other factors. For example, the natural surfaces (e.g., lake, river, and dense vegetation) are always cooler than constructions at the same time.

Regarding the sub-factors of nature, the ratio of surface water and vegetation areas are the most important in comparison to others ($W_{N1} = 0.368$; $W_{N2} = 0.202$). Among sub-factors of society, urbanisation has the highest overall weight ($W_{S1} = 0.411$) following by population density (W $W_{S2} = 0.237$), traffic at intersection ($W_{S3} = 0.149$), transit stations ($W_{S3} = 0.117$) and lifestyles ($W_{S4} = 0.086$). Meanwhile, urban design is the most important element that was believed to significantly cause UHI in urban areas among the infrastructure elements ($W_{I1} = 0.512$). Urban planning is the most critical policy factor that influences UHI through stimulating or hindering urbanisation at a certain city ($W_{P1} = 0.640$). Besides, environmental variables and air pollution were supposed to be favorable conditions amplifying UHI ($W_{E1} = 0.865$).

5 Heat Mitigation Strategies

In recent, there are number of guidelines and proposed solutions to mitigate UHI from different perspectives of urban policies. However, it is obvious that UHI is regulated by a bun of different controlling factors from nature to climate, policy, and society. These factors could even interact and contribute to UHI at different extents. Therefore, the local governments often fail in UHI mitigation efforts because they only control a limited element, or they are too ambitious in trying to adjust too many elements at the same time. The AHP revealed the key controlling factors of each category, which are widely perceived by experts. Therefore, these elements should be prioritised to mainstream into urban planning to effectively mitigate UHI. Additionally, these factors are the highlights that easy to receive the consensus from the community in the development strategies toward a greener city. The following sugguestions of heat mitigation strategies could be considered in future:

- The intergated solutions need to be developed base on the interdisciplinary approaches. In fact, the UHI formed by many different factors as mention in previous sessions, so one single aspect solution could be less effectively adress the mitigation strategies.
- The increase, conservation, and optimisation, and diversification urban green and blue spaces are needed since they are considered as sink landscapes with contributing to cooling urban.
- The practical urban planning and actions based on the finding of scientific reseach intergating with the participatory of local people would be the principle framework contributing in UHI mitigation strategies.
- The pracitical urban design need to consider to construction standards, and distribution planning inside urban areas to encourage urban ventilation as well as increase landscape heterogeneity.
- The intergated implementation of environmental solutions to improve the increasingly degradation of air pollution in urban areas are need to be part of mitigation strategies.
- The raising awareness of local people specific to young people and children on UHI mitigation modelling and visualization would be long term impacts and effectively contributing on mitigation toward the greener city.

6 Conclusions

This chapter analysed the urbanisation and surface urban heat island in a typical city in the Mekong delta. An overall scene of spatial urban development, alternations in urban thermal environment, and controlling factors of UHI under indigenous conditions was depicted by different approaches to reflect the current context of the city. To conclude, Can Tho city owns the following characteristics and highlights:

- The city has rapidly developed with spatial urban expansion clearly observed during the period from 2005 to 2019. The urban density and annual growth rate have significantly increased over time, especially in the main city center, the towns at each regional districts, and the ribbon of urban areas along the Bassac River.
- SUHI has dramatically elevated with close association with urban expansion in developed centers, where have experienced rapid urban sprawl, especially in high concentration areas of constructions and industrial parks.
- The changes in urban microclimate specified as UHI in Can Tho city are relatively similar to other cities. It is dominated by a set of factors including natural and environmental characteristics, society, infrastructures, and policy. Maintaining and improving natural spaces such as water bodies and vegetation are the most promising intervention to mitigate UHI. However, integrated interventions regulating the key elements in each aspect should be a more effective solution to release UHI severity.

Beside evaluating the spatial urban expansion using remote sensed data, the highlight of this chapter is quantitatively measured the important of key elements, which support the valuable information for identifying the priorities to be implemented in urban planning. The lesson learned in Can Tho city, typical emerging city in Mekong region, will be good example for similarly cities to avoid the forming of UHI in development strategy.

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Chapter 14
A Study on Thermal Comfort Assessment Frameworks and Models in Cities

Hadi Alizadeh and Ayyoob Sharifi

Abstract Considering the increasing trends of urbanization, climatic change, and air temperature in cities, the issue of urban heat island mitigation for ensuring thermal comfort is of high importance. Enhancing thermal comfort also has implications for human health, well-being, and productivity. In recent decades, several assessment frameworks and models have been proposed to measure and predict thermal comfort in cities. This chapter tries to explore major assessment frameworks and models that explain and measure thermal comfort in cities by considering physical, physiological, psychological, and behavioral dimensions. It shows that thermal comfort models could be divided into two major categories, namely, knowledge-based thermal comfort methods and data-driven thermal comfort models. Each of these two has subset models for thermal comfort testing in cities. The findings indicate that recent trends in measuring thermal comfort are focused on data-driven models based on simulation algorithms.

Keywords Climate change · Urban heat islands · Thermal comfort · Thermal comfort models

1 Introduction

The increasing trends of urbanization across the globe have caused tremendous pressure on the environment (Zhang, 2016). Such pressure shows itself as unsustainable pattern of urban growth (sprawl), the increasing number of cars, decreasing green

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space per capita, and huge amounts of energy consumption in the cities. These have led to a large-scale modification in urban land use and land cover pattern and, consequently, brought about adverse effects in cities (Mohan et al., 2020). All these, which threaten the health of citizens and urban sustainability, have caused concerns among researchers, policymakers, and urban planners (Bartholy & Pongrácz, 2018).

Recently, the significant growth of some concepts in the literature, such as 'cool cities', 'urban heat islands', and 'thermal comfort' are justified in line with the concern of climatic manifestations of urbanization (Qi et al., 2021; Taha, 2015). Among these, thermal comfort refers to the existence of a satisfactory temperature for individuals in urban spaces that does not lead to endangering their health (Ahmed, 2003). In fact, this matter is related to the quality of outdoor and semi-outdoor spaces in the city, such as parks, squares, pedestrian streets, public recreational spaces, residential areas, sports stadiums, etc., that assist in creating spaces for exercising and socializing of the citizens. The quality of design and placement of these spaces and the pattern of land cover significantly impact the city vitality and livability, especially individuals' thermal comfort (Chen & Ng, 2012).

Considering the importance of urban sustainability, urban climate change adaptation, and urban health, many scholars have attempted to explain how to estimate and create manners to reach thermal comfort in the cities. In this road, particularly, numerous studies have sought to present and expand assessment tools and models to measure thermal comfort in cities. Concerning this matter, previous literature shows that thermal comfort models have mainly focused on two aspects, namely, knowledge-based thermal comfort methods and data-driven thermal comfort models. To this end, an effort has been made to describe these models and assessment tools in this chapter.

2 Knowledge-Based Thermal Comfort Models

Based on the literature, knowledge-based thermal comfort models are known as traditional models that are classified into heat balance models and adaptive models. In brief, heat balance models based on laboratory studies believed that thermal comfort could be obtained by holding body temperature in a narrow range, low skin moisture, and minimizing the physiological effort of regulation (De Dear et al., 2020). On the other side, adaptive models, based on field studies, claim that a variety of temperature ranges can be assumed comfortable for individuals because they can adapt to varying boundary conditions (Yao et al., 2009).

Some of the most famous models related to both aspects are described in the following.

2.1 *Predicted Mean Vote (PMV)*

Predicted Mean Vote (PMV) has been proposed by Fanger in 1970 based on his laboratories and chambers studies (Yau & Chew, 2014). In this model, Fanger expanded a type of heat balance equation, which consists of a combination of six factors that affect achieving a thermal balance between the human body and the environment (Li & Liu, 2020). These factors include four primary and two personal factors shown in Fig. 1.

According to Yao et al. (2009) "The PMV model is based on extensive American and European experiments involving over a thousand subjects exposed to well-controlled, extensive and rigorous laboratory environments" (p. 2089). The PMV model estimates thermal comfort based on the six factors mentioned and quantifies the absolute and relative impact of the factors in light of what is thermally comfortable (Efeoma & Uduku, 2014). The equation of PMV model is shown below:

$$f = (TA, TM, VEL, RH, MET, CLO) = 0 \tag{1}$$

Based on the model equation, it is predicted that in terms of the skin temperature and sweat rate limits, a person will have thermal comfort when the thermal load of his body is equal to zero (Zhang & Lin, 2020). This model has been used widely and measures thermal comfort based on a seven-point scale (+3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, 1 = slightly cool, 2 = cool, 3 = cold) (Zheng et al., 2021). Practically, "PMV is also commonly interpreted by the Predicted Percentage Dissatisfied Index (PPD), which is defined as the quantitative prediction of the percentage of thermally dissatisfied people at each PMV value" (Chen & Ng, 2012, p. 129).

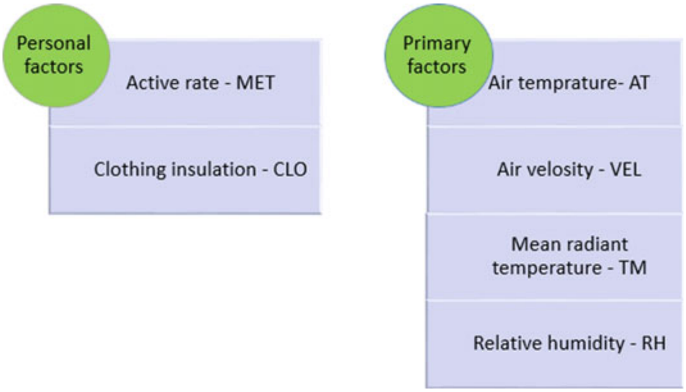

Fig. 1 Constituent factors of PMV model—Modified from (Adapted from Efeoma & Uduku, 2014)

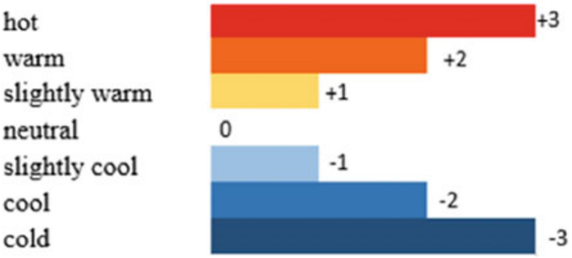

Fig. 2 ASHRAE thermal comfort scale (Adapted from Lu et al., 2019)

2.1.1 ASHRAE

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) gained considerable ground among researchers in the 1990s in terms of field studies (Toe & Kubota, 2013). The model is considered a method to fill the gap between comfort theory and practice. ASHRAE was developed by de Dear and Brager,"is based on the analysis of about 9,000 of the 21,000 sets of raw data compiled from field studies in 160 buildings located in diverse climatic zones around the world" (Carlucci et al., 2021, p. 2).

As shown in Fig. 2, this model measured thermal comfort based on a seven-point sensation scale, which runs from "cold" (–3) to "neutral" (0) to "hot" (+3) and is drawn from the PMV model of Fanger (1970) (Langevin et al., 2012). In the edited version of ASHRAE by Humphreys and Nicol, 2004, ASHRAE scale is from -3 (much too cool) to $+3$ (much too warm).

The Humphreys 1975–1981 database and the ASHRAE RP-884 database as a meta-analysis of a larger database in the context of field surveys were applied for developing ASHRAE adaptive standard. In between, the ASHRAE RP-884 database that could cover various climatic areas, such as hot–humid areas, has been applied by numerous studies (Farghal & Wagner, 2010; Schweiker & Shukuya, 2012; Toe & Kubota, 2013). This database was used as the basis for the development of ASHRAE standard 55: Thermal Environmental Conditions for Human Occupancy. Since then, "the adaptive thermal comfort model was first included in the 2004 edition of the ASHRAE Standard 55; and subsequent revision of the Standard thereafter" (Efeoma & Uduku, 2014, p. 403).

2.1.2 ISO 7730

The ISO 7730 standard is an adaptive thermal standard based on Frager's work with young Danish students on the PMV model (Ealiwa et al., 2001). This standard is presented to predict the general thermal sensation and degree of discomfort. It can analyze and interpret thermal comfort based on the PMV and PPD (predicted percentage of dissatisfied) and local thermal comfort (Zare et al., 2018).

Overall, The ISO 7730 standard was expanded in parallel with ASHRAE 55. This standard is part of a series of ISO standards (Such as ISO 7243, ISO 7933, and ISO/TR 14415) that are revised every 5 years and used in a range of thermal environments from mild to extreme (Wilde, 2020).

2.2 The Physiological Equivalent Temperature (PET)

The Physiological Equivalent Temperature (PET), which is known as a steady-state method, is a temperature dimension index based on degrees Celsius. PET has been formed considering Munich Energy-balance Model for Individuals (MEMI).The MEMI is defined according to the energy balance equation for the human body. Below, the structure of this equation and the definitions of its components are described (Matzarakis & Amelung, 2008):

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \tag{2}$$

M: "the metabolic rate (internal energy production)";
W: "the physical work output";
R: "the net radiation of the body";
C: "the convective heat flow";
E_D: "the latent heat flow to evaporate water diffusing through the skin";
E_{Re}: "the sum of heat flows for heating and humidifying the inspired air";
E_{Sw}: "the heat flow due to evaporation of sweat";
S: "the storage heat flow for heating or cooling the body mass".

Two points is important in this equation. First, the unit of all heat flows is defined based on Watt, and second, "the individual terms in this equation have positive signs if they result in an energy gain for the body and negative signs in the case of an energy loss (M is always positive; W, E_D and E_{Sw} are always negative)" (Matzarakis & Amelung, 2008, p. 165).

PET has been found suitable for the analysis of outdoor thermal comfort. As stated by Chen and Ng (2012) in this model, "the evaluation of a complex outdoor climatic environment translates to a simple indoor scenario on a physiologically equivalent basis" (p. 114) in an easy understanding and interpreting manner.

2.3 Black Box Theory

The black box theory, widely used in cybernetics, applies the variables, such as culture, climate, social, psychological, and behavioral adaptations that significantly impact thermal perception (Shooshtarian, 2019). The main point of this theory is to explore and assess the logical and statistical relationships between information that is applied in the box and instructions that are known as output (De Dear et al., 2020). The principles of this theory can be described as follows:

- Defining a deterministic stimulus for the black box that is the input of the system;
- Black box output and focus on establishing a meaningful statistical relationship between input and output;
- Using mathematical methods to express the relationship and develop the black box with a mathematical model (Yao et al., 2009).

2.4 Adaptive Thermal Comfort Standards

Besides the models mentioned above related to knowledge-based thermal comfort models, adaptive standards have also had a key effect in expanding these kinds of models across the globe. In fact, adaptive standards have had a significant impact on the visibility of adaptive models since 2004. The trend of consideration of adaptive standards began from ASHRAE 55, elaborated in 2004. In addition to ASHRAE 55 and ISO 7730 described above, there are some major standards in expanding the adaptive models. These are briefly explained in the next section.

2.4.1 EN 15251

EN 15251, the European standard, which specifies the indoor environmental parameters, and its revision prEN 16798 are adaptive standards that were applied PMV and adaptive models in their structure (Carlucci et al., 2018). Presented in 2007, EN 15251 was formed based on empirical data obtained from close to 1,500 participants recorded in the pan-European Smart Controls and Thermal Comfort (SCATs) project (De Dear et al., 2020; Pozas et al., 2022).

The main aim of this standard was to reduce the energy usage by air conditioning systems through varying setpoint temperatures in line with outdoor temperature by applying an 'adaptive algorithm'. To this end, numerous physical measurements and subjective responses from numerous locations in France, Greece, Portugal, Sweden, and the UK were recorded. As pointed out by De Dear et al. (2020), to optimize the performance of the EN 15251 standard, "the Griffiths method rather than linear regression was applied to estimate the neutral temperature with Griffiths Coefficient of $G = 0.5$, meaning that thermal sensation votes were presumed to change at the rate of one vote (on the 7 point scale) per 2 K change in operative temperature" (p. 12).

2.4.2 Dutch ISSO 74-2004/2014

This is another adaptive standard used to assess thermal comfort in unconditioned, mixed-mode, and conditioned spaces (Hamdy et al., 2017). Like ASHRAE 55, ISSO is based on data from the RP-884 database. Moreover, the ISSO algorithm for thermal neutrality is in the same manner as the RP-884 project (De Dear et al., 2020).

ISSO followed two application scenarios, namely, Alpha-space and beta-space. The first one is “free-running situations in summer with operable windows and a non-strict clothing policy for the occupants”, and the second one is related to those “which primarily rely on centrally-controlled cooling in summer.” (De Dear et al., 2020, p. 14).

Compared to the 2004 version, in the 2014 version of ISSO, four types of changes were applied: (1) Considering specific interior spaces rather than the entire building. (2) Being based on a smaller and entirely European SCATs database. (3) Division of temperature conditions in four classes instead of three classes, and (4) Adopting a different method in calculating the outdoor temperature and adopting 7-day outdoor temperature horizon instead of 3-day temperature horizon (De Dear et al., 2020).

2.4.3 GB/T 50785

GB/T 50785 standard is a Chinese comfort standard for free-running buildings. This standard is based on a field study, and its data source comes from fourteen major cities in China with five climate zones (Li et al., 2018). The topology of the buildings assessed in this standard is public buildings, such as official and educational buildings, and multi-family residential buildings (De Dear et al., 2020; Xu et al., 2016).

The process of conducting field studies included 28,000 subjects by coverage of summer, winter, spring, and autumn seasons. In this standard, a graphical method has been applied for calculating neutral temperature, and for adopting a climate temperature index, a running mean temperature was used (De Dear et al., 2020). Using a graphical method to calculate the neutral temperature in this standard is an approach similar to that of ASHRAE 55-2013. Also, there are three categories for describing operative temperature: (I) “a still air comfort zone (<0.15 m/s)” (II) “the rest of the acceptable area”, and (III) “unacceptable temperatures” (Khovalyg et al., 2020).

3 Data-Driven Thermal Comfort Models

Since the second decade of the twenty-first century, rapid advances in statistic science have brought new approaches and methods into the human thermal comfort field. Since 2016, using IoT sensing technologies, big data, machine learning, and deep learning techniques has been more popular among researchers to assess thermal comfort (Zhao et al., 2014). These models in the context of human thermal comfort are known as data-driven models (Gao et al., 2021). The ability to simulate different situations and use new methods in data management, classification, and analysis can be one of the advantages of data-driven models.

A variety of algorithms based on new analytical methods and tools can be seen in previous literature. In the next section some of the frequently used data-driven models that have been applied for assessing thermal comfort are described.

3.1 Gaussian Naïve Bayes (GNB) Algorithm

This algorithm is a defined kind of naïve Bayes algorithm. This algorithm can be used in a situation where the requested variables (P) have non-interrupted values to solve. When we work with real-time data in thermal comfort analysis and have this assumption that the data (objectives) (x) associated with each class (y) is regularly distributed with a Gaussian distribution, we can use the GNB algorithm. In fact, this algorithm helps us to have a model with high-performance capability, high training speed, and the ability to correctly predict the characteristics of the data belonging to each class (Srivastava, 2020). At the following, Fig. 3 shows the function of GNB classifier.

According to Fig. 3 and as it has been stated by Raizada and Lee (2013), in the assessment process of GNB algorithm, "for each data point, the z-score distance between that point and each class-mean is calculated, namely the distance from the class mean divided by the standard deviation of that class " (p. 2).

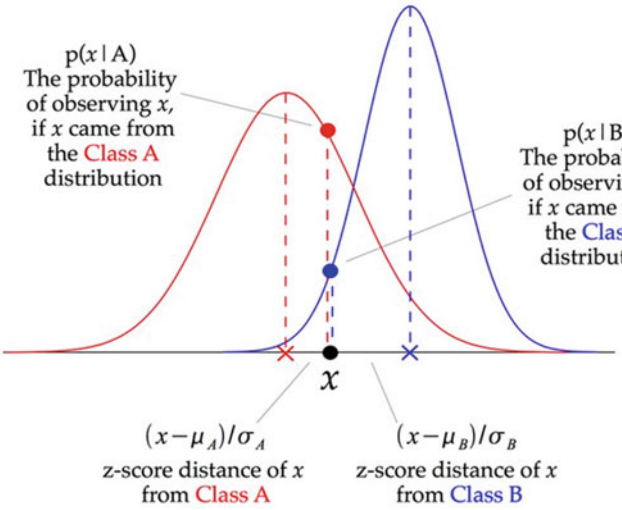

Fig. 3 The function of GNB classifier (Adapted from Raizada & Lee, 2013)

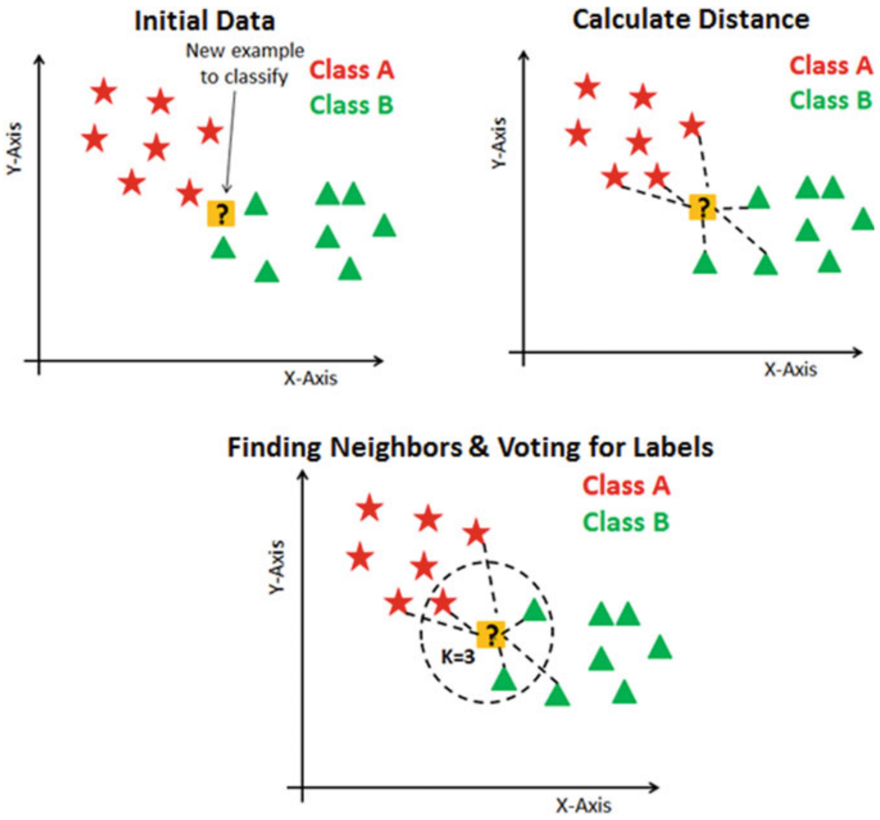

Fig. 4 An example of KNN diagram[2]

3.2 *K-Nearest Neighbor*

K-Nearest Neighbor algorithm (KNN) is known as a supervised machine learning algorithm that can be applied to either classification or predictive regression problems (Xiong & Yao, 2021). The main assumption in this algorithm is that similar points can be placed next to each other (Wang et al., 2019). As can be seen in Fig. 4, for assessing classification problems, a class label is produced considering the majority vote. The meaning of "majority voting" is applying majority of over 50% of vote when just two classes have established the data.[1]

Besides the same manner as classification problems, for regression problems, it is important taking into account the average of the k (as a tuning parameter) nearest neighbors for creating a prediction about a classification (García-Laencina et al.,

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[1] https://www.ibm.com/topics/knn.

[2] https://www.datacamp.com/tutorial/k-nearest-neighbor-classification-scikit-learn.

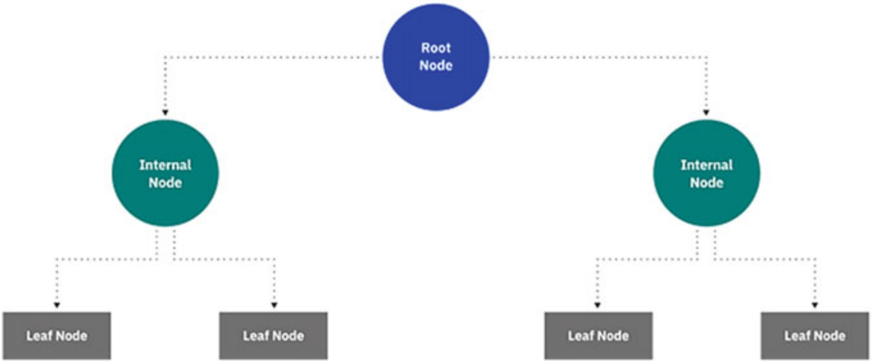

Fig. 5 The structure of DT algorithm[3]

2015). Contrary to classification in which discrete values are used, it is considered continuous values for regression (Gu et al., 2018).

3.3 *Decision Tree*

Known as a non-parametric supervised learning algorithm, Decision Tree (DT) is used for both classification and regression tasks (Ramosaj & Pauly, 2019). This algorithm advances the work of analysis by creating a hierarchical tree graph that expands the partition of a dependent or target variable by multiple independent variables. By this partitioning, the strength of relationships in a dataset is determined through the size of the split at each step (Vellei et al., 2017).

Based on Fig. 5, the structure of DT has been established by a hierarchical structure, which includes a root node, branches, internal nodes, and leaf nodes (Shorabeh et al., 2022).

The analysis process in this algorithm starts from the *root node* and the data space divides into several regions as new nodes. By repeating this process, some more new nodes are created. In the tree-shaped structure of the algorithm, each branch of the tree finishes in a *leaf node*. Leaf nodes provide categories that are the best interpretation of the state of the respective regions as long as the data cannot be further divided than the current state (Vellei et al., 2017).

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[3] https://www.ibm.com/topics/decision-trees.

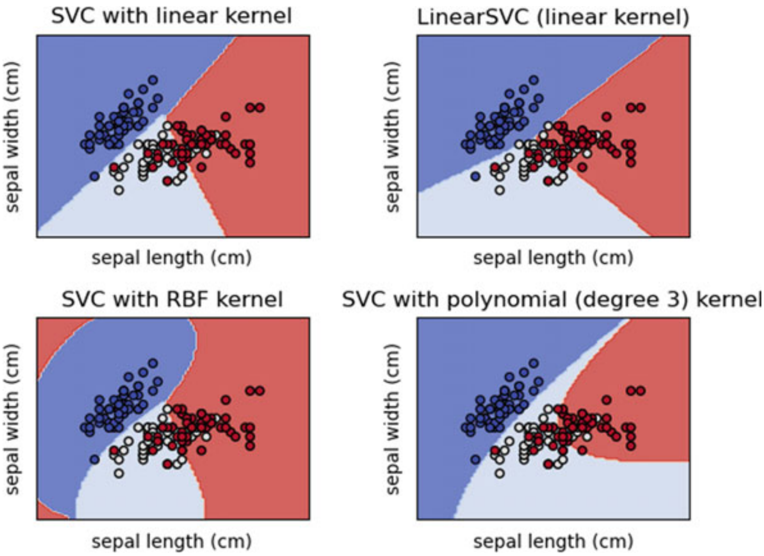

Fig. 6 Examples of SVM outputs by using multiple kernel functions[4]

3.4 Support Vector Machine

Support Vector Machine (SVM) is a supervised learning model related to learning algorithms that analyze data for both classification and regression analysis. Due to generalization ability, SVM classifiers are widely used in the previous literature (Du et al., 2020).

Besides making linear classification, SVMs are able to accomplish a non-linear classification using kernel trick and mapping their data into high-dimensional feature spaces (Tiwari, 2022). in fact, The SVM algorithm can create a variety of learning machines by applying different kernel functions (Du et al., 2020). Figure 6 illustrates SVM classifier outputs by applying multiple kernel functions.

3.5 Random Forest

Random Forest (RF) is a commonly-used machine learning algorithm that provides a single result by the combination of multiple decision tree outputs. RF also handles both classification and regression problems. Regarding this, as stated by Vellei et al. (2017) RF "is an ensemble of tree-based models and can be used for classification tasks when the base models are classification trees, or regression tasks when the base models are regression trees" (p. 18).

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[4] https://scikit-learn.org/stable/modules/svm.html.

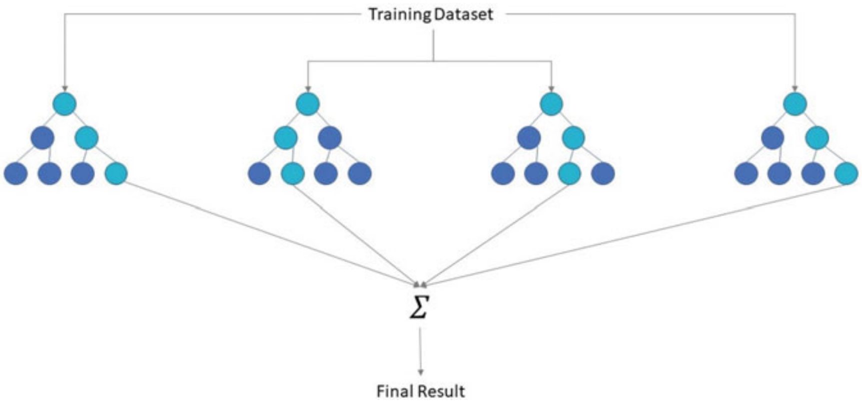

Fig. 7 A diagram of RF[5]

Three main hyperparameters exist in RF: node size, tree numbers, and the number of features sampled (Lulli et al., 2019). Overall, the advantages of this algorithm include its use in big data, being resistant to outliers, dealing with simple and complex linear relationships, and creating competitive prediction accuracy in high-dimensional data (Han & Kim, 2021). Figure 7 shows a diagram of RF.

4 Comparison of the Knowledge-Based and Data-Driven Models

As revealed in this study, the models that are known as thermal comfort models are classified into knowledge-based models and data driven models. The knowledge-based models, called traditional models, started to apply in the thermal comfort analysis in 1970 (Carlucci et al., 2018). In between, the data-driven models became famous, especially since the last decade (Schwieker, 2022). Historically, these two kinds of models have been raised in different times. In fact, considerable advances in analytical and statistical tools make significant differences among them (Park & Nagy, 2018).

The main difference between these models is based on the methodological approach. In this regard, in the knowledge-based thermal comfort models, researchers use laboratory and field studies to obtain and analyze data (De Dear et al., 2020; Zheng et al., 2021). The data are also analyzed considering some pre-articulated standards for assessing the results (De Dear et al., 2020). The analysis process is time-consuming, and the accuracy of the results may be low. Moreover, these models use a series of mathematical deductions with certain inputs, for example, clothing thermal resistance, ambient temperature, and wind speed, to obtain outputs

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[5] https://www.ibm.com/cloud/learn/random-forest.

(Zhao et al., 2021). Carlucci et al. (2018) state that despite promoting the uptake of knowledge-based models, especially adaptive comfort models by practitioners and designers, full exploitation of these models is impossible due to uncertainties related to their application.

On the contrary, data-driven models are flexible and utilize new advanced statistical tools and software (Feng et al., 2022; Park & Nagy, 2018). These models provide and facilitate using big data and simulating different and various situations in the thermal comfort analysis for researchers. This means that the data can be analyzed simultaneously in different and diverse conditions with several statistical methods, and a better comparison of the results can be obtained (Zhao et al., 2014, 2021). In fact, they are established based on big data, machine learning and deep learning algorithms, and neural network and provide high matching of input and output for assessing thermal comfort. Under this circumstance, the prediction accuracy is improved, and the possible errors are reduced (Feng et al., 2022; Zhao et al., 2021). As stated by Zhao et al. (2021) "data-driven models can make accurate and efficient prediction of individual thermal comfort, which will also make the thermal comfort model more practical and have more life-oriented applications" (p. 31).

Overall, compared to the inflexibility, relatively limited amount of data, time-consuming process, and the use of relatively old methods in knowledge-based models, data-driven models are flexible, use new and various methods and big data, and have high efficiency in complex conditions. All these conditions have caused researchers to benefit more from data-driven models in studies related to thermal comfort.

5 Conclusions

Considering the recent transformations of urbanization and the increasing trend of climate change in cities around the world, the issues of urban heat islands and moving toward cool cities and having thermal comfort are essential for urban dwellers. To reach and assess thermal comfort in cities, numerous models and assessment frameworks have been accomplished. According to the literature, there are two major classifications for describing thermal comfort assessment frameworks and models. They are knowledge-based models and data-driven models.

Knowledge-based models and tools are known as traditional methods that have gained their ground among scholars since 1970. These kinds of thermal comfort models obtain their data through both laboratory and field studies. They are divided into heat balance models and adaptive models. Adaptive models and standards have played a pivotal role in transformations and considerable development of thermal comfort models and assessment tools in the past three decades.

Since last decade and following massive transformations and advances in statistics and analytical tools, IoT and smart simulation algorithms based on deep and machine learning have been widely used for assessment of thermal comfort in cities. They are known as data-driven models, which use big data and simulate a variety of situations to analyze and explain an individual's thermal comfort. As we have shown in this study, data-driven models have some major advantages compared to knowledge-based models. These advantages are summarized as: the capability to use big data, the ability to achieve a high level of prediction, robustness to outliers, and the ability to deal withcomplex situations.

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Chapter 15
Who Benefits More from Urban Cooling Strategies? Exploring Climate Justice in Vulnerable Groups' Access to Blue-Green Infrastructure in Mashhad City, Iran

Safoora Mokhtarzadeh and Mahdi Suleimany

Abstract Climate change and consequently global warming have made the decision-makers adopt a set of urban cooling strategies and policies. These policies, the most common of which is the development of blue-green infrastructures, lead to a decrease in the ambient temperature of cities. However, many studies suggest that the uneven development of these infrastructures has led to climate injustice in many cities. In other words, developing blue-green infrastructure to meet predefined standards is one side of the coin in coping with global warming, which indicates the efficiency of urban resiliency measures. While ensuring equitable access to these services and infrastructures is the other side, which shows the effectiveness of adaptation programs. Therefore, in this research, we have analysed climate justice in a case (Mashhad metropolis, Iran) considering vulnerable groups' access to blue-green infrastructure. We have implemented spatial analysis techniques and multi-scale geographic weighted regression (MGWR) model to identify the patterns of the aforementioned climate (in)justice at two scales of city and neighbourhoods. The results have indicated the significant climate injustice in low-income groups' access to blue and green infrastructures on both scales. Besides, the findings have depicted patterns of climate injustice in the access of sensitive age groups, the disabled, and immigrants to blue infrastructure. The most important reason for this injustice is the uneven distribution and development of blue infrastructures and their spatial concentration in the western half of the city which arose from the inequitable decisions of city management and planning. Although these findings are context-specific, the research process is applicable to any other context. We have also provided some recommendations to promote climate justice in the adoption of urban cooling policies.

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Keywords Blue-green infrastructure · Climate justice · Vulnerable groups · Multi-scale geographically weighted regression (MGWR) · Mashhad city

1 Introduction

The persistent global warming in both air and surface temperatures has imposed significant challenges to the planning and decision-making systems at different scales. These challenges, which include a wide range of physical and non-physical issues, have become one of the main concerns of many cities worldwide (Carter et al., 2015; FAO, 2015). The reduction of thermal comfort in human settlements (Hosseini et al., 2022), casualties due to heat waves (CDC, 2020), and the increase in the intensity of urban heat islands (Hsu et al., 2021) are common examples of the aforesaid global warming impacts on various cities. Many cities around the world have adopted urban cooling strategies to cope with these challenges. Urban cooling strategies are a set of spatial policies and physical regulations that benefit urban communities to mitigate the impacts of global warming and adapt to changing climatic conditions (Gunawardena et al., 2017).

Urban cooling strategies, which are discussed in detail in the next section, include public policies and measures that reduce citizens' exposure to heat stress and waves. These strategies include multiscalar decisions from micro (i.e. building structure and design) and meso-scale (i.e. urban blocks and neighbourhood layout and design) regulations to macro policies. Furthermore, many municipalities have allocated part of their public budget to the implementation of these policies and regulations (Cheshmehzangi & Dawodu, 2020). The improvement of green infrastructure (including urban gardens, street trees, and drains) and water bodies (such as urban streams) are prevalent forms of these policies in different urban cases (Marando et al., 2022). Numerous studies and simulations have indicated the significant effect of blue-green infrastructures on urban thermal comfort and the reduction of urban heat island intensity (Li et al., 2022).

Considering that global warming and heat waves are not limited to geographical boundaries, decision-makers must somehow adopt urban cooling strategies that benefit all citizens, especially vulnerable groups (Gunawardena et al., 2017). Planners must ensure equitable access to blue-green infrastructure in cities. Particularly, sensitive groups, such as children, the elderly, the disabled, immigrants, and low-income households, who are more vulnerable to heat waves and climate crises, should be less exposed to these stresses and have proper access to blue-green infrastructure (McMillan et al., 2022). Supporting climate justice in cities and planning to improve blue-green infrastructure are among the fundamental efforts in building climate-resilient communities and sustainable development. Constant monitoring, assessment, and context-specific planning are essential to maintain urban climate justice (Steele et al., 2015).

Funding the urban cooling strategies and the development of the blue-green infrastructures from the public budget, along with the significant need of vulnerable groups to access these infrastructures in the climate change era, face us with two research questions; 1—How is the access of vulnerable groups to blue-green infrastructure in cities compared to other citizens?, 2—What policies and solutions are there to promote climate justice in the adoption and implementation of urban cooling strategies? Indeed, in this study, we seek to explore and assess climate justice in the access of vulnerable groups to blue-green infrastructure. Researching to answer these questions in this study enables us to comprehend how to ensure the equitable distribution of policies and measures (specifically urban cooling) in coping with global warming and climate change.

To answer the research questions and develop a theoretical framework, we have first reviewed urban cooling strategies and climate justice philosophy. Then, using spatial analysis techniques, we investigated climate justice in the access of vulnerable groups to blue-green infrastructure in the case study. Finally, by analysing the obtained results, we provided recommendations to promote climate justice and develop blue-green infrastructure in the case. The contribution of this study to the literature is to provide a process for exploring and assessing urban climate justice with an emphasis on the development of blue-green infrastructure. The process of this study, which has been implemented on a case in this article, helps decision-makers to assess the fairness of their actions in coping with global warming and urban heat waves and to promote climate justice in cities.

2 Cooling Cities with Blue-Green Infrastructure

Global warming, extreme heat waves, and urban heat islands are intense challenges for human settlements today and tomorrow, which impose many consequences on the socio-economic structure of communities. Extreme heat leads to an increase in energy consumption on a large scale and endangers the public health of communities. Numerous studies and reports suggest that extreme temperatures significantly increase mortality rates, particularly among vulnerable groups (CDC, 2020; Tong et al., 2021). Besides climate change and global warming as driving factors, several contextual characteristics influence the temperature of urban environments. Urban form by directing wind and heat flow, reflective surfaces, and blue-green infrastructure are among the most important of these characteristics (Abdulateef & Al-Alwan, 2022; Ibrahim, 2021).

Urban cooling strategies are a wide range of policies and measures to reduce ambient temperature and mitigate the heat exposure of citizens (Khosla et al., 2021). Most of these policies and measures fall into two main cooling strategies: 1—implementing "cool materials" with high solar reflectance as pavements and buildings' façades; and 2—developing blue-green infrastructure which causes passive cooling through evaporation, environmental transpiration, and shading (Hayes et al., 2022; Peng et al., 2020). Green infrastructure refers to any form of urban vegetation, including forests, agricultural fields, pastures, lawns, parks, private gardens, green roofs, green walls, and other facilities; And blue infrastructure directs to water bodies (both natural and artificial) such as lakes, water reservoirs, rivers, wetlands, swamps, water engineering facilities, and the like (Cao et al., 2022; Sanusi & Jalil, 2021).

Blue-green infrastructures diminish the temperature and mitigate the UHI effect through two main natural processes: 1—shading on urban surfaces; 2—improving environmental humidification and evapotranspiration (Antoszewski et al., 2020). While green infrastructure is widely known to reduce the adverse effects of urban heat, the impacts of blue infrastructure to regulate thermal comfort are still understudied (Balany et al., 2022). Blue infrastructure is an essential factor of the urban environment responsible for many ecological services whose UHI mitigation functions are often overlooked. This is because the effect of water facilities in reducing the urban heat is seasonal, and the cooling impacts of reservoirs and waterways are strongly influenced by wind speed and direction. However, blue-green infrastructure as a planned network, could combine natural and designed landscapes in urban areas and embed the spaces aiming to provide various environmental benefits, including urban cooling (Gunawardena et al., 2017).

Blue-green infrastructures and their functional connections and interrelationships within and adjacent to cities have the potential to provide a wide range of ecosystem services for urban residents (Andersson et al., 2019). Besides modifying urgent issues such as rising temperature, and poor environmental quality, these infrastructures can help alleviate broader challenges of urban sustainability, like the need for outdoor recreation, improvement in mental health, and improved socialisation of the community residents by spaces for social activities (Kabisch et al., 2017). The improvement and fair distribution of blue-green infrastructure in cities as nature-based solutions can significantly reduce the ambient temperature of urban spaces. Therefore, the urban decision-making systems should ensure proper and fair access to these infrastructure to mitigate heat exposure of citizens, particularly vulnerable groups, and advance the climatic adaptability of communities (Silva et al., 2018).

3 Climate Justice

Urban cooling strategies have been adopted in many cities to cope with global warming as one of the consequences of climate change. However, studies have indicated that due to the lack of balance and climate justice in the adoption of these strategies and the implementation of related policies, efforts to curb the consequences of global warming have failed in some cases (Juhola et al., 2022). To comprehend the philosophy of climate justice, we must foremost understand the following key aspects:

1. There is no equal responsibility and burden for climate change and global warming
2. Some people and groups are more vulnerable to global warming impacts. There is no equal suffering from climate change and crises

3. This vulnerability arises from the political, economic, and social trends in the communities that led some to have fewer and worse facilities and conditions in face of climate crises
4. The mechanisms of disadvantage ingrained in the current economic systems will cause climate change impacts to worsen as more people live in developing countries
5. Vulnerability and inequality may be exacerbated or maintained by some unequal climate change policies, and uneven distribution of services and infrastructures (Steele et al., 2015).

Climate justice is a broad and common concept in the literature of planning and climate change, and several definitions have been provided for it. In common, climate justice refers to the fair division, equitable sharing, and just distribution of the advantages and disadvantages of climate change in addition to the responsibilities and facilities to cope with its consequences (Schlosberg & Collins, 2014). Considering vulnerable socio-economic groups in climate adaptation programs, including urban cooling strategies, is one of the main prerequisites for improving climate justice. Since vulnerability to climate crises is context-specific, it is necessary to diagnose mitigation and adaptation needs among societal groups to ensure climate justice (Juhola et al., 2022).

Considering that climate justice has a lot in common with social and distributive (spatial) justice, in this research we seek to investigate the distribution of blue-green infrastructure to vulnerable groups (those who suffer more). Fair distribution in climate change adaptation plans and measures, including urban cooling strategies, is one of the foundations of climate justice in communities. This fair distribution requires constant monitoring of adaptation regulations and policies and also evaluation of vulnerable groups' access to blue-green infrastructure (Carter et al., 2015). Although the definition and extent of vulnerable groups vary in different studies and contexts, in common, four vulnerable groups can be identified according to global warming:

1. Sensitive age groups, including children and the elderly, are more vulnerable to extreme heat and urban heat waves due to their physical condition (Meade et al., 2020).
2. Disabled people have less ability to face bad climatic conditions due to physical or mental problems (Mitchell & Chakraborty, 2015).
3. Immigrants are often more vulnerable to extreme heat due to their low adjustment to climatic conditions (Black et al., 2016).
4. Low-income households are often more exposed to extreme heat and urban heat waves due to less access to HVAC[1] systems and public or welfare services (Sandholz et al., 2021).

Some studies have also measured climate justice concerning women (gender equality), ethnicities, and different races (Mashhoodi, 2021). Although these efforts led to the study of climate justice in further dimensions, as mentioned, the concept

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[1] **H**eating, **V**entilation, and **A**ir **C**onditioning.

of vulnerability to climate change and global warming is contextual and should be determined according to existing social, economic, and institutional trends (Fitzgibbons & Mitchell, 2021). The aforementioned groups should be less exposed to climate crises and heat waves due to various limitations and weaknesses. Therefore, these groups should have proper access to the blue-green infrastructure on different scales. Figure 1 represents the conceptual theoretical framework of the study based on the discussed literature.

4 Material and Method

We used spatial analysis techniques to evaluate climate justice considering the access of the four mentioned vulnerable groups to blue-green infrastructure. This analysis included three main steps: data collection, model implementation, and interpretation of findings.

4.1 Data Collection

The data required for this analysis contained demographic information of vulnerable groups in the case study and spatial maps of blue-green infrastructures. We collected demographic information from national census data, which was at the scale of urban blocks. We obtained spatial maps of blue-green infrastructures by remote sensing and satellite image processing, since there were no documented up-to-date and accurate maps of the case blue-green infrastructures. We used the map of the normalized difference vegetation index (NDVI) to determine green infrastructure and the map of the normalized difference water index (NDWI) to determine water bodies (Labib & Harris, 2018). We prepared these indicators by processing Landsat 8 Collection 1 Level-1 satellite images from the https://earthexplorer.usgs.gov/ database. Table 1 represents more details of the collected data.

4.2 Model Implementation

We implemented multi-scale geographically weighted regression (MGWR) model to analyse the spatial accessibility of vulnerable groups to blue-green infrastructure in the case. Geographically weighted regression (GWR) is a geographical statistical approach that addresses the potential limitations of conventional "global" regression models in cases where spatial processes differ depending on the context of the data (Oshan et al., 2019). This model analyses the influence and relationship between independent and dependent variables according to the change of data on the same spatial scale. MGWR is a new modification to the GWR framework that enables each

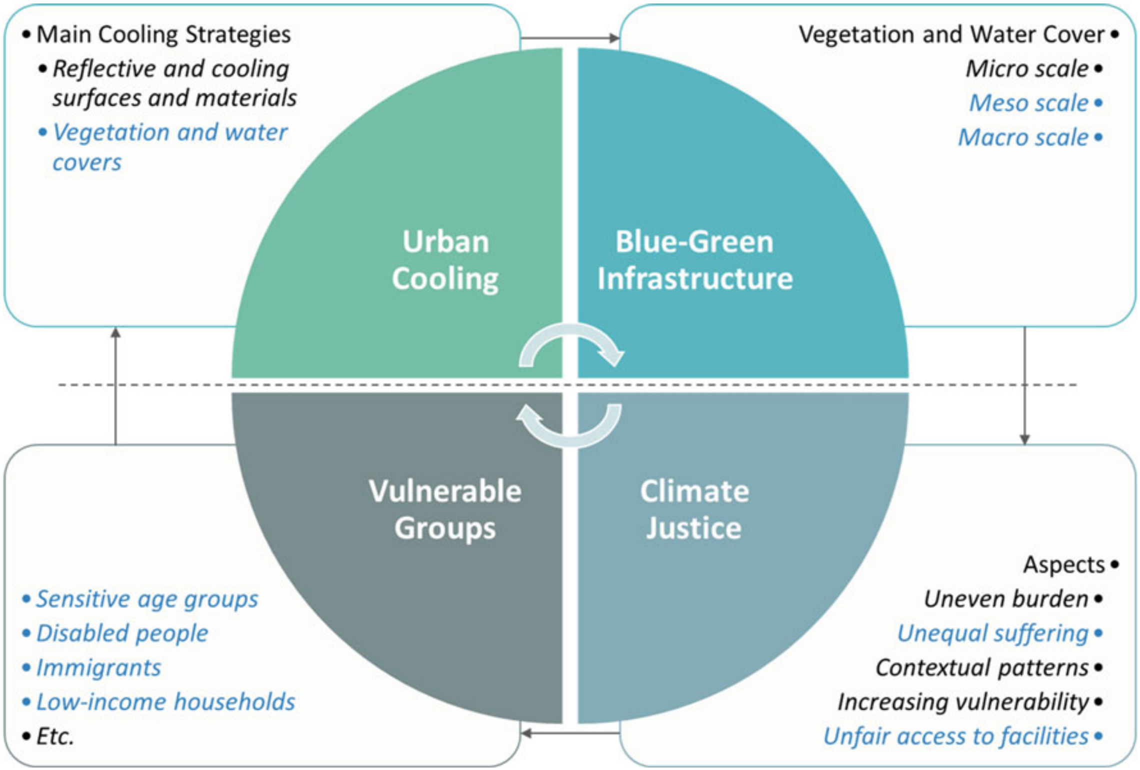

Fig. 1 Conceptual theoretical framework of the study (*Source* Authors)

Table 1 List of data and information used in the research and their sources

Category	Data/information	Scale	Source
Vulnerable groups	Rate of children (less than 10 years old) or elderly people (over 60 years old) residing	Urban Block	National 2015 Census Data
	Rate of residents with any physical or mental disabilities	Urban Block	National 2010 Census Data
	Rate of residents who migrated to the city less than 10 years ago	Urban Block	National 2015 Census Data
	Rate of unemployed residents or those with low-income jobs	Urban Block	National 2010 Census Data
Infrastructures	Green infrastructure (area with the NDVI higher than 0.1)	Map (with 30.m pixel resolution)	Landsat 8 2013–2015 Images
	Water Bodies (area with the NDWI higher than 0.0)	Map (with 30.m pixel resolution)	Landsat 8 2013–2015 Images

Source Authors

connection to change at a different spatial scale. Since the connection between the answer and independent variables is permitted to fluctuate locally, regionally, or not at all, MGWR is significantly less constrained in its deductions than GWR (Stewart Fotheringham et al., 2017).

To implement the MGWR model, we ran MGWR 2.2 open source application which was developed by Arizona State University based on Oshan et al. (2019) proposed python codes (Oshan et al., 2019).[2] First, we calculated the population rate of each vulnerable group and the area rate of blue-green infrastructure for neighbourhoods with ArcMap software. We did this to reduce the number of calculations and enable the examination of changes at the city scale. Subsequently, we extracted the information of each neighbourhood, including the data related to vulnerable groups and blue-green infrastructures, as well as the geographical coordinates of the centre of each neighbourhood to a spreadsheet. We separately defined the blue-green infrastructure area rate of each neighbourhood as the response variable and each vulnerable group population rate as the covariate. Therefore, we implemented this model twice, once to measure climate justice in the access of vulnerable groups to green infrastructure and once in their access to water bodies.

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[2] This free software is accessible at: https://sgsup.asu.edu/sparc/multiscale-gwr.

4.3 Interpretation of Findings

In the neighbourhoods where the regression coefficient is significant (p-value < 0.05), if the regression coefficient is positive, it indicates that vulnerable groups have more access to blue-green infrastructure in the case, and if it is negative, it suggests that these groups have less access to blue-green infrastructure. The global regression, if significant, is interpreted in the same way and indicates climate (in)justice at the city scale.

4.4 Case Study: Mashhad Metropolis, Iran

The case study of this research is the Mashhad metropolis, the second-largest metropolis of Iran, and the centre of Khorasan Razavi province. This city is located in the northeast of Iran and has a population of about 3 million people. The city's latitude is from 36:37′ to 36:58′ north and the longitude is 59:26′ to 59:44′ east, and it has an area of about 300 square kilometres (Mansouri Daneshvar et al., 2019). According to the Köppen-Geiger climate classification, Mashhad city has a dry climate It has cool winters and hot summers. The city has an average annual rainfall of 250 mm (9.8 in), and summers have high temperatures that sometimes exceed 35 °C (Naserikia et al., 2019).

Mashhad metropolis experienced rapid growth from 1988 to 2017, along with intense land cover change. Its cultural, religious, and economic attractions have caused many people to travel or migrate to this city for different purposes. This has led to a dramatic increase in construction, especially in recent decades. With the vast increase in population and the development of built areas and infrastructure, a significant area of vegetation and ecosystem services have been converted into built-up surfaces (Soltanifard & Aliabadi, 2019). Furthermore, climate change has manifested in prolonged periods of drought and, as a result, reduced water levels (blue area) in the city. These changes, along with socio-economic inequalities and widespread marginalization, especially in the northern and eastern parts of the city, have caused inequitable access to urban services for some socio-economic groups (Mansouri Daneshvar et al., 2019). Today, the intensification of urban heat islands and the increase in land and air temperatures are instances of the climatic challenges of the Mashhad metropolis. With the growth of the built area, the natural vegetation cover has decreased and been replaced by urban uses and built coatings such as concrete and asphalt, which leads to additional heat on mutual surfaces (Naserikia et al., 2019). Figure 2 represents the geographical and political location and blue-green infrastructures of the Mashhad metropolis.

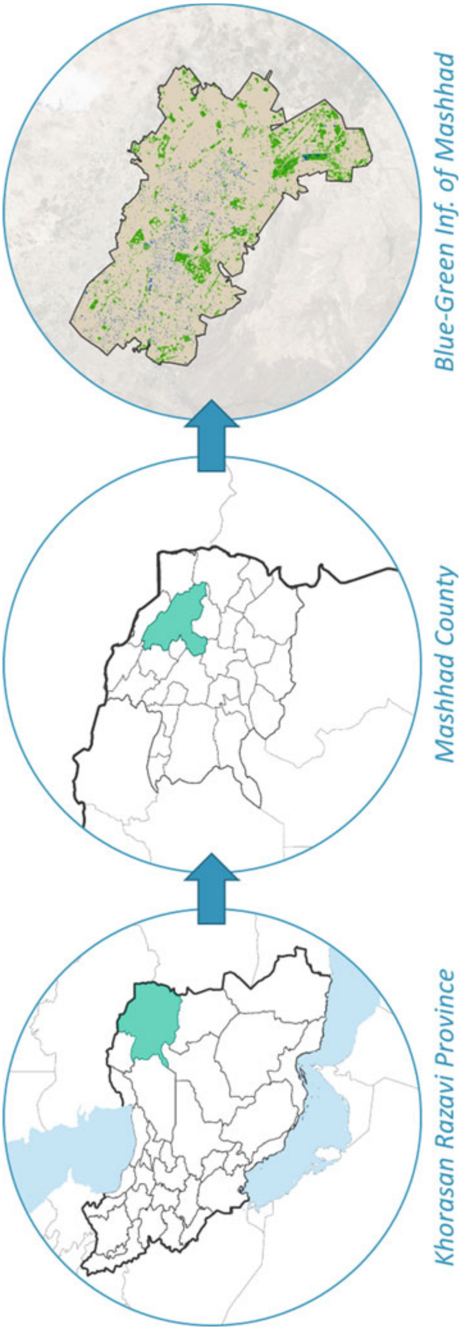

Fig. 2 Location and blue-green infrastructures of the Mashhad metropolis (*Source* Authors)

5 Findings and Discussion

Developing blue-green infrastructure and safeguarding ecosystem services to meet predefined standards is one side of the coin in coping with global warming, which indicates the efficiency of urban governance resiliency measures. While ensuring equitable access to these infrastructures and services is the other side of the coin, which shows the effectiveness of adaptation measures and programs (Ambrey et al., 2017; Coutts & Hahn, 2015).

We have analysed the access of vulnerable groups to blue-green infrastructure in the Mashhad metropolis to evaluate climate justice, in two global scale and spatial units, comparisons by neighbourhoods. Table 2 represents the global regression results. Global regression results demonstrate no significant injustice in access to green infrastructure. This implies that access to green infrastructure is equitable at the city scale. In contrast, the results of the global regression indicate a severe injustice in the access of low-income people to blue infrastructure. This can lead to an increase in the heat exposure rate of these people and intensify their vulnerability.

Considering that the purpose of this research is not to find the cause and analyse the effect, the moderate value of *R*-square can be justified. However, adding physical and environmental vulnerability variables to the model, as a control variable, can increase the explained variation of the model (Mashhoodi, 2021). Although the global regression results show only one pattern of injustice at the city scale, the MGWR results indicate different spatial patterns of climate injustice at the neighbourhood scale. Figures 3 and 4 depict the significant results related to access to blue and green infrastructure. In these maps, the orange spectrum reflects the injustice in the access of vulnerable groups to blue or green infrastructure. While the green spectrum means that the vulnerable group has more access to these infrastructures than other citizens.

Table 2 The results of global regression by separating access to blue and green infrastructure

Access to green infrastructure				Access to blue infrastructure			
Variable	β value	t(β/SE)	*p*-value	Variable	β value	t(β/SE)	*p*-value
Aged rate	−0.121	−1.193	0.233	Aged rate	−0.046	−0.467	0.640
Disabled	−0.428	−1.763	0.078	Disabled	0.840	3.527	0.000
Immigrant	0.149	1.466	0.143	Immigrant	0.140	1.409	0.159
Low income	0.385	1.601	0.109	Low income	−0.733	−3.114	0.002
R^2		0.482		R^2		0.429	
Adj.R^2		0.461		Adj.R^2		0.419	

Source Authors—Output of MGWR software

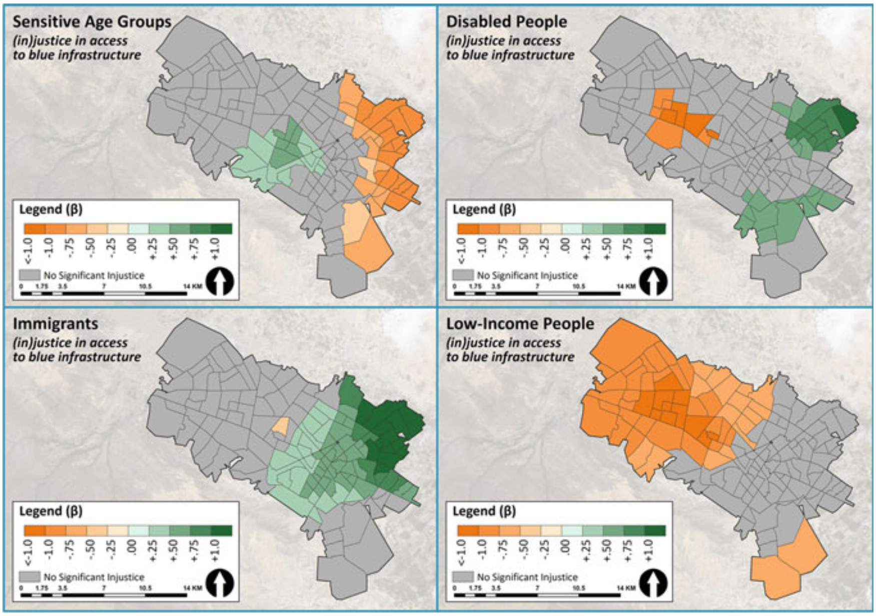

Fig. 3 Spatial patterns of climate injustice in access to blue infrastructure at Mashhad metropolis (*Source* Authors)

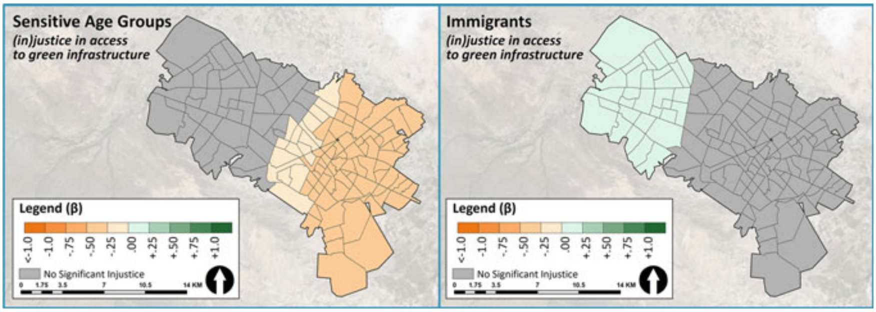

Fig. 4 Spatial patterns of climate injustice in access to green infrastructure at Mashhad (There is no significant association among the disabled or low-income population with the area of GI in neighbourhoods) (*Source* Authors)

5.1 Low-Income Groups' Access to Blue-Green Infrastructure

The analysis of the distribution of blue-green infrastructures in the Mashhad metropolis, concerning the low-income residents in the neighbourhood scale, indicates that there is no significant injustice in the access of this group to green infrastructures. Since a major part of the city's green infrastructure dates back to before modern planning and new designs, the remaining green areas and gardens are from the rural backgrounds of the neighbourhoods. Therefore, there is no specific spatial concentration of these lands in different parts of the city (Naserikia et al., 2019). Furthermore, the green infrastructure in the Mashhad suburbs is very scattered and dependent on the surrounding agricultural lands and does not have a significant correlation with the income of settled citizens. In contrast, there is an intense injustice in the access of low-income people to blue infrastructure in the central and western neighbourhoods.

Mashhad metropolis does not have any other natural blue infrastructure (e.g. rivers or lakes) except a seasonal waterway in the north-western part. This waterway is often dry in recent years due to successive droughts. Therefore, most of the blue infrastructures in Mashhad are artificial and built. These areas are often blue infrastructures in local and urban parks (such as ponds or artificial lakes) or water facilities related to tree irrigation or street green axes. The distribution of these infrastructures shows that the marginal areas of Mashhad city, especially the northern, north-eastern, and eastern margins, are the most deprived of these infrastructures. Therefore, as blue infrastructures have been affected by recent city plans more than green infrastructures in the Mashhad metropolis, these infrastructures have been unfairly distributed throughout the city. Blue infrastructures are often spatially concentrated in the central and western neighbourhoods where high-income groups have settled and there is a significant injustice in the access of low-income groups to these infrastructures.

5.2 Sensitive Age Groups' Access to Blue-Green Infrastructure

Sensitive age groups, including children and the elderly, have a greater spatial concentration in the central and eastern neighbourhoods of Mashhad. Most of the natives and people with a long history of residence in Mashhad have settled in these parts which caused more elderly people to live in these areas. Furthermore, the high rate of Afghan refugees and the residence of low-income groups in the northern and eastern marginal areas made the average family size and the number of children to be more due to socio-cultural issues (Mokhtarzadeh et al., 2012). Therefore, we can expect a significant correlation between these sensitive groups and blue-green infrastructures in these parts.

Analysing the changes in the green infrastructure of Mashhad metropolis from 1988 to 2017 reveals that a large part of the inner natural green area and infrastructure, especially in the north-eastern and eastern neighbourhoods, has been degraded. In contrast, many parts of the green areas in the western neighbourhoods have been preserved and most of them are gardens owned by private sectors and less used publicly (Naserikia et al., 2019). Therefore, the high population of the elderly and children and the considerable degradation of green infrastructure have led to intense patterns of climate injustice in the access of sensitive age groups to green infrastructure in the eastern neighbourhoods.

The access of sensitive age groups to blue infrastructure is also relatively less in the eastern neighbourhoods. The poor development of blue infrastructure along with the high population of sensitive age groups in eastern parts are the main reasons for this inequality. However, sensitive age groups have relatively more access to blue infrastructure in several wealthy neighbourhoods in the central districts. The difference in the access of vulnerable groups to blue infrastructure in the eastern and western areas clearly shows the role of urban planning and management decisions in the unfair development of this infrastructure and the aggravation of climate injustice in the Mashhad metropolis.

5.3 Immigrants' Access to Blue-Green Infrastructure

Immigrants living in the Mashhad metropolis generally include two groups; Iranian immigrants and Afghan refugees. Most Iranian immigrants are relatively wealthy households who immigrated to the city due to its religious and economic attractions and settled mainly in the western areas. While Afghan refugees are often low-income people who mostly live in the northern and eastern suburbs, according to some field surveys (Mokhtarzadeh et al., 2012). However, due to informal migration and lack of legal identification documents, many refugees are not counted in national censuses. Therefore, the results of immigrants' access to blue-green infrastructure in the eastern and northern areas of the city cannot be discussed and followed up. But in the western neighbourhoods, due to the residence of more Iranian immigrants and the high spatial concentration of private gardens and meso-scale green infrastructure, the immigrants relatively benefit from better access to green infrastructure and green areas.

5.4 Disabled People Access to Blue-Green Infrastructure

There are fewer cases of climate injustice in the access of disabled people to blue infrastructure at the neighbourhood scale. This is due to the low number of disabled people in the city and their residential concentration in areas with an average level of blue infrastructure. It should also be noted that there is no significant injustice in the access of disabled people to green infrastructure at the neighbourhood scale.

6 Conclusion and Recommendations

In this research, we have analysed climate justice in Mashhad city concerning the access of vulnerable groups to blue-green infrastructure. We have implemented spatial analysis techniques and multi-scale geographic weighted regression (MGWR) model to identify and investigate climate injustice patterns. Although the research results (patterns of climate injustice) are context-specific, the research process is applicable to any context. In other words, urban decision-makers can implement this study process to measure climate justice and consequently the effectiveness of their mitigation and adaptation plans.

The findings of this study indicate the patterns of climate injustice at two urban and neighbourhood scales in the Mashhad metropolis. The patterns of climate injustice in the access of vulnerable groups to blue infrastructure are more significant and intense than to green infrastructure. This injustice in access to blue infrastructure, which is more intense for low-income individuals and households, arose from the uneven distribution/development of blue infrastructure and inequitable city cooling policies. Here are some recommendations to improve climate justice in urban cooling policies:

- Planning for ecosystem services, especially in suburbs, and development of meso-scale blue-green infrastructure in each neighbourhood (taking into account the neighbourhood area, temperature, and vulnerable population) can help to ensure climate justice in the city. This also can be a part of the regeneration and empowerment programs of deprived areas, historical core, and informal settlements.
- Safeguarding the existing blue-green infrastructure is a fundamental measure in promoting climate justice. Urban management can ensure the monitoring and preserving of these infrastructures in city developments by training and cooperating with local stakeholders along with establishing protection regulations.
- Integrated management and planning of blue-green infrastructure as a city-wide network allow urban decision-makers to promote climate justice in new urban developments. This includes the development of blue-green infrastructure at different scales and can be combined with other urban cooling policies such as the use of reflective surfaces.

Although the access of vulnerable groups to blue-green infrastructure was the criterion for measuring climate justice in the current study, climate justice can be measured with a more complete set of indicators. These indicators can include a set of the natural and built environment and also urban services/infrastructures indicators that affect the vulnerability of communities to global warming and climate crises. Furthermore, measuring climate justice and the effectiveness of urban cooling policies, considering the vulnerable groups' access, requires accurate location information from these people. This information is not limited to the place of residence or the number of vulnerable people living in a spatial unit and can include their place of employment and education. Lack of access to this up-to-date information, especially regarding illegal refugees, was the main limitation of the present study. The lack of micro-scale blue-green infrastructure information also prevented us to analyse the climate justice in access to these cooling facilities at the sub-neighbourhood scale. This micro-scale climate justice should be investigated in future research.

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Chapter 16
Urban Biometeorology of Tropical Climate: Af, Am, Aw, a Propensity of 34 Provincial Cities in Indonesia

Beta Paramita and Andreas Matzarakis

Abstract Indonesia lies between 6° North Latitude and 11° South Latitude and 95° to 141° East Longitude. Located in the eastern hemisphere, this geographical location causes Indonesia to be included in the equatorial zone and has a tropical climate. Indonesia is the largest archipelagic country in the world with 17,000 islands, 416 districts and 98 cities in 34 provinces. In general, there are three city characteristic that are in the coast (+0masl) have maximum temperatures above 33 °C. In lowland areas (10–20 masl) the maximum air temperature recorded above 30 °C Meanwhile the cities located in the hills area (above 500 masl) which are not many in number, have the lowest maximum air temperature between 25 and 28 °C. Based on Köppen-Geiger, climate of Indonesia is almost entirely tropical. Dominated by the tropical rainforest climate (Af); tropical monsoon (Am); and tropical savannah (Aw) that occurs on every Indonesian island. This article then reveals the perspective of biometeorology of 34 cities of provincial capital in Indonesia. Cities that represent the tropical rainforest climate such as Medan, Balikpapan, Padang, and Pontianak. Meanwhile Jakarta, Semarang, and Yogyakarta represent cities with tropical monsoon climate. Last, Denpasar and Surabaya represent cities with tropical savannah climate. The climate data is generated from 2009 to 2019 that provides a link between the microclimate elements and human activities that affected on human perception in their living space. The biometeorology perspective for each climate characteristic gives an understanding on meteorological vulnerability and physiological aspects in the city inhabitant, such as thermal stress.

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Keywords Urban biometeorology · Hot and humid climate · Physiologically equivalent temperature

1 Introduction

The study of built-up urban areas or urban agglomerations worldwide calculated 990 cities with urban characteristics and 57.1% of them are located on the Asian continent (Demographia, 2022). Indonesia contributes 3.2% of the total urban population in the world which includes 56.7% of the 237.5 million total population of Indonesia (BPS-Indonesia, 2019; Demographia, 2022). Located in low latitude, cities in Indonesia generally have tropical characteristics of hot and humid. Based on the Koppen classification, most cities in Indonesia specifically have the characteristics of A tropical rainforest climate (Af), tropical monsoon climate (Am) and tropical wet and dry climate (Aw) (K̈oppen et al., 2011; Peel et al., 2007). Figure 1 shows the spread of tropical characteristics Af, Am, and Aw throughout Indonesia. The general climate of tropical cities, long solar radiation, high air humidity, and low wind speed cause outdoor spaces to be unable to offer outdoor comfort at a neutral preference temperature in the tropics at 26–30 °C (Binarti et al., 2020; Lin et al., 2010). In spite of the fact that most tropical inhabitants are accustomed to heat, there may be an increase in morbidity and loss of productivity due to stresses caused by well-established climate modifications, such as the heat island phenomenon. The study of urban outdoor thermal quality especially related to human-biometeorology in Indonesia consider less compared other hot and humid climate regions. In fact, residents in tropical cities tend to do their work in outdoor spaces for long hours. This is based on the employee data that informal sectors are still dominated 57.27%, compared with formal workers 42.73%, in 2019 (Lokadata, 2019). Informal sector workers who are located in the outdoor urban areas include: (1) business selling street vendors (2) non-permanent workers (mostly in construction sites) or markets, (3) freelance workers in agriculture, and (4) free workers in the transportation sector (motorcycles/online car). They are not only vulnerable to air pollution from traffic plus urban heat trapped in urban outdoor spaces.

As the biggest archipelago country in the world, Indonesia consists of 17,000 islands (BIG, 2022), and has 93 cities with 34 provincial capitals (plus 3 new provincial capitals with the expansion of Papua no data can be retrieved yet). This article then discusses the propensity of urban outdoor thermal quality in 34 provincial cities of Indonesia, how the alteration of urban climate impacts to the human-biometeorology. The hourly climatic data was taken from 2009 to 2019 to find the tendency on urban biometeorology. Furthermore, to determine urban performance, a biometeorological index is made which is expressed in Physiologically Equivalent Temperature (PET). It is defined as the equivalent of the air temperature required to reproduce in a standard room setting, also to provide the ultimate standard and observed skin temperature under certain conditions (Höppe, 1999; VDI, 1998).

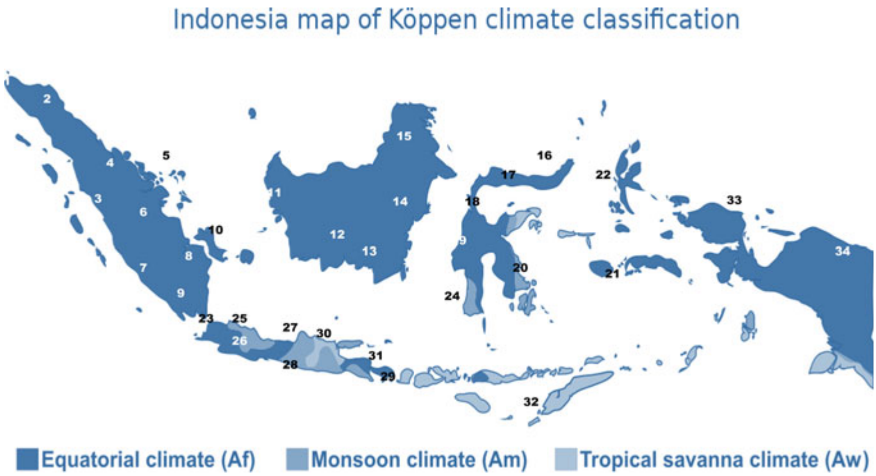

Fig. 1 Tropical climate of Af, Am, Aw in Indonesia[1] (*Source* Present and Future Köppen-Geiger climate classification maps at 1-km [adapted from Beck et al., 2018])

The causal relationship between the atmospheric environment on the one hand, and human health and comfort on the other can be analyzed by a human-biometeorological classification that considers:

1. Thermal complex (consisting of meteorological elements that have thermo-physiological effects on humans)
2. Air pollution complex (consisting of solid, liquid and natural gas and anthropogenic air pollutants that affect human health)
3. Actinic complex (consisting of the visible spectrum of the sun and ultraviolet radiation that has a direct biological effect).

Understanding the urban biometeorology, thus, will provide an overview, how to mitigate urban heat exposure due to the long duration of solar radiation in tropical cities of Indonesia.

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[1] The climate map represents the majority characteristic only, some other climate characters but very rare and not in urban areas including Arid, steppe, hot (BSh); Temperate Temperate, dry summer, warm summer (Csb); Temperate, dry winter, warm summer (Cwb); Temperate, no dry winter, warm summer (Cfb); Temperate, no dry season, cold summer (Cfc); Polar, tundra (ET).

2 Background Knowledge

2.1 Climate in Indonesia

Indonesia is located at low latitudes between 6° North Latitude and 11° South Latitude, and spans from 95° East Longitude to 141° East Longitude. The three time zones in Indonesia include WIB (Western Indonesian Time), WITA (Central Indonesian Time) and WIT (Eastern Indonesian Time).

The geographical location that lies along the equator has made Indonesia's climate tends to be relatively even year-round which experiencing only wet and dry seasons with no extremes of summer or winter. During May to October will be dry season, meanwhile the wet season falls between November and April. The seasons that occur in Indonesia are influenced by the monsoon climate because the movement of the monsoon winds changes direction every half year.

As the archipelago country, Indonesia is surrounded by seas and waters, where the water body is bigger than land area. This condition also causes some parts of Indonesia which borders the waters to have a marine climate. This situation makes the region have low temperatures, high humidity and high rainfall compared to others (Fatma, 2017; Frederick & Worden, 2011).

Generally, climate in Indonesia is entirely tropical, Köppen-Geiger classified it in group A (tropical), which is dominated by tropical rainforest climate (Af) that is found in cities of every major island of Indonesia. Cities along Java's coastal north are predominantly influenced by tropical monsoon climate (Am). Other typical tropical savanna climate (Aw) found at cities in Sulawesi's coastal south and east, Bali, lowland East Java, coastal southern Papua and smaller islands to the east of Lombok.

A tropical rainforest climate (Af) located in 10–15 degrees latitude of the equator. This area faces excessive annual temperatures, small temperature ranges, and rain that falls in the course of the year. A tropical rainforest climate is generally hot, very humid, and wet. Meanwhile, a tropical monsoon climate (Am) has either less marked dry seasons or more rainfall than a tropical savanna environment. Compared to a tropical savanna climate, a tropical monsoon climate has less annual temperature variation. The driest month in this environment almost invariably falls during or right after the winter solstice. In other condition, the dry season can be particularly harsh in tropical savanna (Aw) regions, and drought conditions can persist throughout the year. Due to their dryness, tropical savanna climates frequently include tree-lined meadows as opposed to dense rainforest. The Aw and As climates are frequently referred to as the tropical savanna because of this extensive presence of tall, coarse grass, or savanna. There is substantial debate over whether tropical grasslands are caused by the climate. Pure savannas devoid of any trees are also uncommon rather than the rule (McKnight Darrel, 2000) (Table 1).

Table 1 Tropical climate characteristic for 34 provincial cities in Indonesia

No	Tropical climate characteristic	Cities		Annual phenomenon
1	Tropical rainforest climate (Af) – 23 cities	(1) Banda Aceh, (2) Medan, (3) Padang, (4) Pekanbaru, (5) Tanjung Pinang, (6) Jambi, (7) Bengkulu, (8) Palembang, (9) Bandar Lampung, (10) Pangkal Pinang, (11) Pontianak, (12) Palangkaraya, (13) Samarinda,	(14) Banjarmasin, v15) Tanjung Selor, (16) Manado, v17) Gorontalo, (18) Palu, v19) Mamuju, (20) Kendari, (21) Ambon, (22) Sofifi, (23) Serang	**hot, very humid, and wet** → They experience high mean annual temperatures, small temperature ranges, and rain that falls throughout the year
2	Tropical monsoon climate (Am)	(24) Makassar, (25) Jakarta, (26) Bandung, (27) Semarang, (28) Yogyakarta, (29) Mataram		**less wet and dry**, in between Af and Aw → monthly mean temperatures above 18 °C in every month of the year and a dry season
3	Tropical savanna climate (Aw)	(30) Surabaya (31) Denpasar (32) Kupang (33) Manokwari (34) Jayapura		**severe dry** → the dry season can become severe, and often drought conditions prevail during the course of the year

2.2 *Urban Biometeorology*

The study of urban biometeorology not a new knowledge, but it is challenging to analyze the impact of urbanization on various elements of weather. The effect of the urban climate and the urban-induced changes (including air pollution) on the health and well-being of the population living in cities constitutes the realm of biometeorology (Höppe, 1997; Jauregui, 1997; Nouri & Matzarakis, 2019). To define the quality of urban biometeorology, it uses PET index that refer to a model of the body's thermal conditions based on Munich Energy-balance Model for Individuals (MEMI). PET is defined as the air temperature at which the human body's heat budget is balanced at the same core and skin temperature as it would be in the complex outdoor setting of assessment (without wind or solar radiation). PET also found as the most frequently used outdoor thermal comfort indices for hot-humid regions (Binarti et al., 2020). The study on 29 tropical areas that span from Am, Af, Aw, Cfa, and Cwa that using software package such as ENVI-met, RayMan, SOLWEIG, OTC

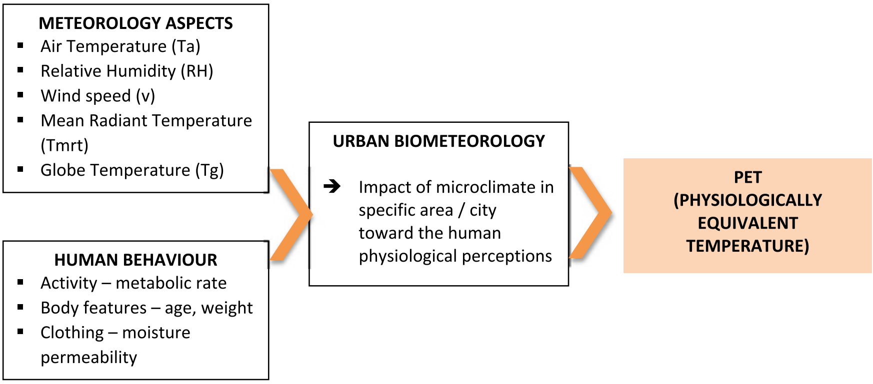


Fig. 2 PET as the urban biometeorology index

model, also UTCI. Apparently, the study PET that published in the indexed journal in Indonesia still limited, including the study on building layout (Paramita et al., 2018), connection between urban morphology and microclimate (Paramita & Matzarakis, 2019), thermal condition mitigation strategies for a climate-resilient archaeological park (Binarti et al., 2022), and PET as an index for urban performance (Paramita et al., 2022). Other studies in hot and humid climate including the use of RayMan software to calculate all thermoregulatory process also capable of predicting the real skin and body core temperature, sweat rate and skin wittedness (Bastanfard & Darbani, 2020; Lin et al., 2010; Liu et al., 2014; Middel et al., 2016, 2017; Rodríguez Algeciras et al., 2016).

Henceforth, the human behavior input are: activity, body feature (age ad weight), as well as the clothing.

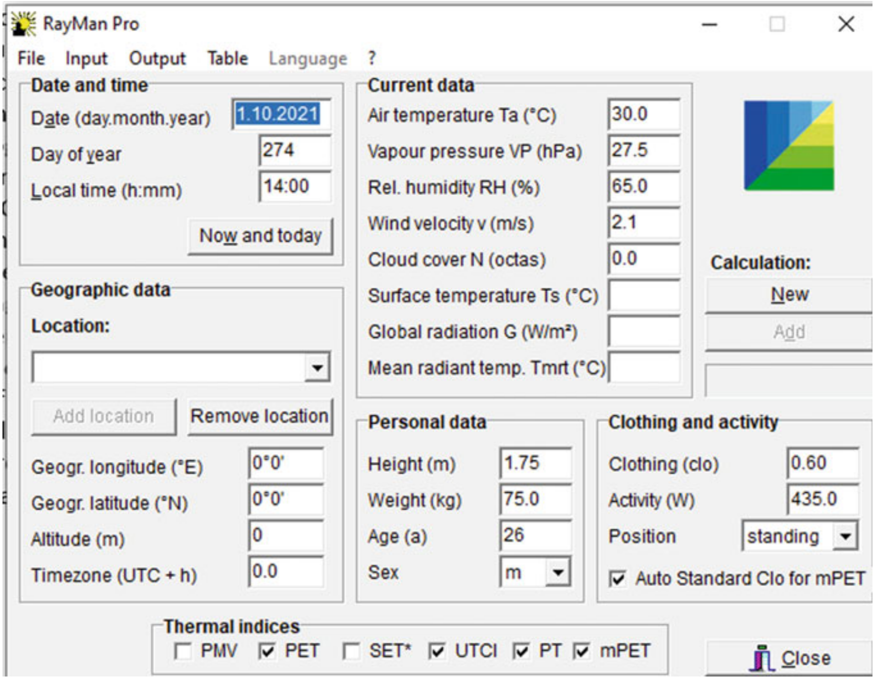
The data collection from 2009 to 2019, it can be generated the atmospheric data, such as air temperature (Ta), relative humidity (RH) and velocity (v). Later, from this data we can obtain the urban biometeorology condition for each city. Figure 2 shows us the input for urban biometeorology that stated in Physiologically Equivalent Temperature (PET °C).

2.3 RayMan Pro

RayMan stands for “radiation on the human body”. This software is free to use and can be accessed through https://www.urbanclimate.net/rayman/index.htm. The software focused on the radiation fluxes that are computed using model approaches that take into account factors including air temperature and humidity, the amount of cloud cover, air transparency, and the time of year. It is also necessary to specify the solid angle proportions and the surrounding surfaces’ albedo. Many times, well-known formulas are used to determine the radiation fluxes from meteorological and astronomical data. The main issue with using this method for regional and urban planning is determining how much direct and diffuse radiation is being blocked by buildings. One experimental approach for figuring out the sky view factor uses fisheye pictures.

Because the consideration of a variety of complicated horizons, the model RayMan given here is highly suited for the estimation of radiation fluxes, particularly within metropolitan structures. When using RayMan on a PC, there is an input window for urban structures (buildings, deciduous and coniferous trees), and there is also the option of drawing the horizon freely and producing an output of the horizon (natural or non-natural) for the estimation of the sky view factors. The amount of clouds in the sky can also be depicted freely, and their influence on radiation fluxes can be calculated. The most crucial question in the fields of urban climatology and human-biometeorology is whether or not the object of interest is in shadow. As a result, the shadow cast by man-made and natural obstacles is represented in the model.

Although PET is developed and used by high latitude countries, this software accommodates geographic data input such as longitude, latitude, altitude and time zone input. This software also providing the information of global radiation input, as the main influence for mean radiation temperature. The features of RayMan Pro seen at Fig. 3.



Date and time

Date (day.month.year) 1.10.2021
Day of year 274
Local time (h:mm) 14:00

Geographic data

Location:
Geogr. longitude (°E) 0°0'
Geogr. latitude (°N) 0°0'
Altitude (m) 0
Timezone (UTC + h) 0.0

Current data

Air temperature Ta (°C) 30.0
Vapour pressure VP (hPa) 27.5
Rel. humidity RH (%) 65.0
Wind velocity v (m/s) 2.1
Cloud cover N (octas) 0.0
Surface temperature Ts (°C)
Global radiation G (W/m²)
Mean radiant temp. Tmrt (°C)

Personal data

Height (m) 1.75
Weight (kg) 75.0
Age (a) 26
Sex m

Clothing and activity

Clothing (clo) 0.60
Activity (W) 435.0
Position standing
☑ Auto Standard Clo for mPET

Thermal indices

☐ PMV ☑ PET ☐ SET* ☑ UTCI ☑ PT ☑ mPET

Fig. 3 RayMan pro features

3 Climate-Resilient Strategies and Implications at the City Scale

3.1 Tropical Rainforest Climate (Af)

Af tropical rainforest climate has characteristic as hot, very humid, and wet. There are 23 provincial capitals with these climatic characteristics. The data from 2009 to 2019 shows that the lowest air temperature (Ta) is at 27.6 °C, and the highest temperature is 43.9 °C. Even though it shows a high Ta value, by multivariate correlation Ta effect is not significant on PET ($r = 0.43$). Humidity apparently becomes the benefit meteorological element to reduce the value of PET. Low humidity often occurs in May–August, this causes the thermal discomfort level of the outdoor to be high. However, the addition of humidity values did not have a significant effect on the decrease in the PET value ($r = -0.19$). The meteorological element that most influences the PET value is the Tmrt (mean radiant temperature) ($r = 0.85$). This means that outdoor spaces that are exposed to direct solar radiation, will potentially increase the value of PET. Meanwhile wind velocity (v), which has an effect on fluid dynamic heat exchange, does not appear to have a significant effect in reducing the PET ($r = -0.19$). The multivariate correlation shown as scatterplot matrix in Fig. 4.

3.2 Tropical Moonson Climate (Am)

Am tropical moonson climate has characteristic less wet and dry. There are only six provincial cities that included in this cluster. These six cities are also metropolitan cities with a population of over 2 million. Ta found as the meteorological element that influence PET value, even is not that strong enough ($r = 0.55$). Meanwhile here in moonson climate, v found as the preference factor to reduce the PET value Based on multivariate correlation, the meteorology element that influence on PET value ($r = -0.38$). Even though Am is located in a coastal city, with high temperatures, Tmrt doesn't seem to have any effect on the PET value. The correlation value of Tmrt to PET is only $r = 0.23$. A city with an Am character then has to provide open spaces to accommodate the urban ventilation, to sweep the hot air temperature. The scatterplot matrix of multivariate Am character is seen in Fig. 5.

3.3 Tropical Savana Climate (Aw)

Aw tropical savana climate has very specific on severe dry. Similar with Af character, Tmrt has a big influence in shaping the PET value ($r = 0.87$). Cities with Aw characters have strong winds so that they can become meteorological elements that can reduce the value of PET ($r = -0.49$). Meanwhile, the influence of Ta seems not strong

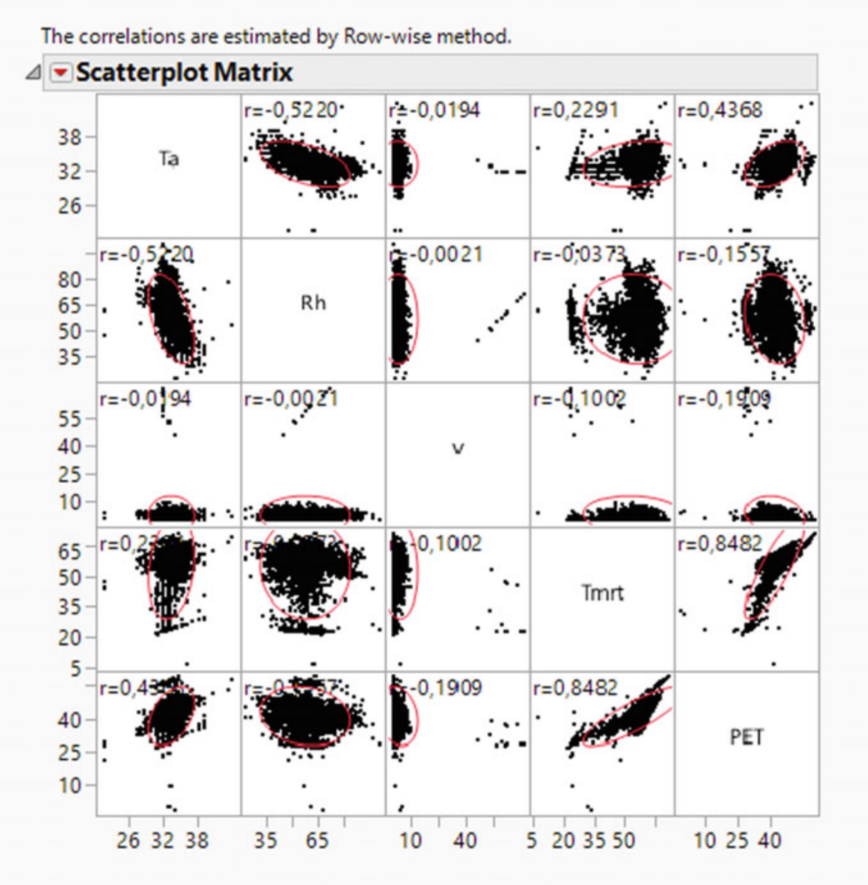

The correlations are estimated by Row-wise method.

Fig. 4 Multivariate correlation 23 cities with Af characteristic

enough to increase the PET value (r = 0.43). July to December are the months with humidity below 50%. This will affect rainfall, and subsequently have an impact on long droughts. Unlike Af and Aw characters, cities with Aw characters do not have humidity above 80%. Thus, humidity has no significant influence in shaping the PET value (r = 0.064). The scatterplot matrix to show the multivariate correlation between PET and Ta, RH, v and Tmrt is shown at Fig. 6.

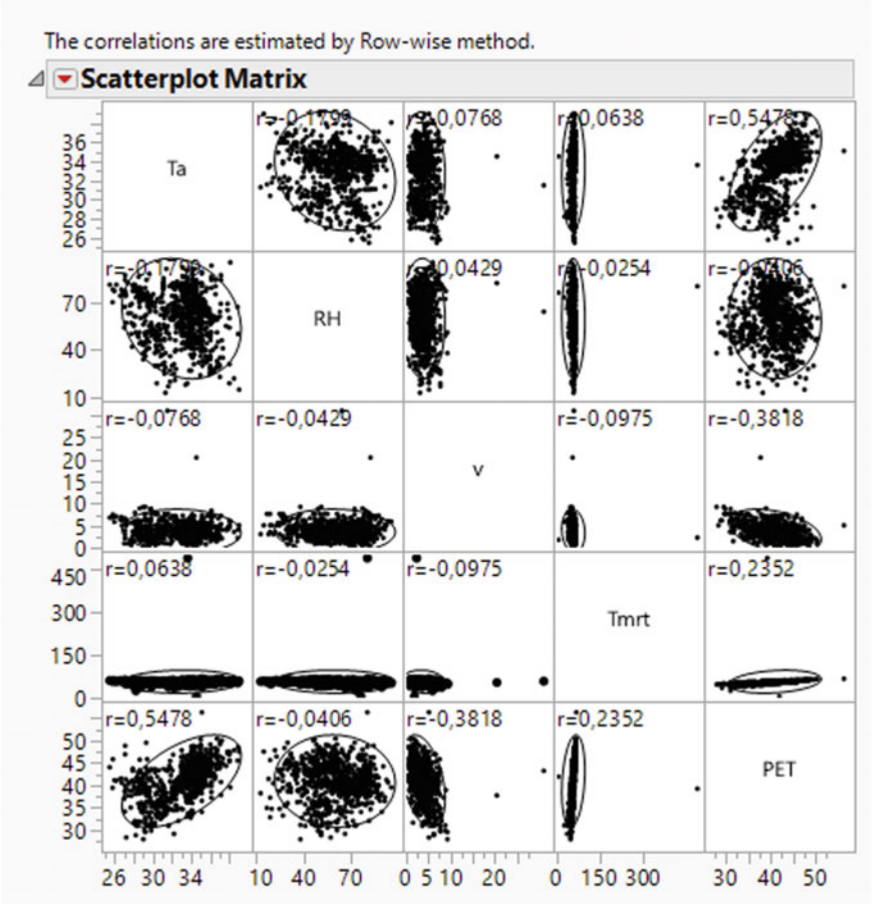
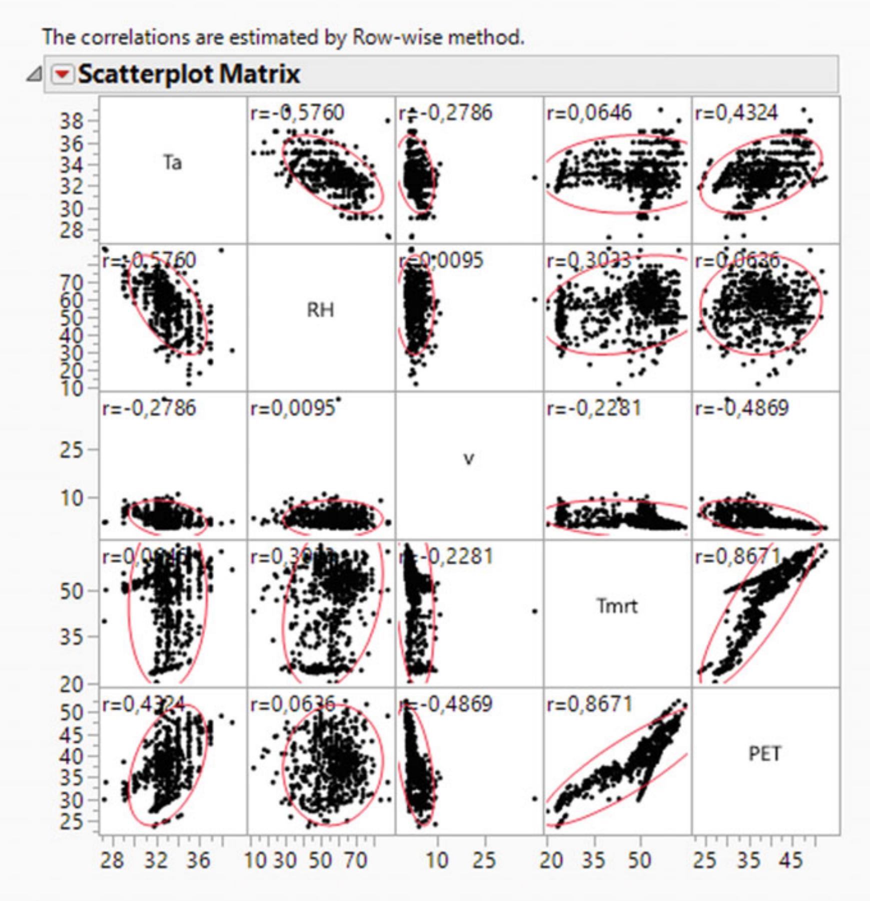


Fig. 5 Multivariate Correlation 6 cities with Am characteristic

4 Discussion and Implications

The difference in climate character in each city provides information that the management strategy for a climate-resilient city depends on the meteorological elements that compose it. each city must provide detailed information to the public, especially regarding the months with extreme phenomena. Espec.

ially for high humidity warnings associated with high rainfall, or low humidity will have an impact on drought. Broadly, information related to urban biometeorology, will have an effect on spatial planning of the city. This is have been studied in the previous article that building coverage ratio significantly impact on the outdoor thermal comfort that stated in PET (Paramita et al., 2022). The urban biometeorology that accumulated in 11 years can be seen in the Fig. 7. The range of PET used refers



The correlations are estimated by Row-wise method.

Fig. 6 Multivariate correlation 5 cities with Aw characteristic

to the results of the Lin et al. (2010), study which conducted experiments on 300 pedestrians in open spaces of Taiwan City in hot and humid climates.

The diagram above explains that tropical city in the low latitude difficult to achieve its PET in the neutral range of outdoor thermal comfort. Whatever the characteristics of tropical climate, the air temperature is relatively hotter than the air temperature in other climate zones. Also, located on the equator causes the cities in this area to be covered by long sunlight (between 11 and 12 h a day) that imply to the value of Tmrt. As previously mention that PET in the cluster Af and Aw mostly influenced by Tmrt value. However, despite having high diurnal temperatures, it must also be borne in mind that areas such as the Aw cluster offer moderately high winds. This is certainly advantageous for the value of PET which is not too high.

The average of PET value from 2009 to 2019 then is shown at Fig. 7 explains that Surabaya offers lowest PET, meanwhile Palu offers highest PET within 11 years.

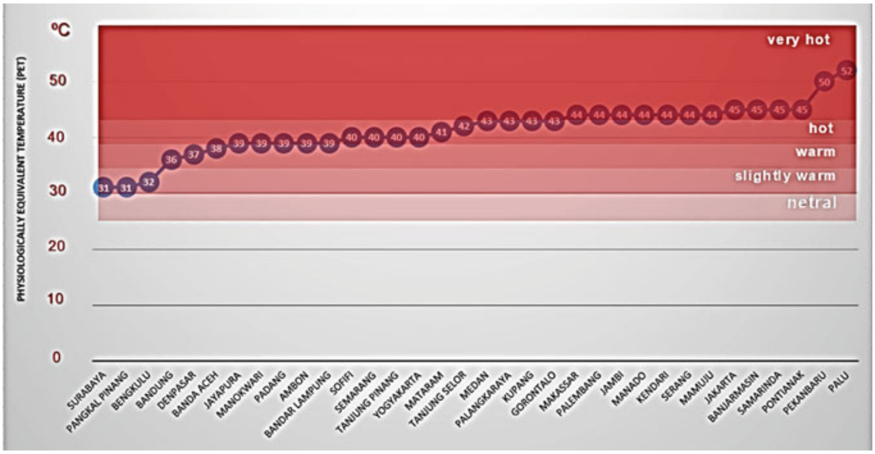


Fig. 7 Average of PET from 2009 to 2019 of 34 provincial capital cities in Indonesia

5 Concluding Remarks

The study of urban biometeorology within eleven years in 34 provincial capitals throughout Indonesia can provide information for handling climate-resilient cities. Due to the different causes of discomfort in the outdoor space, different treatments will also be given to urban spatial planning. Cities with Af characters as the majority of cities in Indonesia must provide a lot of shade to fend off solar radiation in open spaces. Coastal cities which are usually characterized by the character Am, have the advantage of high wind velocity, must provide opportunities for city forms that support urban ventilation. Cities with Aw characteristics should have deeper strategies related to drought mitigation. Rain water harvesting in the months of high precipitation needs to be recommended to the public. The government needs to encourage an integrated system related to food security and water availability due to the serious impact of drought on the Aw cluster.

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Chapter 17
Conclusions and the Way Forward

Ayyoob Sharifi, Andreas Matzarakis, Bao-Jie He, and Ali Cheshmehzangi

Abstract The growing trends of urbanization and climate change have increased urban heat exposure and challenges in the past few decades. Extreme heat conditions have become more common in the past few years, with climatic changes and extremes becoming more evident in the future. Even if the world can make progress on mitigating climate change by drastically reducing the emission of Greenhouse Gases (GHGs), these trends are projected to continue in the coming decades. This chapter first discusses natural- and human-made drives of extreme urban heat events. We then highlight major urban heat adaptation and mitigation measures and strategies that are explored in this volume. We argue that mitigation measures have received more attention in science and policy circles, and a more balanced approach is needed

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to strengthen the adaptive capacity of communities. For this purpose, it is essential to adopt systemic approaches that are facilitated by decision-support tools enabled by advances in information and communication technologies and big data analytics. Such systemic approaches would also help promote justice in the context of urban heat adaptation and mitigation.

Keywords Urban heat · Climate change · Mitigation · Adaptation · Justice · Urbanization

1 The Urgency of Urban Heat Adaptation and Mitigation and the Contribution of This Volume

Urban heat challenges are products of the combination of extreme heat conditions and the urban heat island effect. Extreme heat conditions have become more common in the past few years, with the climatic changes becoming more evident with every passing year (He et al., 2023). According to the World Meteorological Organization (WMO), the past eight years have been the warmest years on record, with 2016, 2019, and 2020 being the top three (WMO, 2023). Even if the world can make progress on mitigating climate change by drastically reducing the emission of Greenhouse Gases (GHGs), these trends are projected to continue in the coming decades due to the historical emissions (IPCC, 2023). Indeed, the recent synthesis report of the Intergovernmental Panel on Climate Change (IPCC) makes it clear that extreme heat events can occur even at low global warming levels (IPCC, 2023). Needless to mention that under some future climate scenarios, the average temperatures can exceed 5° beyond the pre-industrial levels, with enormous consequences for the ecosystem, economy, infrastructure, and human health and well-being (IPCC, 2023).

In addition to climate change, the urban heat island effect is a key driver of extreme urban heat. It is a condition when temperatures in urban areas are higher than in the surrounding rural areas. Various factors, such as the physical design of cities, the albedo of urban surfaces, the type of materials used, the amount of heat exhaust from automobiles and air conditioners, etc., contribute to the urban heat island effect. Urban heat is not only limited to the Urban Heat Island (UHI). It includes several other factors, like humidity, air pollutants, and combined effects of atmospheric factors.

It is evident that measures aimed at addressing extreme urban heat challenges should address issues related to climate-induced extreme heat events as well as those associated with the urban heat island effect. The key point to keep in mind is, however, that the window of opportunity to take action in urban areas is narrow and will close in the coming decades. Currently, about 56% of the world's population lives in urban areas, and this share is expected to reach approximately 68% by 2050 and always keep in mind that the surface covered by cities is only 3% (UN, 2018). Most of the future world urban population growth will occur in the developing countries of Africa and Asia. The way these new urban settlements are going to be built will have major implications for addressing urban heat issues. It is essential to consider urban heat mitigation and adaptation strategies throughout different stages of urban planning, design, and management in both new and existing cities. Such strategies can provide multiple co-benefits in terms of reducing health risks and quality of life, ensuring better environmental quality, minimizing infrastructure damage, and reducing socio-economic inequalities (Sharifi, 2022; Sharifi et al., 2021). In addition, given the tight nexus between urban heat and energy consumption, measures aimed at addressing urban heat challenges will also provide co-benefits and synergies for climate change mitigation (i.e., reducing sources and/or enhancing sinks of emissions) (Lwasa et al., 2022; Sharifi, 2021).

This volume advances the knowledge of urban heat mitigation and adaptation strategies by offering new insights into "Concepts, Theories, and Trends" (Part I), "Mitigation and Adaptation Strategies" (Part II), and "Policies" (Part III). Figure 1 shows that various issues and measures related to mitigation and adaptation have been addressed throughout the volume. The dominant measures are related to green infrastructure (e.g., ponds, green walls, roofs, urban greenery, vegetation, etc.), urban planning and design (urbanization patterns, street canyon design, shading environment, courtyards, land use planning, etc.). These are mainly related to mitigating urban heat risk. However, they could also contribute to urban heat adaptation. Regarding the latter, it can be observed that issues related to justice and vulnerable groups are also covered in the volume. However, they have received relatively less attention despite the urgency of taking action to address such inequalities in cities.

Fig. 1 The main thematic issues that are addressed throughout the volume (*Source* The Authors)

2 The Way Forward

A recent study by He et al. (2023) has highlighted the thematic focus of the literature on urban heat adaptation and mitigation. The key thematic focus areas covered by the existing literature are shown in Fig. 2. Comparing Figs. 1 and 2 shows that this volume has covered most of the popular research themes. More specifically, issues related to urbanization and implications for land surface temperature and urban heat island effect, green and blue infrastructure for urban heat adaptation and mitigation, and design measures for improving outdoor thermal comfort are common between the two figures. The two figures also show that issues related to adaptation, health, and vulnerability have received relatively less attention from the scientific community.

While understanding the physical and climatological drivers of urban heat and exploring the effectiveness of different mitigation strategies is essential to address the issue, it can be argued that already a good amount of knowledge on these issues exists that can guide action plans. More research, however, is needed to address the implications of urban heat adaptation/mitigation measures for other urban issues such as justice, air quality, and vulnerability. Figure 3 indicates that some of these

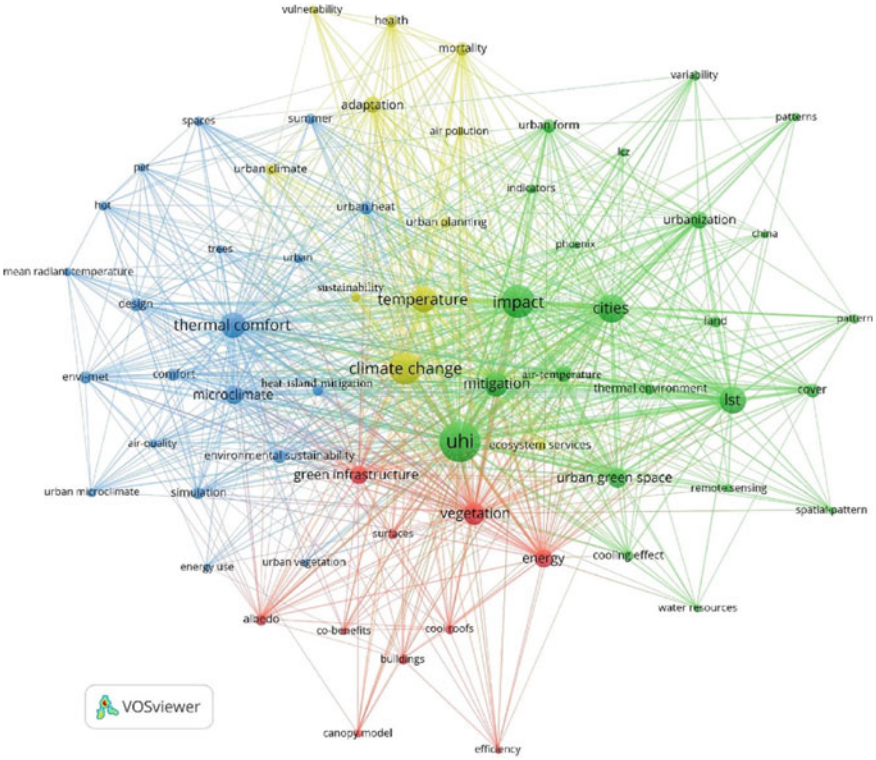

Fig. 2 Major issues addressed in the literature on urban heat (He et al., 2023)

Fig. 3 Major policy-related issues addressed in Part III of volume

issues have been addressed in Part III of this volume, which is focused on policies. However, more work is needed to understand better what models should be promoted to develop effective, efficient, and just urban heat adaptation and mitigation strategies. Finally, as also emphasized in He et al. (2023), the existing research landscape is unbalanced, with mitigation receiving more attention. More systemic approaches that allow balanced attention to mitigation and adaptation are, therefore, needed. The advances in modeling and big data analytics offer opportunities to promote more systemic approaches and should be further explored in future studies.

Finally, the framework of climate-resilient development should be considered. It combines strategies to adapt to climate change with actions to reduce greenhouse gas emissions to support sustainable development for everyone. This means reducing exposure and vulnerability to climate hazards, cutting back greenhouse gas emissions and conserving biodiversity are given the highest priorities in everyday decision-making and policies on all aspects of society, including energy, industry, health, water, food, urban development, housing, and transport and is mostly required and demanded in urban areas. It is about successfully navigating the complex interactions between these different systems so that action in one area does not have adverse effects elsewhere and opportunities are harnessed to accelerate progress toward a safer and fairer world (IPCC, 2023).

Climate Resilient Development isn't achieved with a single decision or action. It is the result of all of the choices we make about climate risk reduction, emissions reduction, and sustainable development on a daily basis. New scientific evidence shows that addressing the risks and impacts of climate change successfully involves a more diverse set of actors than previously thought—it not just policy-makers but everyone in government, civil society, and the private sector (IPCC, 2023). Lastly, we hope this volume is a suitable collection for urban sustainability research, providing new knowledge, capacity, and case study examples for cooling city concepts, strategies, and policies.

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