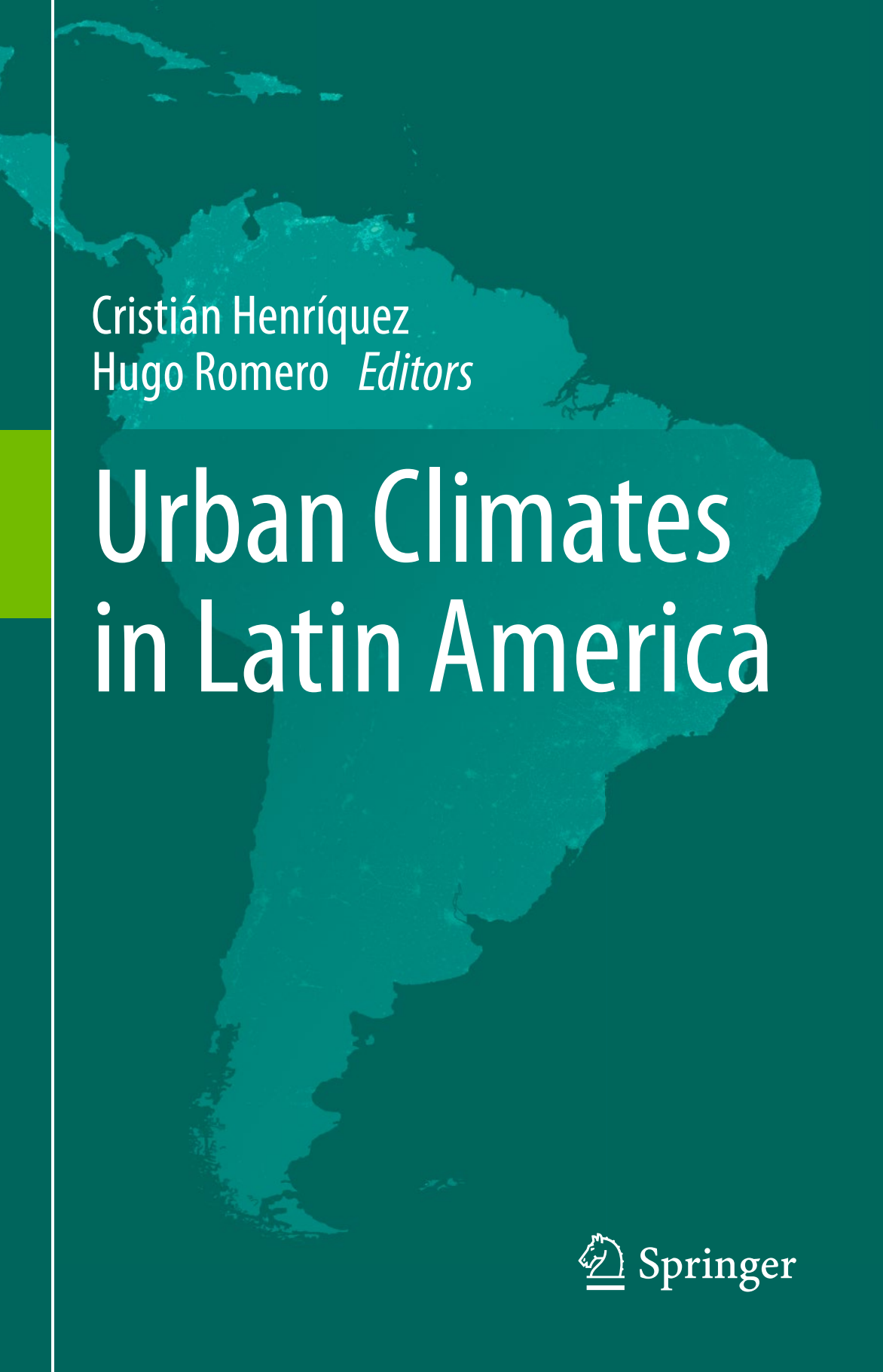
Cristián Henríquez
Hugo Romero Editors
Urban Climates in Latin America
Springer

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Cristián Henríquez • Hugo Romero
Editors

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In memory of Magaly Mendonça
Professor of the Geosciences Department of the Federal University of Santa Catarina, Florianópolis, Brazil.

Foreword

In the present, where there is little time for quiet reflection, summary, and synthesis, and where there is pressure and haste to publish articles in international journals that are no doubt necessary for advancing knowledge, but which are sometimes unfocussed and unconnected, with no defined line of reasoning, you have in your hands – dear reader – a book that brings together a considerable body of research about urban climate in Latin America.

Latin America has seen its urban population swell steadily and spectacularly over recent decades, ranking two of its cities – Mexico City and Sao Paulo –in the top ten most populated urban agglomerations in the world. Tens of millions of Latin Americans are already subject to altered climate conditions, with respect to the regions where they live, as a direct consequence of the urban metropolis. As in other cities in the world, the urban heat island (UHI) phenomenon is the most obvious manifestation of local climate modification. Subsequently, in addition to unequivocal global warming – a new reality to which we must adapt, there is a thermal surplus in urban areas produced by urban heat islands. Often, at least in large city centers, the temperature increase due to UHI is as high as, or greater than, the temperature rise associated with global warming.

This work compiles extensive research on climate change in Latin American cities, with information on thermal comfort, air quality, risk, health, and urban planning. Although not an exhaustive analysis, the 15 chapters of this book comprise an excellent compendium of knowledge about urban climate and its effects.

This work has been edited by two Chilean geographers: Professors Cristián Henríquez and Hugo Romero. Without a doubt, Hugo Romero is the most internationally renowned Chilean geographer and one of the most illustrious geographical thinkers in the Hispanic world. His broad experience in many areas of geography and related sciences provides him with an all-encompassing vision of reality, ideal for a project like this. Cristián Henríquez, an outstanding disciple of the former, is the perfect co-editor owing to his command of modern techniques and his considerable present and, undoubtedly, future renown. Together, the professors ensure the

distinguished quality of this work. Similarly, publication by the publishing house Springer also guarantees the quality and structural excellence of this publication.

Therefore, I would like to welcome *Urban Climates in Latin America* to the world. I hope that it will be an important work of reference for climate research in Latin American cities and other parts of the world from the moment it is published.

Professor of Physical Geography at the Universidad de Barcelona
Barcelona, Spain
November 2017

Javier Martín-Vide

Preface

During 2015, from 20 to 24 July, the 9th International Conference on Urban Climate (ICUC) took place in Toulouse, together with the 12th Symposium on the Urban Environment, organized and hosted by Météo-France. On that occasion, in addition to presenting our work and discussing with urban climatologists from different parts of the world, we were cordially invited by representatives of Springer to submit a proposal entailing the preparation of a book on urban climates in Chile. At first, we thought it would be important to show the contributions of Chilean urban climatology based on ongoing research, primarily carried out in universities with the support of the National Fund for Scientific and Technological Development (FONDECYT[1]), the Fund for Research Centers in Priority Areas (FONDAP[2]) and other research projects.[3] However, despite the proposal being well-evaluated, the concern and need arose to broaden it to a greater geographical scale, which allowed the approaches and advances of Latin American urban climatology to be emphasized. In this way, the idea of producing this book was emerging, considering the close academic relations existing among our Latin American geographer colleagues, especially Brazilians and Argentinians, with whom we have shared seminars, meetings, and research on the environmental problems that affect our cities, also with researchers from different disciplines.

The complexity and interdisciplinarity required to address the problems of the climatology of cities, involved the challenge and need to extend the invitation to

[1]FONDECYT Grants N° 1100657 "*Evidencias del cambio climático en centros urbanos en Chile: Implicancias sobre los riesgos naturales y la capacidad adaptativa*" and N° 1130305 "*Estudio y modelación del clima urbano a escala local, como base para la proposición de lineamientos de adaptación frente al cambio climático en una red de ciudades chilenas*."

[2]CONICYT/FONDAP N° 15110020 Center for Sustainable Urban Development (CEDEUS) and CONICYT/FONDAP N° 15110017 National Research for Integrated Natural Disasters Management (CIGIDEN).

[3]CARE Project: Empowering Urban Climate Resilience, Erasmus+ Programme, funded with support from the European Commission.

specialists from other related areas and countries, to enrich and strengthen the perspectives of the book. In this way, more researchers who work in different Latin American universities and research centers joined, which not only provided a different geographical perspective, but also ecology, engineering, architecture, environmental chemistry, and other perspectives necessary to advance in this field of knowledge.

We believe that the following contributions not only represent examples of what is currently being researched in Latin American cities, but also constitute a great opportunity to communicate and disseminate this work from a multidisciplinary perspective. The theoretical and methodological approaches found in the text are diverse and heterogeneous, especially those originating from the Brazilian school, which has extensive experience in the study of urban climate. The book should be a great opportunity to review climatic problems as fundamental components of the complex and unfavorable environmental situation unfolding in Latin American cities. These cities continue to face a growth of their urban areas, sources and concentrations of pollutants, growing levels of socio-environmental inequality, and implementation of strategies and policies restricted to space, time, and actions that facilitate market forces against regulation.

This work is the product of the selfless and supportive contribution of each of the authors of the chapters. Without the time and effort dedicated by them, it would not have been possible to reach the proposed goal. Our gratitude is especially for them, because they generously and enthusiastically accepted this challenge and sent their contributions in response to the initial call formulated in August 2016. This has double merit, insofar as they responded in a very short time with contributions that enriched the knowledge about urban climates from their respective specialities, but also completed the difficult task of translating them from their native languages, Spanish and Portuguese, into English.

Once the contributions were received, the organizers had the difficult task of trying to organize the texts in a harmonious and attractive way for the reader. We think that the best way is by invoking the book call (August 2016): “The main purpose of the book is to emphasize that the urban climates of Latin America are a social construct with high diversity, both in terms of the general climatic and geographical situation and the social condition of its inhabitants and their growth pattern. The book seeks to emphasize the urban climate as an adaptive system, according to the dynamics of urban growth and unique aspects of local, regional and global climate change.” The call urged us to address the study of the reciprocal influences of cities on urban climates and the climate on the city, in addition to the impacts of these on the most vulnerable and destitute social groups from a local perspective, considering specific aspects of the cities selected according to their location, extent, and climate zone (tropical, subtropical, temperate, desert, mediterranean, coastal, and continental).

Additionally, the impacts of climate change and levels of social vulnerability are geographically differentiated both among and within the cities. For this reason, it is very important to show the social, environmental, and economic particularities of Latin American cities, and based on this reality, to propose mitigation and adaptation strategies suited to the local context.

To do this, the book is structured around three pillars, following the approach proposed by the renowned Brazilian scientist, Monteiro. In 1976, he proposed the Urban Climate System (UCS), composed of the thermodynamic subsystem (heat islands, thermal comfort, health), the physical–chemical subsystem (air quality, urban activities, energy matrix), and the hydrometeorological subsystem (weather systems, extreme hydrometeorological events, disasters, and urban resilience).

The book begins with an introductory chapter presenting the main challenges of Latin American urban climatology. Then, in the first part, five chapters address urban climate cases of thermodynamic subsystems; in the second part, three chapters are grouped to show the physical–chemical subsystem and urban climate relationship; finally, the third part, corresponds to hydrometeorology and the challenges of urban adaptation, which consists of six chapters.

With this structure, we have tried to take a global approach to the urban climate, but there are some omissions. For example, the cities that have been selected do not reflect the full range of sizes, functions or types of urban climates of Latin America, however they do provide insights in particular cases from which broader conclusions may be drawn. The necessary representation is partially lacking from some relevant countries of the North American subcontinent (Mexico), Central America, and the Caribbean; in addition, not all approaches are represented to address the issue from a physical, human, and political ecology perspective. All of the above demonstrate weaknesses that only motivate us to continue working towards future cooperation and integration of Latin American research.

Our sincere thanks go to Springer Publishing, represented by Mrs. Margaret Deignan, for trusting and believing in the project and for their patience. The process had extensive difficulties due to the coordination, revision, translation, evaluation, and follow-up that the texts required. This required significant patience and understanding on the part of the publishing and editorial team and the authors. The result fills us with pride and enthusiasm.

Finally, our appreciation goes to our students, assistants, and collaborators, who allowed this work to be developed. Special thanks go to Esteban Soler for the manuscript editing. Without them, this academic initiative could not have been completed. This work is directed and dedicated to them, and to future students and those interested in the study of urban climates. For the editors, it is gratifying to see the result that began in August 2015, first locally and then with an international scope. We hope that it will be useful for the scientific community, decision-makers, and the public more generally.

We expect that this book will enable us to continue moving forward in understanding the problems of urban climate, contributing to the search for multi- and interdisciplinary solutions to achieve the sustainable development of cities, improving the processes of climatic adaptation from a Latin American perspective and in dialogue with the international community.

Santiago, Chile

Cristián Henríquez
Hugo Romero

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Chapter 1
Introduction

Cristián Henríquez and Hugo Romero

Abstract Urbanization has become one of the most omnipresent features of the twenty-first century world. More than half of the world's population lives and develops their activities in cities, and by 2050, this figure is expected to include two-thirds of people worldwide. These urban changes have created specific natural and social environments, including urban climates, not only in the large metropolis, but also in mid-sized cities. In this context, this chapter introduces the main urban, environmental, and climatic problems of Latin American cities. The modification of the local climate is characterized by a change of climate conditions, with higher temperatures, lower humidity and ventilation, atmospheric pollution, and poor environmental quality. In Latin American cities, these conditions have large geographic variations in terms of latitude (from 32°N to 56°S), altitude (from sea level to over 5,000 m), watershed, topography, and ocean influence, among other natural factors. Using the Urban Climate System Monteiro (Teoria e clima urbano. 16 USP/FFLCH thesis (Livre-docência), São Paulo, 1976) approach, the book is structured in three parts or subsystems: thermodynamic, physiochemical, and hydrometeorological subsystems. The focus is on the geographic dimensions of thermal comfort, air quality, and extreme events, and how, through planning and adaptation, proposals can be developed to cope with such challenges.

Keywords Urban growth · Socio-environmental inequality · Thermal comfort · Air quality · Hydrometeorological events · Urban climate system

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Urbanization has become one of the most omnipresent features of the twenty-first century world. More than half of the world's population lives in, and develops their activities in cities, and by 2050, this figure is expected to include two-thirds of people worldwide (United Nations 2014). Indeed, some authors speak about "planetary urbanization" (Brenner 2013, 2014; Brenner and Schmid 2011) or even the emergence of an "Anthropocene Age" (Crutzen 2005; Lewis and Maslin 2015; Steffen et al. 2011), to highlight the influence of human activity over the global urban environment. A complex situation is taking shape for urban suitability, and, given the projections, this situation could become even more critical in the coming years (Tebaldi et al. 2006).

The Latin America and the Caribbean region is not immune to this global trend; 79.5% of the population lives in cities (UN-Habitat 2011). The negative effects of urbanization are evident on all spatial scales: megacities, large cities, and medium-sized cities. However, in metropolises such as Mexico City, São Paulo, Buenos Aires, Lima, Bogotá or Santiago, urbanization presents very distinct features with respect to the hegemonic countries of the first world system. These include gigantism and uncontrolled growth of urban spaces, apparent disorder and dispersion, privatization of land and environmental components, socioenvironmental fragmentation, informal employment, markets and services and, as a result, impoverishment, exclusion, conflicts, violence, and pollution affect most of their societies (Pradilla and Márquez 2008). Latin American cities have experienced rapid urbanization over the past few decades and this has generated significant effects in socioeconomic and environmental terms. On the one hand, there is noticeable segregation and marginalization of the population, and on the other, there are places where wealth is concentrated and causes an "elitist" distribution of space. Consequently, according to the model proposed by Borsdorf (2000), cities are following a fragmented city pattern that represents transformations associated with social inequalities, symbolized by the unregulated distribution of residential areas, industrial zones, the location of shopping centers throughout the city, intra–extra urban highways, and by the presence of gated communities that protect the exclusive social sectors from "citizen insecurity," among other urban artifacts. It is also characterized by built area densification and gentrification in the city center, consolidation of slums on the periphery, and urban renewal programs in many locations. Another feature of this dynamic is that urban growth was not only caused by migratory pressure, but also by other driving forces such as socioeconomic status, generating a very segregated city (Henríquez 2014; Hidalgo et al. 2008).

The classic urban form of Latin American cities associated with the colonial style and the compact city is moving toward a fragmented and sprawling form. Some urban patterns, such as ribbon urbanization, are controlled by a massive and homogeneous displacement of the population toward the edges of the urban areas. The "leap frog" growth, linked to urban commuters in search of living in a gated community, such as a "country club," "*loteamentos fechados*," or "*parcelas de agrado*" is representative of several Latin American cities. This corresponds to spatially discontinuous peri-urban development, where the urban enclaves occupied by different social segments look for amenities that nature or rural spaces offer. At

the same time, the *"tentacles"* pattern present in many cities shows horizontal growth from structured pathways, and is highly dependent on the use of a private car. All of these types of urban change have created specific natural and social environments, including urban climates, not only in the large metropolises, but also in mid-sized and smaller cities.

1.1 Urban Climates and the (Un)Sustainable Development of Latin American Cities

The creation of urban spaces reflects vital social needs, cultural adaptation to the fluctuations of nature, and aspirations based on popular consciousness where a common goal is to promote systems of knowledge and practices that often imitate forms that have been generated elsewhere, thus rejecting local or indigenous models. These societal objectives are intermediated and controlled in contemporary society by predominant political–economic systems on a global scale. In the case of Latin America, the predominant system has been based on the neoliberal doctrine. Among these premises, an important component is the separation and commodification of individual environmental elements, such as climate, land, water, and vegetation, and their interactions that are expressed throughout landscapes and territories. Privatization, another fundamental premise of this model, has led to the disappearance of a set of common goods and services, which include not only natural resources, but also previous social and cultural practices relating to territories and urban spaces (Romero and Vásquez 2006).

The components of the natural landscape (climate, water, land, biodiversity) and built systems (urbanizable land, housing, roads, urban highways, ports, water supply services, electricity and fuel, health and education, among others) have been largely commercialized and privatized – explicitly or tacitly – in many Latin American countries. Chile has been a pioneer in the implementation of this system for more than 40 years, covering all areas of social development, natural resources, territories, and places. Therefore, the experience of this country can be useful for comparing the environmental effects of recent urbanization processes and the current state of sustainability of urban spaces in this part of the world.

The urban environment has been a main protagonist in recent socio-economic transformations in the region. Urbanization and the consequent abandonment of rural areas, caused by the intensification, modernization, and automation of globalized monocultures, among many other factors, has involved a massive concentration of the national population in metropolises and cities. The main metropolises and some intermediate cities have received migrants within spaces characterized by their environmental fragility, high climatic variability, and the presence of significant natural threats. Droughts, intense and concentrated rains, floods, considerable atmospheric stability and the presence of a warm inversion layer that affects vertical movements of air (and the loss of its capacity for purification), and reduced ventilation are examples of natural processes that affect many urban environments in Latin American cities.

Rapid urbanization in Latin America has not been accompanied by the resources needed to undertake proper urban planning and management, which is necessary to supply local societies and places with the required services and environmental quality. As a result, irregular occupation of unsuitable sites for urbanization and the lack of concern and financial support invested in the provision of necessary facilities has meant that millions of new inhabitants have often endured difficult conditions of adaptation to their new habitats. Although Chile is currently one of the countries with the highest per capita incomes and ranks among the top performers in the human development index in the region (including the the lowest poverty figures), all Chilean cities continue to concentrate neighborhoods where poverty is linked to a lack of opportunities and infrastructure, and where higher levels of insecurity result from combined natural and socio-economic threats.

Latin American cities currently present an increasing spatial concentration of people, artifacts and processes that are simultaneously considered to be indicators of socioeconomic development and environmental degradation. Satisfying the demand for goods and services of a heterogeneous society that essentially shares its urban condition – with the challenges of fulfilling housing needs, improving quality of life, an increasing amount and better quality of urban equipment, and the existence of a healthy and safe environment – has become increasingly difficult to achieve with the social, economic, and cultural resources available.

Additionally, opening countries to the global economy and increased trade flows has meant the consolidation of an uneven social situation between growing high-income social groups that demand an unlimited quantity and quality of spaces, goods, and services, and those middle and lower-income groups trying to satisfy their basic needs. As a result, Latin American cities, particularly the large and medium-sized cities, reveal a clear division between an uncontrolled and growing presence of multiple environmentally negative externalities caused by excessive consumption of goods and services concentrated in areas where the richer people live, and the lack of them or their inefficient distribution among middle class and lower class inhabitants that occupy most of the urban environment (Romero 2000).

The need to make space for urban sprawl and to facilitate the transformation of natural and rural spaces into urban areas is one of the reasons why Latin American cities, are constantly expanding without a strategic environmental assessment of its growth areas or environmental impact assessment of large urban projects. These assessments should consider both the improvement and conservation of source areas of clean air, water, and environmental services, in addition to the maintenance of land cover and uses, and urban design that favors the control of temperatures, adequate atmospheric humidity, and the persistence of ventilation flows that contribute to air and climate quality.

The loss of quality of urban climates has been a prevalent matter of concern in most Latin American research, and academic contributions on this topic have multiplied in recent decades. Nevertheless, no specific strategies or programs are known that explicitly attempt to reverse current situations, reflected in plans, programs, and urban development projects. Scientific contributions on urban climate characteristics and its quality do not seem to affect public decision-making to any

degree; they are rarely taken into account in the adoption of new plans or in the recognition of social demands. Decision-making processes are almost always resolved as a function of social urgency and immediate economic returns.

For example, the availability of green areas, which is fundamental in the control of temperature, humidity, winds, air quality and quality of life in cities, depends mainly on the existence of private gardens inside or around homes and buildings, or is related to the socio-economic status of neighborhoods in which they exist. Only richer neighborhoods have sufficient private or public resources to generate and maintain squares, parks, and streets with vegetation. Conversely, if the inhabitants of the neighborhood are poor, then green areas rarely exist or are present in only small areas. As a result, climatic features produced by green areas represent levels of socio-environmental injustice within Latin American cities.

Poorer urban inhabitants in Latin America are not only exposed to environmental deficits, but also to climatic extremes on a larger scale, because they are located in areas affected by constant natural hazards, or they receive flows of polluted air, domestic and toxic waste and water, which in some cases, come from richer areas to their residential areas.

On the other hand, ecosystem services and environmental amenities provided by vegetation to produce comfortable urban climates and to prevent and control hazards such as heat and cold waves, flash floods and inundations, tend to be concentrated in the richer zones of the city (Romero et al. 2010). Some common environmental services such as regulation of temperature, availability of shade, air moisture from evapotranspiration, flood control, conservation of biodiversity, and the strength of cultural values, such as peacefulness and beauty, do not mostly depend on social and collective projects in public spaces, but on solutions controlled primarily by the existence of related family and municipal economic resources.

Urban areas that suffer most from the effects of so-called natural disasters or extreme dangerous events (such as storms, floods, waterlogging, gales, heat waves or cold snaps, and concentration of atmospheric pollutants) are mainly located in areas where the population with the fewest resources resides. These are places that have steep slopes, are particularly affected by debris flows, or are situated in closed topographic depressions or along river beds, and in zones under thermal inversion layers therefore with greater atmospheric stability and pollutant potential. Sometimes, they are in proximity of forests or plantations, exposed to wildfires or pollution caused by the excessive use of agrochemicals. Many urban settlements are near toxic and hazardous industries, along roads with greater traffic pollution, in the proximity of wetlands, coastal swells, or domestic and industrial waste deposits. Some of these places are so-called “sacrifice zones,” because not only do they have the worst spatially concentrated environmental conditions, they also receive waste from the entire city, without compensation.

The growth of Latin American cities also follows different social, economic and cultural patterns, which have a significant influence on the quality of urban environments and climates. Higher income families settle in suburbanized zones located at increasing distances from city centers, polluted zones, and hazardous areas. This favors the generation of polycentrism where new nodes for goods and services are

provided, including construction, commerce, recreation, health, and education, but which degrade previously pristine and natural landscapes. New urban heat islands and air pollution concentrations (caused by high-rise building, numerous private cars, fertilized gardens, and domestic heating systems) become a characteristic climatic feature of these recently incorporated landscapes. On the other hand, lower-income inhabitants, including immigrants in search of lower land and residential costs, are forced to occupy degraded, abandoned, central neighborhood districts or reside in spaces at increasing distances from sources of goods, services, and work.

Each of the different social groups introduces land use and cover changes without corresponding socio-environmental assessments. The outcomes are the creation and transformation of urban climate characteristics and quality. Indeed, in the case of Santiago de Chile, higher income sectors that are increasingly located at more distant places from city centers not only devastate natural or rural landscapes, but also require private transport and the provision of higher-cost and segregated good and services. Additionally, the large number of trips and distances needed for travel produce adverse environmental effects such as imperviousness and air pollution. These environmental costs transfer to the rest of the population as social costs. Sometimes, and when faced with evidence for environmental deterioration, the recovery of natural areas through the installation of parks or green corridors not only involve high economic costs expenditure (and therefore are restricted to rich neighborhoods), but also do not restore the conditions of the original ecosystem.

The absence of environmental urban planning, regulation, management and assessment in general, and particularly in terms of urban features associated with the social heterogeneity and uneven development of urbanization, results in a complex and dynamic mosaic of urban landscapes and climates that is difficult to understand. An infinite multiplicity of specific areal, point-specific or linear features complicates the study of urban climates with the public information available. Few studies show the heat and cold islands, fragments of vegetation cover, the predominance of neighborhoods without significant green areas, nuclei and corridors that generate pollutants, and the diversity of densities and types of construction. This makes it difficult to generalize spatial and temporal patterns of urban climates in Latin American cities. Urban climate seems to be an archipelago of varied temperature, humidity, and ventilation features instead of a set of modellable landscapes. Comparison between surface temperatures obtained from satellite imagery and meteorological data captured in conventional stations, urban plots, and transect measurements across cities have shown a lack of correspondence. Point-specific data are clearly influenced by land use and cover that surround, or are contained in the monitoring sites. Synoptic meteorological conditions and the natural matrix where cities are located introduce significant variations in daily and even hourly records. Limited resources, the absence of standardized procedures, and the unresourcing of the public institutions in charge of urban climates are some of the limitations that explain the lack of importance of this issue in Latin America, where nearly 80% of the population live in cities.

Effective planning for the negative effects of global and local climate changes on urban societies and the need to mitigate and adapt to them, is constrained by the

scarce information and knowledge available to the general public and decision-makers in particular. Consequently, there is a lack of political support to implement concrete measures. A large proportion of urban dwellers permanently suffer from a loss of climatic quality in their daily life and an increasing exposure to the risk of disasters. Some of this loss is – in the generation of permanent heat or cold urban islands in boundaries layer climates, for example – is due to new urban development processes that affect their neighbourhoods by altering urban climatic conditions. At the canopy layer, urban design and the material insulation of buildings tend to be precarious in climatic terms for most of the inhabitants. In the case of Chile, practically the same type of social housing extends several thousand kilometers from the arid desert in the north to the glacial weather in the south, or from the coast to the Andes mountain highlands. Public policies have not been able to promote and sustain relevant urban climate transformations on a local scale that translate the mitigation and adaption commitments assumed internationally. It seems that political indifference, cultural resistance, social and economic priorities, and the lack of dedicated institutions prevent the planning and management of sustainable urban spaces in Latin America. At best, they are restricted to case studies, isolated in space and often ephemeral over time.

The development of urban climatology is increasingly important in Latin American countries. The limited available scientific and local knowledge has not mustered the strength to change the current situation. There are only a few groups of researchers within universities who must fight for survival with little social and institutional support. Accumulated and disseminated knowledge seems to be neither sufficient nor appropriate for societal and decision-maker understanding. Urban management continues to be held ransom to social, economic, and political urgency. One of the challenges is to develop a permanent dialogue between social actors and stakeholders so that climate issues appear in public discussion on a daily basis and not only in the face of extreme events or disasters when nature is mentioned as being responsible. Scientific, social, political, human, and ethical responsibilities have not been adopted by most social actors.

1.2 The Construction of the Urban Climate in Latin American Cities

Currently, the city is recognized as a complex ecosystem able to modify the local climate, essentially by the urban heat islands (UHI) effect (Douglas 1983; Oke 1987) and affect living conditions. This corresponds to an inadvertent effect of climate transformation from the natural landscape to the anthropic environment, dominated by a substitution of natural soils to different types of impervious surfaces with a greater heat capacity and lower reflexivity, that produce an increase in air temperature and a decrease in air humidity and local winds (Oke 1987). Other aspects involved in urban climate dynamics are related to heat, gases, and particles generated

by human activities, which alter the energy balance and atmospheric compositions (Moreno 1998).

The modification of the local climate is characterized by a change of climate conditions, with higher temperatures, lower humidity and ventilation, atmospheric pollution, and poor environmental quality. In Latin American cities, these conditions have large geographic variations in terms of latitude (from 32°N to 56°S), altitude (from sea level to over 5,000 m), watershed, topography, and ocean influence, among other natural factors. In fact, the dynamics of urban centers are intimately linked to geography. For example, latitude determines a city's need for more or less energy to run air-conditioning and heating systems within its buildings, industries, and houses (UN-Habitat 2011). Many cities exhibit intense UHIs associated with their topological position, a fairly closed watershed or by the presence of a thermal inversion layer.

The rapid urbanization process of Latin American cities, in terms of either the built-up area or the number of urban inhabitants, has contributed to important climate and environmental changes. Air pollution, thermal discomfort, health problems, natural events, and climate change are increasingly relevant aspects of urban life. This requires a myriad of viewpoints to understand the urban climate.

The atmospheric pollution produced by industrial emissions and different types of transportation has transformed into one of the main problems for the environmental management of urban areas. According to the Clean Air Institute in Latin America and the Caribbean, at least 100 million people are exposed to air pollution above the limits recommended by the World Health Organization. The report warns that, of the 16 cities that measured PM10 concentrations in 2011, all exceeded the levels recommended by the WHO, and 9 of them exceeded the annual European Union standard (Green and Sánchez 2013). Cities such as Mexico City, Bogotá, and Santiago are exposed to high levels of air pollutants (particularly PM10), affecting the health of all local populations (Romero-Lankao et al. 2013). In Santiago, a direct relationship has been found between the distribution of UHI and the concentration of air pollution in poorer areas of the city on days with the worst air quality conditions (Romero et al. 2010).

Besides the increase in these types of pollutants, the use of wood-burning fuel for cooking and heating residences play a relevant role in the degradation of indoor air quality, especially in the fall and winter. Chilean cities such as Chillán, Temuco, and Coyhaique register high levels of particulate matter linked to wood-burning. At the same time, the pollutants act as neurotoxic compounds, which increase in locations that have a high level of traffic. For example, primary schools located near the street and children exposed to this pollution are associated with worse school performance and lesser cognitive development. For these reasons, some authors (Capel 2016) have named this situation an "airpocalypse", revealing environmental injustice in urban areas and an urgent need to generate social awareness.

1.3 Book Structure: The Approach of the Urban Climate System

To understand Latin American urban climates, it is necessary to take into consideration the location, topology, and position of cities in large-scale frameworks, such as climatic regions, topographical scenarios, and watersheds.

In the case of some large Latin American cities located in the Andes, there is a strong dependence on the city life support system of water accumulated in the Andean mountains. This is also the case for some of the other cities in South America, such as Santiago, Lima, Quito, and Bogotá. Atlantic cities, on the other hand, are heavily dependent on the performance of topoclimates developed along coastal and inland ranges, such as the case of the Mata Atlantica and "sierras" throughout Brazil.

In this context, a challenge in studying the urban climate is to strengthen and promote a conceptual and theoretical integration of Latin American researchers in urban climatology. From a historical point of view, one of the most highlighted studies of urban climate in Latin America is the Brazilian "Monterian" geographic approach. Carlos Augusto Monteiro (1976) based his work on the studies of Max Sorre and proposed, in his PhD thesis, the Urban Climate System (UCS) as a theoretical–empirical framework for the study of urban climates.

The author proposes that UCS organization must contemplate three subsystems mediated by channels of human perception:

- Thermodynamic/thermic comfort: includes the thermodynamic component of the system, which, in its relationships, is expressed through heat, ventilation, and humidity within basic references belonging to this concept
- Physicochemical/air quality: composed of elements inherent to the impacts of emissions and concentrations of atmospheric pollutants within the urban environment
- Hydrometeorological/impact media: grouped into all forms including water (rain, snow, fog), mechanical (tornados) and electric (storms) that have, sometimes, manifestations of intensity that can have an impact on the life of the city by disturbing circulation and services

These three elements of climate are highly transformed within cities and have helped in structuring this book. For each of them, the corresponding problems are identified and addressed through specific phenomena such as: UHIs, urban cool islands, temperature discomfort, thermal stress, flooding, thermal inversion, air pollution, among others (Mendonça 2015). For example, this approach has been applied in Brazilian cities such as the city of Dourados (dos Santos and da Silva 2014). Other relevant contributors to the study of urban climates in Latin America come from Mexico, Argentina, and Chile, including authors such as Jauregui, Mikkan, and Romero. In this context, Chapters 2 and 10 of the book address some theoretical topics of the study of climate in Latin America.

The occurrence of heat and cold waves is a frequent disturbance in Latin American cities. In many tropical and subtropical cities, heat waves are becoming not only an increasing feature of climatic discomfort (see Chaps. 5 and 6), but also a source of disease (see the example of dengue in the Chap. 12) and wider health impacts (Chap. 11 for a Chilean case). The continental shape of South America, with a straight Southern cone, and the archipelagic condition of Central America and the Caribbean, partly moderates the accumulation of heat due to oceanic and coastal ventilation. The topological and topographical location of Latin American cities, especially on coastal zones and riverbeds, is a source of uncertain climatic, safety, and air quality concerns. Chapter 3 reviews the cases of Guayaquil, Lima, Antofagasta, and Valparaíso along the coast of the Pacific Ocean.

In many cities, the population has been confronted with urban sprawl, unscrupulous land use and cover changes, and the presence of UHIs, which are increasing thermal discomfort levels (see Chaps. 5, 6 and 10). It can be assumed that many people do not live under viable climatic conditions, while some inhabitants are displaced to areas where climatic conditions are better and more secure. However, this is not a clear goal in most urban planning and policies, urban design and land use programs and projects. Economic reasons and the subordination of nature and ecology to other social and political priorities explain the current situation, where most of the urban inhabitants have the lowest levels of quality of life, and are relatively poor and excluded, and are permanently threatened by hazards, insecurity, and a lack of institutions to manage their growth and urbanization processes effectively.

The founding of many Latin American cities in the middle or lower position of river basins, or in the foothills of mountain systems, is mainly explained by the water supply, and the need to discharge natural wastewater for protective purposes. Today, it is clear that these geographic factors cannot adequately support large numbers of people, dwellings, vehicles, industries, and other sources of pollution. In addition to such topographical constraints, adverse features, such as UHIs, humidity islands, and ventilation islands, are severely compromising climate and air quality and, as a consequence, the quality of life of an increasing population. Most Latin American urban inhabitants live with challenging local climates and are located in some of the most polluted cities on a global scale (Mexico City, Bogotá, Quito, Sao Paulo, Santiago) (see Chaps. 7 and 8). This requires not only pervasive and immediate improvements, but also available scientific knowledge to incorporate climate change, climate quality, climate comfort, and climate justice in urban and regional planning and management (see Chap. 9).

The occurrence of many extreme events such as droughts, floods, and waterlogging, greatly increases the vulnerability of urban spaces in all Latin American cities. Although in tropical cities, hurricanes and large storms are frequent natural threats and permanent sources of risk (see Chap. 10), droughts, floods, and waterlogging continuously affect cities located in subtropical latitudes and arid lands across the region. Consequently, a relevant number of disasters occur every year, which cause major damage in material goods and services, increased morbidity and mortality (see Chap. 11).

Until recently, the integration of urban climate in urban planning, and green infrastructures has have barely been taken into account. Furthermore, few cases have used climate and air quality as an indicator of quality of life. Consequently, there are few proposals to improve climate quality and to increase climate justice as part of socio-economic equity programs within the cities. Urban planning, urban design, and land use allocation affect urban climate dynamics and patterns at different atmospheric layers across three spatial scales: the urban boundary layer, the urban canopy layer, and the microclimate scale (Oke 1987); these dynamics include the UHI effect, cold and fresh air production, and drainage areas. On a local and micro scale, local climate zones (LCZ) (Stewart and Oke 2012) and urban canyons (Oke 1981) have been used for the analysis and modeling of climate in an international context, and the challenges is to apply these more widely in Latin American cities (see Chap. 4).

One relevant feature on this scale is the study of thermal comfort (TC). TC is defined as a mental condition that indicates satisfaction with environmental thermal conditions. From an environmental perspective, the study of TC has focused on the construction of indices and models that integrate climatic variables. However, multiple studies have highlighted the importance of conducting this type of research using additional variables for analysis, such as physiological status (thermo-regulation and metabolism) and perceptions, in addition to the attributes of urban space, since these are all influential (Nikolopoulou and Steemers 2003; Vanos et al. 2010). Even some relationships between violence and high temperatures in urban area (Pereira et al. 2016) have been developed, with applications. In some European cities, e.g. in Greece, Switzerland, and the UK. However, few experiences have been applied to Latin American cities (see Chaps. 5 and 6).

A last challenge is that of climate change and its relationship with urban scale. The effect of climate change on urban centers is clear, especially through the phenomenon of the UHI (see Chap. 2). Alongside rapid urban growth, climate change is already a fact. Consequently, many cities are highly vulnerable to its impacts (OECD 2010) and at the same time, are the leading source of greenhouse emissions (Mills 2007). Despite Latin American cities having little overall contribution on a global scale, they are highly vulnerable to the impacts of climate change. Tropical cyclones, floods, droughts and heatwaves are increasingly frequent events and have a great influence on the level of risk. According to a CAF report on the Vulnerability Index to climate change in South America it is Paraguay and Bolivia that reveal the highest vulnerability risks. Also, the capital cities in the region show significant vulnerability to climate change, with 48% categorized being at "extreme risk." The highest levels of vulnerability in urban areas are not concentrated in the region's megacities, but in medium-sized cities (Mapplecroft 2014).

Currently, research and public strategies that address urban adaptation plans are being applied in several countries to face climate change. In this regard, the study by Jean-Jacques Terrin (2015) generates interesting proposals for addressing the impacts of UHIs in several European cities, which should be expanded to Latin American cities. In this vein, see the examples in Chaps. 13, 14, and 15.

A relevant example of a natural risk management plan is the case of the city of Manizales, Colombia. The plan includes management areas that are directly related to the prevention of, and recovery from natural hazards, and are mainly related to landslides caused by heavy rains, in addition to incorporating the Territorial Land Use Plan (POTs in Spanish) as a fundamental axis in risk management. The "Guardians of the Slope" program stands out, which seeks to reinforce a culture of risk prevention by understanding the threat and the provision of tools to manage it, and the recognition of women as a central part of the monitoring program (Londoño 2003; PREDECAN 2009).

Some Latin American metropolises have received financial support to implement adaptation or resilience plans from international agencies such as the Helmholtz Centre for Environmental Research – UFZ or the Rockefeller Foundation (100 Resilient Cities), but there are few contributions from a Latin American regional base. As previously mentioned, the lack of basic knowledge is one of the main obstacles. This produces a paradox as the countries and cities that have less information when facing the most negative impacts of climate change are the most vulnerable.

In this context, the main goal of this book is to generate, disseminate, and discuss knowledge about urban climate topics in Latin American cities, and to increase the understanding of its relationships with other dimensions using an inter- and multidisciplinary approach. In this sense, the book expands upon the Monteiro (1976) approach and intends to bring examples of Latin American and, more specifically, South American cities, to an international arena of urban climate research.

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Part I
Urban Heat Islands, Local Climate Zones, and Thermal Comfort

Chapter 2
Urban Climates of Large Cities: Comparison of the Urban Heat Island Effect in Latin America

Pablo Sarricolea and Oliver Meseguer-Ruiz

Abstract The large cities (at least five million inhabitants) in Latin America have grown in terms of both population and spatial extent and have modified the climate more drastically than medium to small cities. These modifications include surface and atmospheric urban heat islands, air pollution, dry islands, etc. Furthermore, the distribution of these modifications in cities follows the morphologies acquired by the various sectors of the city, which are defined as local climate zones. This chapter contains an exhaustive review of the literature of the eight larger cities of Latin America and a presentation of some of the differences and similarities between them and their urban climates. The authors have concluded that not all the large Latin American cities have been studied with the same intensity and that, therefore, the results for the various cities are quite different. Nevertheless, the intensities of the heat islands in these large cities have been found to vary between 3 °C and 8 °C, and population density and latitude offer partial explanations for these differences between urban and non-urban temperatures. A pending task for the large Latin American cities is the incorporation of the new analytical methodologies that are currently proposed with regard to local climate zones.

Keywords Urban heat island · Large cities · Local climate zones · Latitude · Population density

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2.1 Introduction

Urban climatology is the study of local climatic changes that are caused by cities. As with any climate study, urban climate studies cannot be considered in isolation, as they are the result of the statistical averages of the types of weather that occur in a territory. The urban climate is also in continuous exchange with its surroundings and conditioned at other (meso-scalar, synoptic and planetary) levels. Among the most significant modifications that cities exert on climate are land cover changes (substitution of land uses), albedo (decreased reflectivity of its materials) and surface roughness.

The urbanization process leads to radical changes in territories and their atmospheres. It alters the radiation balances, the thermal characteristics, and properties of the surface, the humidity and the winds; therefore, both the natural energy balance and the natural hydrological balance are disrupted.

According to the Fourth Assessment Report (hereinafter AR4) of the Intergovernmental Panel of Experts on Climate Change (IPCC), the contribution of cities to global warming between 1905 and 2005 was 8.1% (calculation based on the ratio of 0.74 °C/100 years of climate change to 0.06 °C/100 years of urban effect), which expresses only the radiative forcing due to changes in land use (IPCC 2007). However, more than 50% of the seven billion human beings on the planet live in cities, which are hot spots for production, consumption, and the generation of waste. According to the United Nations (Ash et al. 2008), cities account for 75% of global energy consumption and 80% of greenhouse gas emissions. In addition, Ash et al. (2008) point out that, without investment and careful planning, cities will be overwhelmed by growing environmental problems. Therefore, the impact of cities on climate change far exceeds those of other terrestrial ecosystems.

The size or magnitude of any "urban effect" on local climatology is often difficult to estimate. Ideally, it would be advisable to possess a broad set of measurements of the region's climate under pre-urban conditions to be able to contrast the observations with the urban condition and make comparisons between the two. However, this is possible only on rare occasions. Instead, studies are commonly based on the comparison of meteorological data from the center of an urban area to those of rural (or non-urban) areas. These urban/rural comparisons provide only an approximation of urban modification.

In short, urban climates comprise both the obvious and the inconspicuous shifting of a regional climate from one type to another, which is influenced and can be largely explained, by urban morphology. This definition reflects changes observed in climatological elements such as temperature, relative humidity, wind, cloudiness, and precipitation, or in more complex indicators of bioclimatic comfort. As a city constitutes a significant change from natural or rural surfaces to other impermeable types of coverage, it becomes necessary to compare its changes with its immediate surroundings.

Urban heat islands are the most widely studied of the changes caused by urban climates (Landsberg 1981; Oke 1987; Roth et al. 1989). This term refers to the

differences between the temperatures recorded in the interior of the city and those of the immediate rural (or non-urban) environment. It should be noted that only those urban and non-urban locations having similar characteristics with respect to altitude, distance to watercourses, and geographic factors should be compared.

A number of mitigation measures have been taken with regard to urban heat islands in recent decades. These measures stem from urban planning and environmental management. One of the most relevant contributions in this sense is the proposal of local climate zones (Stewart and Oke 2012); this concept incorporates those properties of urban morphology (sky view factor, height of buildings, building densities) that have an effect on the heat island and other changes to the urban climate (wind, soil moisture, etc.).

The cities that are most affected by heat islands are those with densely concentrated populations; this has been verified by Oke (1973) and more recently by Roth (2007). They suggest that there might be a direct relationship between the population of a city and the intensity of the heat island to which it is subjected.

Latin American cities have begun to occupy the top positions in global population rankings (United Nations 2014). Although Buenos Aires was the only Latin American city with more than five million inhabitants in 1950, there were already eight cities in that category by 2015 and 34 cities in Latin America have more than two million inhabitants. This illustrates the growing urbanization of Latin America, with both its great advantages and its negative aspects.

The Latin American cities with populations of more than five million are São Paulo, Rio de Janeiro and Belo Horizonte (Brazil), Mexico City (Mexico), Buenos Aires (Argentina), Lima (Peru), Bogota (Colombia), and Santiago (Chile) (Figs. 2.1 and 2.2).

Practically all the large cities in Latin America share common urban morphology features (Borsdorf 2003), with subtle differences, but generally very similar, i.e., a central business district of colonial origin on which the city has grown compactly outward to some round perimeter (radial) representing the border of the compact city. Beyond this is a tentacular growth that follows high-speed axes and then advances in a diffuse urban-rural gradient.

From a climatic perspective, the large cities of Latin America can be subjected to tropical, desert or temperate climates. These zonal macro-climates induce isolated urban climates, as the macro-climate (or regional climate) conditions the properties and intensities of the heat islands, even determining the time of day and year in which the maximum intensities are reached.

Thus, the objective of this chapter is to analyze the properties of the urban climates of the large cities in Latin America. For this purpose, a comprehensive review of the scientific literature on these cities was carried out individually, and then an integrative analysis was performed on all of the information collected (documents retrieved from Google Scholar). This is why the extension of the individual analysis for each city is determined by the quantity and quality of research on urban climate. For the purposes of ordering, the account of the research for each city follows a chronological order, and from the most researched to the least researched.