Cristián Henríquez
Hugo Romero *Editors*

Urban Climates in Latin America

Springer

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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.

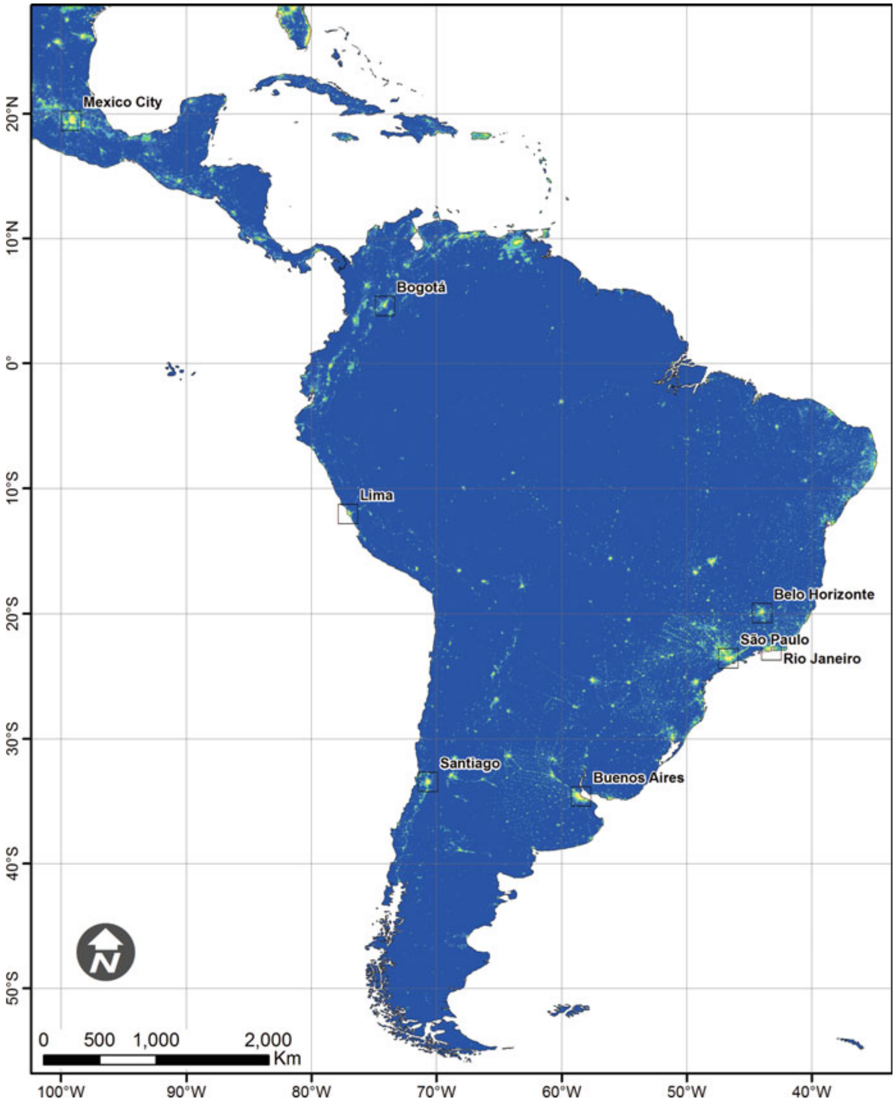

Fig. 2.1 Large cities in Latin America. Based on the National Oceanic and Atmospheric Administration (NOAA's) National Centers for Environmental Information (NCEI) 2013

2.2 Urban Climate of Mexico City

Mexico City is a conurbation in which more than 20 million inhabitants are currently concentrated (Morton-Bermea et al. 2016), and this figure may be even greater if informal settlements are taken into account. The total area of Mexico City is 2,100 km^2. It has a temperate climate with dry winters; this climate is designated

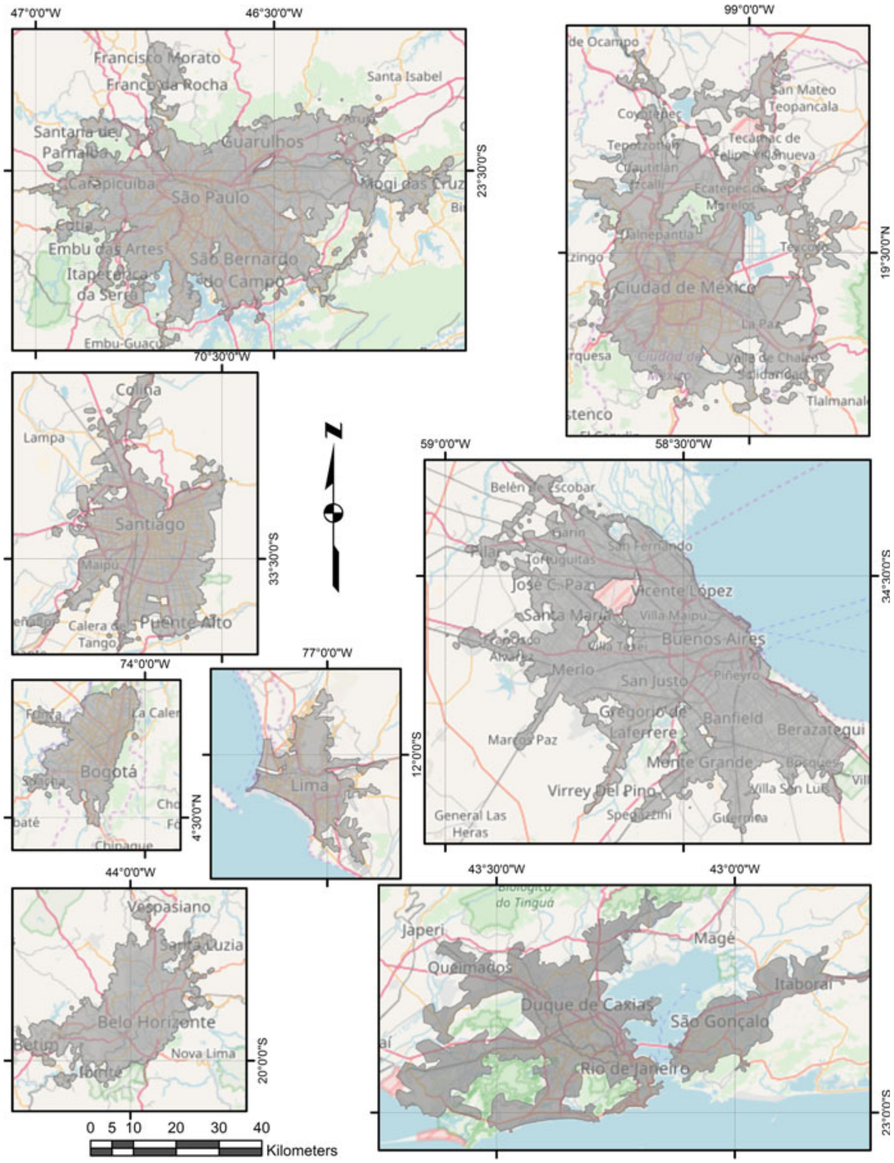

Fig. 2.2 Urban built-up area of large cities in Latin America. Based on the Atlas of Urban Expansion. (http://www.atlasofurbanexpansion.org) and World Urban Areas (Esri, DeLorme Publishing Company, Inc.)

as Cwb according to the Köppen–Geiger climatic classification (Beck et al. 2016). It is located at 19.43°N and 99.14°W, more than 275 km from the coast, at an approximate elevation of 2,250 meters above mean sea level (AMSL). It has an

Table 2.1 Average differences in minimum temperatures between an urban (C.F.E) and a rural (Los Reyes) station in Mexico City (°C)

J	F	M	A	M	J	J	A	S	O	N	D	Avg.
7.6	7.6	7.7	6.5	6.5	4.9	3.5	3.4	5.1	7.3	6.9	9.9	6.4

Source: Jáuregui (1973)

anticyclonic type of weather from October to April (Jáuregui 1973), which intensifies the heat island effect.

It is, without a doubt, one of the cities of Latin America that has been the subject of the most urban climate studies. The most important author of the extensive literature on the urban climate of Mexico City is Ernesto Jauregui (1923–2014). His initial studies were on urban climate. In 1958, he wrote *The Increase in Air Turbidity in Mexico City*, beginning a prolific trajectory on urban climatology, the most significant in Latin America.

Jáuregui (1973) characterized the western area of Mexico City as being cloudier and having even more precipitation than the eastern area, with annual amounts ranging from 1,000 mm in the west to about 500 mm in the east. He compiled the first thermal maps of Mexico City, noting differences of 2 °C in mean temperatures as compared with its surroundings. Regarding the minimum temperatures, he found differences of between 3.4 °C and 9.9 °C (Table 2.1), and an average difference of 6.4 °C.

Jáuregui (1973) emphasizes that the heat island reaches its greatest intensity during the dry season (December–March), as there is a greater frequency of thermal inversion due to subsidence (typical of anticyclonic weather). As he himself acknowledges, his results are very similar to those obtained by Chandler (1965) for the city of London.

To ascertain the spatial distribution of Mexico City's urban heat island, he carried out mobile transects between October 1968 and February 1969, primarily on clear, calm nights. The best results were obtained between 4:15 am and 6:15 am, i.e., before dawn, when the minimum temperature is recorded. The heat island is concentric and slightly displaced to the SW.

Jáuregui (1973)analyzed not only the temperature, but also the pollutants in the air, and what he called the urban rain island, which, with daily data from more than 30 stations, coincides with the distribution of the urban heat island on some days, although this pattern does not appear in the annual average.

These initial observations have been substantiated by Jáuregui (1997) who reaffirms that the heat island of Mexico City, which he characterizes as tropical, occurs at dawn (up to 5 °C of difference), as opposed to those middle-latitude cities whose heat islands reach their maximum intensity before midnight (Oke 1982).

Another finding concerns the evolution of the heat island during the twentieth century (Jáuregui 1993); a comparison of data from urban and rural observatories reveals that the intensity of heat islands has increased with the demographic growth and spatial expansion of the cities. Curiously, the article does not mention anything about climate change, which surely influences the observatories.

During the dry season, the intensity of Mexico City's heat island can reach 8 °C (Jáuregui 1997, 2000) before dawn (6:00 am) under clear, calm skies. Surely, the time at which the heat island reaches its greatest intensity has discouraged the realization of satellite image studies. However, special attention should be given to the work of Cui and De Foy (2012), which confirmed the occurrence of cold islands during the day at any time of year and of surface heat islands during the dry season, using Terra MODIS satellite imagery. In addition, Cui and De Foy (2012) indicate that, during the night, the relationship between the heat island and atmospheric stability is more pronounced than its relationship to urban vegetation. The maximum surface heat island intensity is 10 °C and it occurs near midnight.

Recent trends in urban climate studies have followed the logic of local climate zones (Stewart and Oke 2012), and Mexico City has been no exception. Oscar Brousse and Alberto Martili have generated local climate zones for Mexico City and these can be seen at http://www.wudapt.org/cities/in-the-americas/. However, the information is preliminary and requires verification by an expert.

2.3 Urban Climate of São Paulo

São Paulo is the largest conurbation in Latin America (the total area of the city is 2,119 km^2). It has more than 21 million inhabitants and lies 700 m above sea level and about 50 km from the coast, which gives its climate an oceanic influence characterized by frequent sea breezes (Bourscheidt et al. 2016). Added to this is its situation at the tropical/subtropical boundary (23.55°S and 46.64°W), which gives it a rainy, temperate climate (Cfb) according to Beck et al. (2016).

The São Paulo metropolitan area has been the subject of several studies on urban climatology. Notable among these is the work of Carlos Augusto Figueiredo Monteiro, who directed numerous studies along these lines following the blueprint of the Urban Climate System (UCS) which he presented during the 1970s. The "Brazilian School of Urban Climatology" had its origins in his work. Mendonça (2015) tells us:

> When developing the proposal for UCS, Monteiro pointed out that sciences in general, and geography more specifically, began to show interest in the study of cities. After more than 40 years, the concern of scientist and politicians worldwide has shifted emphatically toward urban areas and the numerous problems associated with these areas.

However, the first study on the urban heat island of the city of São Paulo and its metropolitan area was carried out by Lombardo (1985), who identified its diurnal, seasonal, and spatial variation by means of combining temperature and relative humidity measurements at 45 locations and using surface temperature images at a spatial resolution of 1 km^2.

Lombardo's study identified temperature differences of between 5 °C and 10 °C between the center of the city and the outskirts of the urban area. A second study

(Prefeitura do Municıpio de São Paulo 1993) was carried out in 1993 with similar results.

The contributions of Tarifa and Armani (2001) to the study of climate zones are significant, as they developed a classification system that was greatly simplified compared with that proposed by Stewart and Oke (2012).

In the case of Ribeiro Sobral (2005) the term "thermal pollution" is included to affirm that it is necessary to correlate the spatial distribution of temperature with the spatial distribution of air pollution.

It is important to note that most of the studies carried out for the city of São Paulo have involved the use of satellite images, and with a strong preference for Landsat. At the time the images were captured (local solar noon) seriously hinders determination of the time of maximum intensity for the heat island. For studies with fixed stations, we must cite Ferreira et al. (2013: 36), whose work was primarily concerned with determining the urban energy balance; in spite of this, they indicate that "In cities located in tropical and subtropical regions, the UHI (urban heat island) is less intense than at higher latitudes, and it is more pronounced during the day and in the summer because the UHI intensity is predominantly driven by solar radiation heating of the urban canopy at lower latitudes." This statement differs from other case studies (e.g., Mexico City).

Ferreira et al. (2013) indicate that their study "showed that the maximum UHI intensity in the city of São Paulo occurs during daytime, between approximately 14:00 and 16:00 h, varying between 2.6 °C (July) and 5.5 °C (September)."

Finally, the work of Barros and Lombardo (2016) indicates that the maximum intensity of the São Paulo heat island is 8 °C.

There are three studies regarding the local climate zones of Stewart and Oke (2012), at http://www.wudapt.org/cities/in-the-americas/, but only one of them can be viewed.

2.4 Urban Climate of Santiago, Chile

Santiago is the economic, demographic, industrial, commercial and financial capital of Chile. With a surface area of 15,403.2 km^2, it is the smallest of all the regions in the country, but with a population of approximately seven million inhabitants, it is also therefore the most densely populated region. It has a *Mediterranean* climate, which exhibits an extended dry season and rainy winters. According to the Köppen–Geiger classification, it exhibits a temperate climate with dry summers (Csb; Sarricolea et al. 2017). Regarding the extreme temperatures for the 1981–2010 reference period, the average maximum temperature recorded in January is 30.1 °C, whereas the average minimum temperature recorded in July is approximately 3.9 °C, which implies a thermal oscillation of 26.2 °C. The annual average temperature is 14.7 °C; January is the warmest month, with an average temperature of 21.2 °C, and July is the coldest month at 8.2 °C, with the average thermal amplitude being approximately 13 °C.

The initial studies of the urban heat island for the city of Santiago were conducted by Aceituno and Ulriksen (1981) and then by Salinas (1982), all of whom made thermal transects at night by car. Salinas (1982) detected differences of 3–4 °C. Two decades later, new transects were conducted by another team of researchers from the University of Chile, led by Hugo Romero. The results obtained by Molina (2007) were similar to those of previous decades, but this time, transects were conducted three times during the day (10:30 am, 14:30 pm, and 22:30 pm), and correlated with surface uses. These studies were followed by Smith and Romero (2016) who were looking for explanatory variables of intra-urban temperatures.

Satellite images were also used, as was the case for studies in other cities. One of the most outstanding studies along these lines is that of Romero et al. (1999), who introduced the use of NOAA thermal images to characterize Santiago's urban climate. Using Landsat images, Peña (2008, 2009) distinguished urban heat sinks at noon and located the heat islands outside the city, at the western periphery.

However, none of the studies conducted for Santiago had established the month, time of day, season, and synoptic condition of the maximum intensity of the heat island phenomenon. The study by Sarricolea and Martin-Vide (2013, 2014) stands out in this regard. First, the study established that the maximum heat island intensity in the city of Santiago occurs at midnight during the summer, with differences of up to 9 °C compared with the air temperature of Cerrillos and Talagante. Then, the spatial distribution was detected with 53 Terra-MODIS satellite images from 2010 (all free of clouds). The results show that the urban surface heat island tends to reach a maximum in the central and eastern municipalities, where it exhibits intensities of greater than 5 °C.

The studies on pollution and urban climates that stand out the most are those of Romero et al. (2010), who shed light on the environmental injustices in the city of Santiago, as the most polluted areas are those in which the population has the lowest income, whereas those who contribute the most to air pollution breathe air that is less polluted.

Regarding local climate zones, there have been considerable advances on the part of the team led by Henríquez et al. (2015), Henríquez (2017) and the partial study conducted by Irarrázaval (2012).

2.5 Urban Climate of Buenos Aires

Buenos Aires (34.61°S, 58.40°W), the capital of Argentina, is the 13th most populated conurbation in the world and the third most populated in Latin America (United Nations 2014). The Buenos Aires metropolitan area has approximately 15.2 million inhabitants and lies at an average elevation of 25 m AMSL. It has a warm, temperate, rainy climate (Cfa) (Beck et al. 2016), and there is a slight seasonality to its precipitation that results in pluviometric maximums during the summer.

The first urban climate study for the city of Buenos Aires was the doctoral thesis of Camilloni (1995). This thesis refers to previous works. One of them was by

Camillioni and Mazzeo (1987), who compared data from the Buenos Aires Central Observatory (BACO) and Ezeiza Airport (EZA) between January and July 1982 and observed that the maximum differences are recorded during daylight hours in July and at night in January. Another study mentioned was that of Rusticucci and Vargas (1991), who analyzed temperatures at the same observatories at 02:00, 08:00, 14:00, and 20:00 during the period from 1968 to 1980 and found that the heat island occurs during the night and the cold island at 14:00.

Camilloni (1995) indicated that the first heat island to occur in the series was around 1950 and it has intensified since then, but with a lower rhythm than initially (1950–1965). Thus, between 1975 and 1990, the BACO and EZA series exhibited a pause (heat island hiatus).

This was followed by the study of Figuerola and Mazzeo (1998), which indicated that the heat island begins to intensify after sunset, reaching its maximum intensity at 6:00 am. This is quite similar to Jauregui's findings for Mexico City. The heat island reaches its greatest intensities in the winter (4.6 °C), but does not exhibit great differences from the summer intensities (4.1 °C).

In any case, there is a consensus in the literature that the Buenos Aires heat island is more pronounced in the winter months and is primarily associated with very cold air masses (Bejaran and Camilloni 2003).

All of the previous studies on the Buenos Aires heat island have used synoptic hours. Thus, the study conducted by Camilloni and Barrucand (2012) constitutes a very significant contribution. They analyzed time series at BACO and EZA between 1976 and 2007. The average intensity of the heat island reached 2 °C between 00:00 and 06:00 am. The season in which the heat island exhibits its greatest intensity is summer, followed by spring, fall, and finally winter, contrary to previous studies. Another finding is that the intensity has decreased in recent decades with 1996–2005 being the decade exhibiting the lowest intensity, followed by 1986–1995 and 1976–1985. This decrease occurs in all seasons.

2.6 Urban Climate of Bogota

Bogota is the largest city in Colombia and the sixth largest in Latin America. It has a population of 9.8 million. It is located in the middle of the Andes Mountains at 4.61°N and 74.08°W and has an average elevation of 2650 m AMSL. It has a mountain climate, but according to Beck et al. (2016), its climate is Mediterranean (Csb), with January being the month with the least precipitation (<40 mm) and a total annual precipitation of approximately 1,000 mm.

There are only two urban climate studies for Bogota: those of Pabon et al. (1998) and Ángel et al. (2010). Pabon et al. (1998) point out that the heat island, which is located in the city center and expands northward, has become noticeable since 1970. Ángel et al. (2010) substantiate these results, but show the heat island expanding toward the north-west of Bogota. The heat island reaches an intensity of 3 °C. This agrees significantly with Alcofarado and Matzarakis (2014), who demonstrated, after analyzing more than 150 cities throughout the world and their latitudinal position, that heat islands in tropical cities have the lowest intensities, and that heat islands in cities located between 40° and 60° (N or S) reach the highest intensities.

In the case of Bogota, the time of day and the season in which the maximum intensity of the heat island occurs are unknown.

2.7 Urban Climate of Lima

Lima (12.04°S and 77.03°W) is the capital of Peru and is located in the western region of South America on the shores of the Pacific Ocean. It has 9.9 million inhabitants, which makes it the fifth most populous city in Latin America. It has a warm desert climate (BWh according to Beck et al. 2016). This desert condition has given rise to few urban climate studies, as changes in land use have not involved replacing green surfaces with cement. The changes have been, more than anything, in terms of the roughness of the terrain.

The only mentions of Lima's urban climate have been made by Roth (2007) who cites Jáuregui (1986), but they did not include any data relevant to the characterization of the climate. In 2010, Barros completed an engineering thesis entitled "Modificaciones térmicas en la ciudad de Lima: análisis de la presencia de la isla de calor urbana," to which access is not available. However, Soberon and Obregon (2016) point out that Barros identified the occurrence of the heat island during the summer, with warm nuclei in the center and at the times that coincide with maximum daytime temperatures (16:00 h).

Soberon and Obregon (2016) used Landsat images for their work, based on the substantiation of the surface heat island. Their results show that the heat island is negative at the time at which the satellite passes, and there is little correlation with air temperature.

In summary, the intensities of the heat island are unknown according to these works, but there are indications of greater frequency in summer and at 16:00 h. As in the case of Santiago of Chile (Peña 2008), Landsat satellite images show the heat sink effect, in this case, in the eastern hills of the city.

2.8 Urban Climate of Rio de Janeiro

Rio de Janeiro is the second most populous city in Brazil and the fourth most populous in Latin America (12.9 million inhabitants). It is located at 22.90°S and 43.21°W at an average elevation of only 11 m AMSL. Its regional climate is very similar to that of São Paulo, but the Köppen–Geiger climatic classification defines it as tropical monsoon (Beck et al. 2016), as its average temperatures are greater than or equal to 18 °C throughout the year, and its dry season occurs during the winter months (June, July, and August); its annual precipitation exceeds 1,000 mm.

According to Marques Filho et al. (2009), urban climatology studies in tropical cities differ greatly from those of temperate climates; they stress that Rio de Janeiro exhibits an urban heat island that is generated during the morning, rather than during the night as occurs in temperate zones. The heat island exhibits a greater intensity of 4–5 °C during the transition from summer and during the dry winter (February–May) compared with the range of 2–3 °C during the rest of the months. The cold islands occur around 18:00 h, the key determinant being the weakness of the wind (urban breeze) over the urban area.

Using Landsat images for the winter months, De Lucena et al. (2013) give some indications regarding the heat islands in Rio de Janeiro, citing vegetation as an explanatory variable for the temperature differences between urban and rural areas. In fact, the island is concentric in the urban center and diminishes at the periphery. The problem with this study is that it does not establish the intensity of the heat island and concedes that it made use of only three satellite images taken under the synoptic conditions that are conducive to the occurrence of the heat island.

Subsequent to these studies, Sena et al. (2014) conducted a follow-up study with satellite imagery; the difference is that this study used MODIS images. It used a total of 4 h daily: 02:00, 05:00, 13:00, and 16:00 UTC (respective local times of 23:00, 02:00, 10:00 and 13:00) between 2003 and 2010. The heat island's greatest intensity occurs at 16:00 UTC, with minimum urban–rural differences of 10 °C during the winter and a maximum summer intensity of more than 15 °C.

2.9 Urban Climate of Belo Horizonte

The city of Belo Horizonte is the third most populous city in Brazil and the 8th most populous in Latin America, with approximately 5.7 million inhabitants. It is located at 19.92°S and 43.94°W at an average elevation of 760 m AMSL, at a distance of 350 km from the coast. Its regional climate, which is temperate with a summer rainy season and dry winter, is classified as Cwa according to Köppen–Geiger (Beck et al. 2016).

The city has been the subject of fewer studies than the more populous cities of Brazil, but it has some interesting and quite recent nuances in terms of the study of climatic comfort and microclimates; there are, however, few references to the urban heat island.

One of the first studies was by Abreu and Assis (1998), who detected Belo Horizonte's heat island, with an intensity of more than 3 °C and a maximum development at 15:00 local time, by means of mobile transects.

Magalhães Filho and Abreu (2010) subsequently investigated Belo Horizonte's heat island, but their methodology, which uses standardized temperatures, precludes a determination of intensities and the time of maximum development for the heat island. Nevertheless, it is located in the city center.

An earlier study, the doctoral thesis of Magalhães Filho (2006), is more explicit and proposes a heat island with an intensity of 4.7 °C between 16:00 and 18:00 h.

Finally, with reference to Belo Horizonte's climatic comfort, Hirashima et al. (2018) place it between 16 °C and 30 °C. That is, the thermal perception in a *tropical* climate is different by almost 4 °C than other climates. This means that the comfort zone has to be matched to the respective climate region in studies.

2.10 Summary

There are urban climatology studies for all large cities in Latin America; however, the studies differ greatly in terms of emphasis and the methodologies used. In many cases, these are very different.

Undoubtedly, the most frequently studied urban conurbation has been Mexico City, the studies of which are very similar to those of the world's larger cities. The salient South American cases are those of Buenos Aires, São Paulo, and Santiago, Chile. Less extensive studies have been carried out for the other cities, and these require further investigation.

Table 2.2 summarizes the results obtained for each city.

This shows that Bogota is the only city whose heat island is of relatively low intensity relative to its population. There are no studies for Lima that enable the intensities to be established; this needs to be addressed in terms of urban climatology.

The future and pending challenges of territorial planning in large cities are to include urban climatology in both the diagnostics and the zoning proposals for land use and coverage, not only because of the temperature, but also because of climatic

Table 2.2 Eight cases of varying urban heat island (UHI) and suburban heat island (SUHI) intensities

City	UHI intensities (°C)	Hour UHI (local times)	Season UHI	SUHI intensities (°C)	Hour SUHI (local times)	Population
São Paulo	8.0	16:00	Summer	–	–	21,066,245
Mexico City	8.0	06:00	Winter	10.0	00:00	20,998,543
Buenos Aires	4.6	06:00	Winter	–	–	15,180,176
Rio de Janeiro	5.0	06:00	Fall	15.0	–	12,902,306
Lima	–	–	Summer	–	–	9,897,033
Bogota	3.0	–	–	–	–	9,764,769
Santiago	4.8	00:00	Summer	5.5	00:00	6,507,400
Belo Horizonte	4.7	16:00	–	–	–	5,716,422

comfort and the quality of life of the population. Many solutions to urban problems and local climate depend on better public spaces, better construction standards, and more social inclusion.

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Chapter 3
Urban Climate in the South American Coastal Cities of Guayaquil, Lima, Antofagasta, and Valparaíso, and Its Impacts on the Energy Efficiency of Buildings

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Abstract Sustainable urbanization remains one of the central challenges for South America. Cities of this region are expanding very fast and this impressive urban growth has a significant impact on the environment, on energy consumption, and on public health. This chapter explores the urban heat island (UHI) effect on the climate of Guayaquil, Lima, Antofagasta, and Valparaíso. These four cities are important urban centers on the Pacific coast of South America. The UHI effect is simulated by using the Urban Weather Generator tool (UWG), a coupled atmospheric–building simulation model that uses urban form parameters to transform rural weather files into urban weather files. Urban form parameters considered in the analysis are the built-up ratio, the facade ratio and the green area ratio, obtained for 24 one-hectare random samples and running a principal component analysis and a k-mean cluster to group them. Simulation results show the presence of a UHI effect that varies between 2 and 5 °C during the night and a more dispersed situation during the day. Valparaíso

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and Guayaquil seem to have higher UHI than Lima and Antofagasta, probably because of the difference in the temperature ranges (higher maximum temperatures). Some hypotheses regarding the influence of the Pacific Ocean, such as urban form, heat generation in the street, building energy use, impervious materials on the resulting UHI effect are formulated and discussed, along with an estimation of the impact on the built environment looking at energy consumption, comfort felt by users, and vulnerability to heat waves.

Keywords Urban climate · Urban Heat Island · Energy consumption of buildings · Coastal cities · South America

3.1 Introduction

Cities are dissipative structures that transform energy into heat (Prigogine 1984). They need enormous quantities of energy to maintain specific urban functions such as transportation systems, offices, commercial and residential buildings, air conditioning, etc. (Madlener and Sunak 2011). As a result, urbanization has a direct impact on climate, for example:

(1) It has an impact on the energy consumption of buildings
(2) It has an impact on the air quality and on public health
(3) It has an impact on the comfort felt by people in buildings and streets

Moreover, built structures deeply modify ecological processes (Alberti 2005). Urban form changes the wind flows, generating residual heat in some urban canyons, reducing the homogeneity of several environmental parameters. Impervious materials such as roads and buildings absorb solar radiation – re-emitted later in the form of thermal radiation – and reduce the evapotranspiration of the green biomass. Under global climate change, with average temperatures increasing, urban climates in the future will have a greater influence on the energy demands of cities induced by a reduced thermal comfort, jeopardizing the public health of urbanites.

The urban climate concept is used to analyze the climate modification generated by the built environment (Landsberg 1981). Urban climatology studies the specific pattern of urban heat generation, resulting in a radiation trapping from directly produced heat inside the buildings and in the streets: the urban heat island (UHI). Over the last 30 years, numerous studies have recorded the UHI effect for many cities, especially in Europe, Asia, and Australia (Santamouris 2007, 2015, 2016; Kim and Baik 2004; McCarthy et al. 2010; Goldreich 1995; Giridharan et al. 2007; Hua et al. 2008; Mirzaei 2015). In South America, the UHI monitoring has been limited to a small number of cases (Sarricolea and Romero 2010; Palacios 2013; Guillén and Orellana 2016; Inostroza 2017). Conducting more research on urban climate and UHIs is of great relevance for several reasons, to mention but a few:

(1) South American cities have very high rates of urban expansion (Inostroza et al. 2013), which dramatically increase UHI generation
(2) The urban sustainability of Latin American countries could be the edge of the ecological challenge of the world (Palme 2015)
(3) The impact of climate change and of heat waves could be extreme on cities (IPCC 2014)
(4) Severe changes are expected in the patterns of energy use in cities, especially the South American megacities (Cohen 2004, 2006)

This chapter analyzes the urban climate, focusing on the UHI phenomenon in four cities located on the Pacific coast from Ecuador to Chile: Guayaquil (2,000,000 inhabitants), Lima (about 10,000,000 inhabitants), Antofagasta (an estimated 450,000 inhabitants), and Valparaíso (1,500,000 inhabitants). These four cities can provide an illustrative urban climate panorama for South American coastal cities, looking at the aforementioned future challenges. First, they are important economic centers, where the expansion rates and the GDP growth have an impact on the patterns of energy and material use. These cities are also urban areas with great inequality of resources distribution, and in this sense are absolutely representative of the South American region. At the same time, these four cities have different climates: Guayaquil's climate is tropical wet, Lima and Antofagasta have arid climates, and Valparaíso has a Mediterranean climate. Although coastal cities normally have lower UHI compared with other emplacements (Sakakibara and Matsui 2005), owing to the presence of sea–land breezes, arid environments could have also lower UHIs, because of the nocturnal cool down, by radiating the heat produced during the day to the sky.

Some studies conducted in Asia suggest that cloudiness might be a less relevant factor than the availability of breezes (Kim and Baik 2004). Studies conducted principally in Europe show unclear results regarding the seasonality of the UHI phenomenon: in some cases, the winter season has the highest UHI intensities, whereas in others, the summer season is more affected by UHI (Santamouris 2007; Morris et al. 2001). Within the inter-tropical region, it is possible to find more uniformity across the year because of the reduced seasonal variations in temperature and solar radiation. For this reason, a difference between Guayaquil and Valparaíso can be expected. The seasonality of the humidity is also a relevant factor. In Lima and Antofagasta, the cloudiness is more intense during the winter morning, reducing the radiation exchange between the city and the sky.

3.2 Climate and Building Sector Regulations in Ecuador, Peru, and Chile

South America has a broad variety of climates, from the tropical humid to the coldest mountain and tundra climates, following the Köppen–Geiger classification (Kottek et al. 2006). The Pacific coast presents a large variety of climates, from the tropical to the oceanic (Fig. 3.1). In general, the South American coastal climate is controlled by the cold Humboldt Current and by the Pacific anticyclone, which generate the sea–land breezes. At latitudes closest to the Ecuador, the Intertropical Convergence Zone (ITCZ) is responsible for warm currents. A very important phenomenon, which happens every 3–4 years, is the so-called “El Niño Southern Oscillation” (ENSO), that is, a change in the ocean temperatures that modifies the ITCZ and often inverts the air circulation patterns of many zones of influence in Central and South America. In Chile, the ENSO frequently causes severe rains in the arid Atacama region (the last one in 2015), which represents a dangerous event for unprepared societies. As observed by some researchers (Garreaud and Rutllant 1996; Vargas et al. 2000), before the “El Niño” occurs, intense rainfalls take place across central and northern Chile. For a detailed analysis of the present-day South American climate, refer to Garreaud et al. (2009).

With respect to the climate change, some studies indicate that in the coastal environment, average temperatures are decreasing by 0.2 °C per decade, whereas in the Andes, temperatures are increasing by 0.25 °C per decade (Falvey and Garreaud 2009). This fact is extremely important, because many cities of the region lead onto the Pacific Ocean coast, such as the four cities investigated here. Studies conducted in the United States (Lebassi et al. 2011) also indicate that UHI in the coastal environment could generate an increase in the sea–land temperature gradient, that is, counteracting the phenomenon by itself, increasing the wind intensity. The implications for the summer cooling of the built environment (both on a city and a building scale) could be very severe, because natural ventilation is the most frequently used conditioning strategy for most inhabitants of the cities studied (Palme et al. 2016b).

The Köppen–Geiger climatic classification, however, is not directly usable for urban and building sector analysis. For this reason, some alternative classification methods have developed maps directly related to habitability, considering the four environmental variables that influence thermal comfort (Fanger 1970; Olgyay 1963): temperature, humidity, solar radiation, and wind speed. In Ecuador, Peru, and Chile, the respective Housing Ministries have developed climate maps and norms establishing the minimum standards for the building sector. In Ecuador, it is possible to identify at least three important macro-climatic regions: the coast, the highlands, and the equatorial rainforest. However, this classification is not representative of all the climate variations, from the Af and Aw of the coast and rainforest to the Cfb and Cwc of the highlands. For this reason, a new classification was proposed for the new Norm of Construction (NEC), currently in review. The map is already available, published together with guidelines for energy housing efficiency in Ecuador (Palme et al. 2016c). In this new map, the country has been divided in six zones: very hot humid, hot humid, continental rainy, continental temperate, cold, and very cold (Fig. 3.2).

In Peru, the macro-regions are very similar: coast, highlands, and equatorial rainforest; however, the coastal region looks totally different from the Ecuador coast: it is arid and colder. In Peru, it is possible to identify the Af, Am, and Aw regions, the BWh, BWk, BSh, BSk, and the Cfb and Cwc regions. For urban and

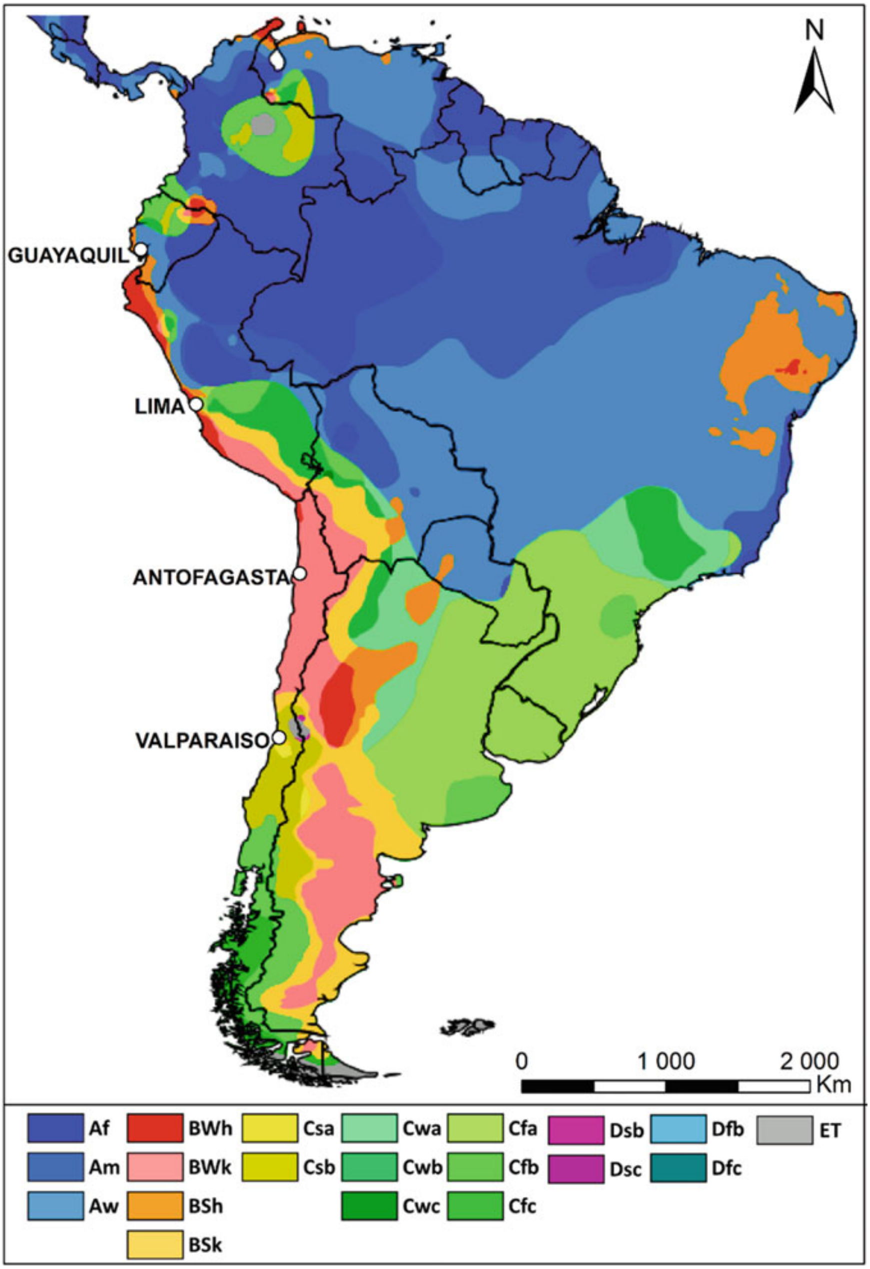


Fig. 3.1 Köppen Geiger climate distribution for South America. The climate definition considers five main climates (A: equatorial, B: arid, C: warm, D: snow, and E: polar). These main climates are divided according to the precipitation (W: desert, S: steppe, f: full humid, s: summer dry, w: winter dry, m: monsoonal) and temperature (h: hot arid k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, F: polar frost, T: polar tundra). Adapted from Peel et al. (2007)

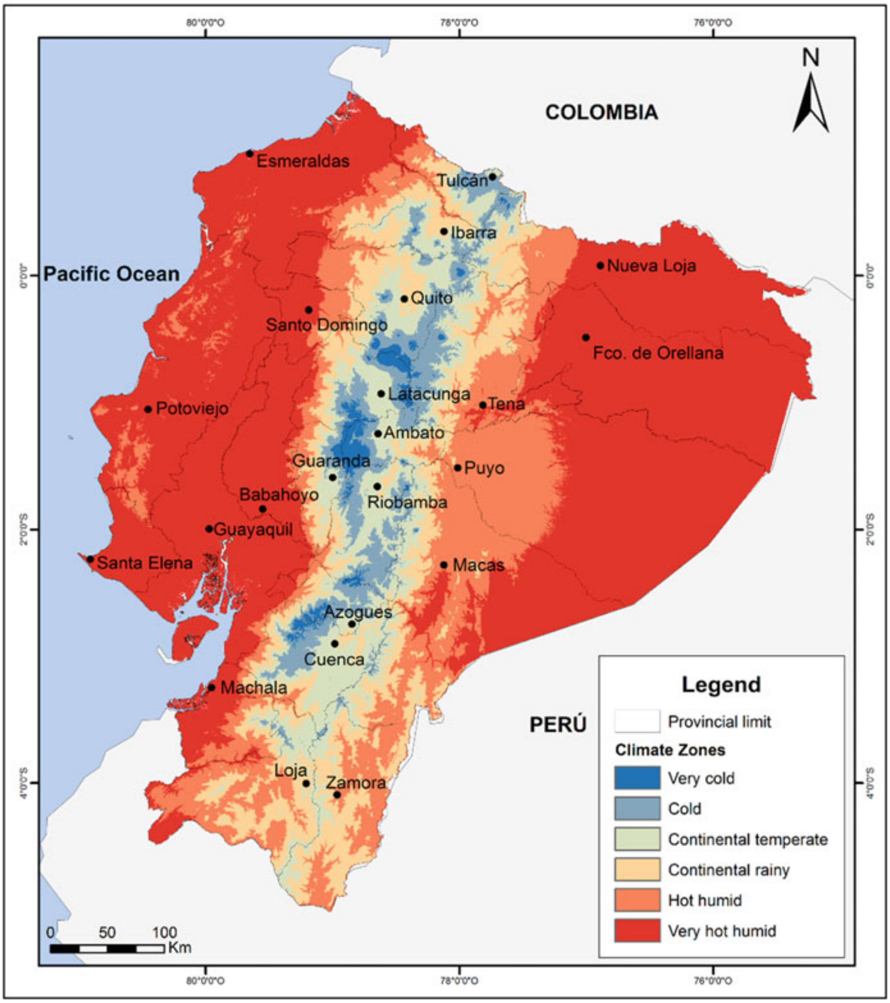


Fig. 3.2 Climate definition for housing in Ecuador. Adapted from Palme et al. (2016c)

building purposes, the Housing Ministry defines nine zones: coastal desert, desert, humid subtropical, humid tropical, and five different Andean climates (Fig. 3.3).

In Chile, it is possible to identify at least five macro-regions following Köppen–Geiger: BWk, Csb, BSk, Cwc, and ET. A more detailed classification for Chile can be consulted in Sarricolea et al. (2016). The Chilean regulation NCh 1079 (2008), developed in 1973 and reviewed in 2008, defines nine zones from the point of view of habitability: the coastal desert, the internal desert, the highlands, the transversal valley, the central coast, the central internal, the south coast, the south internal, and the extreme south (Fig. 3.4). The Housing Ministry, however, proposed another classification, using the concept of "heating degrees day" (MINVU 2008). The

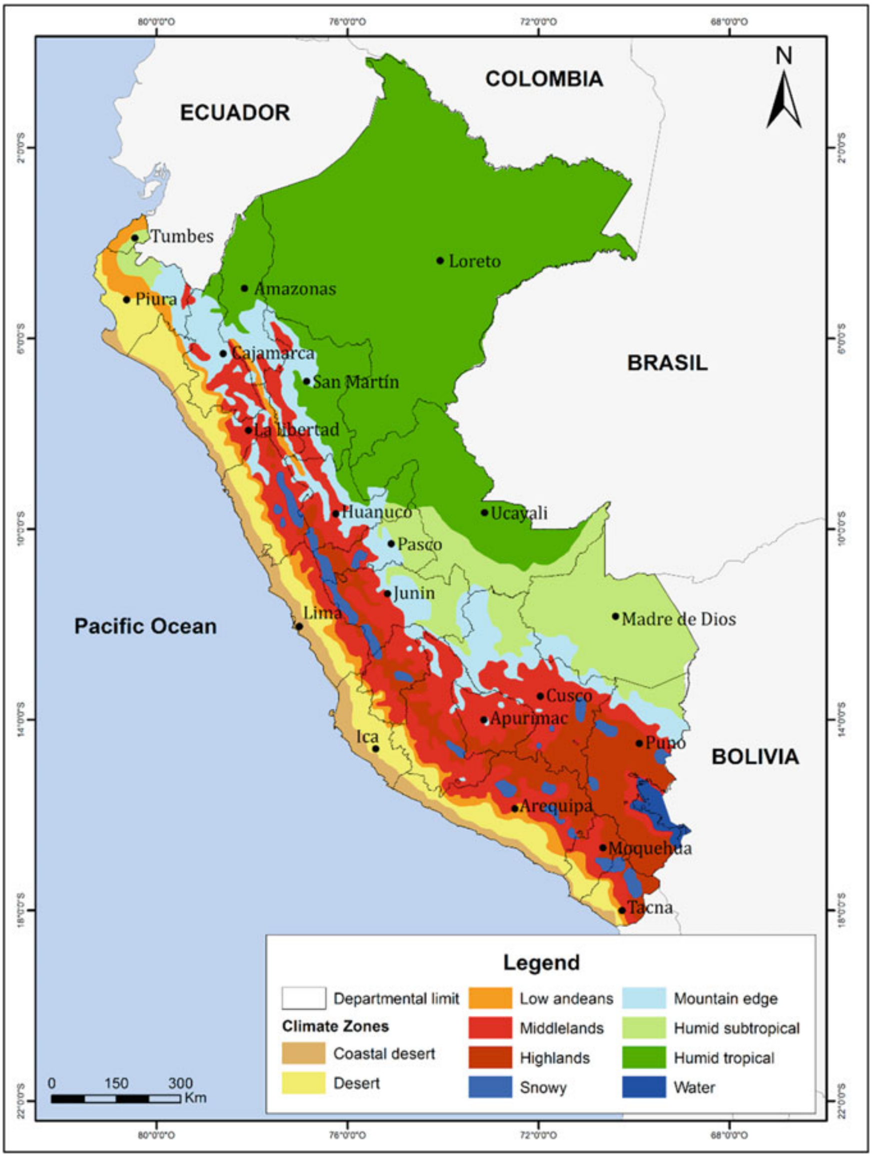


Fig. 3.3 Climate zone definition for housing in Peru. Adapted from the Peruvian Government (2016)

general problem with these methods of generating regulations is that the change in the environment is not considered: in a warmer world, due to climate change, and especially under urban conditions, the applicability of the resulting standard values for the thermal behavior of construction materials and building design is extremely

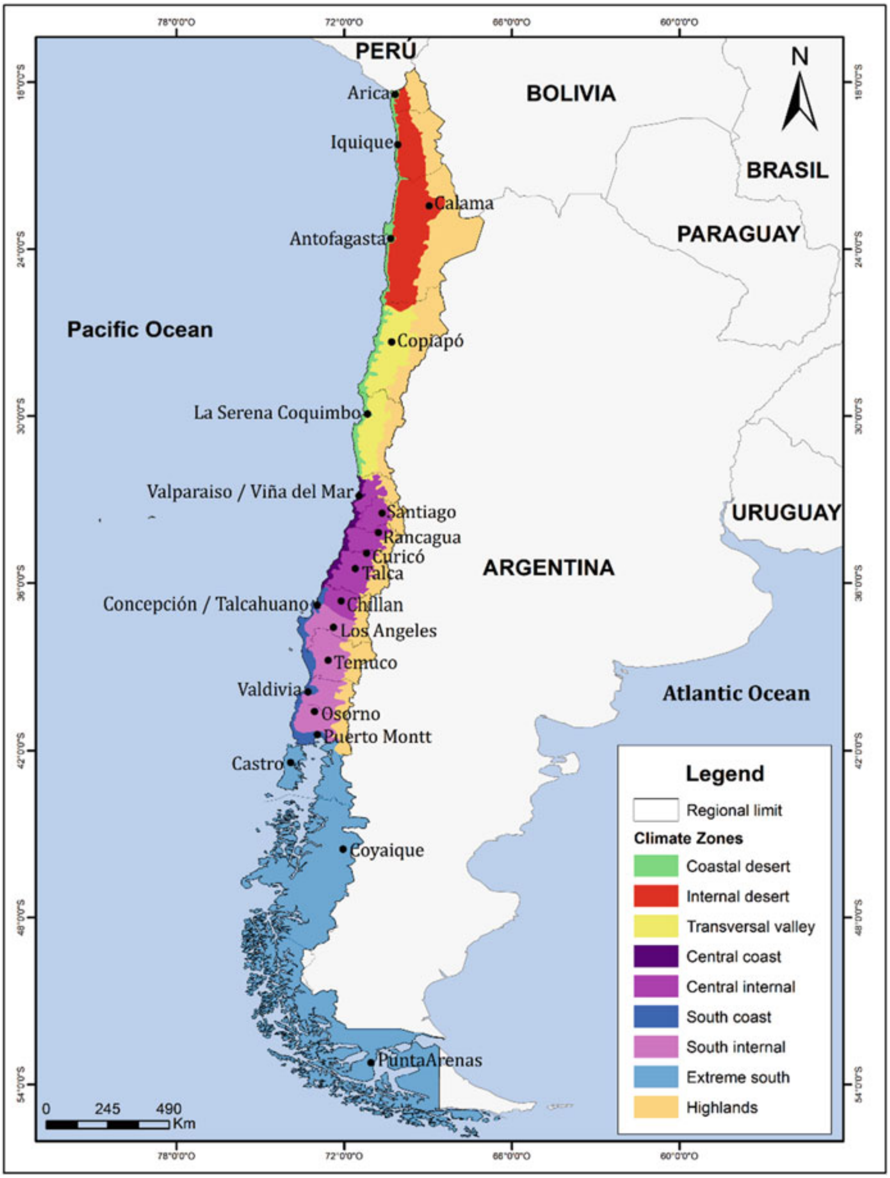


Fig. 3.4 Climate zone defined by NCh 1079. Adapted from Nch 1079 (2008)

reduced and, in some cases, absolutely wrong (Palme 2014, 2015; Palme and Vásquez 2015). Assessing the UHI impact in South American cities helps to generate new sets of norms, better adapted to the real environment in which we are living.

3.3 Cities of the South American Pacific Coast

Many important cities of South American Region lead onto the Pacific Coast. In Ecuador, the big city of Guayaquil leads onto the river Guayas, in a very hot and humid climate. The city was characterized by fast growth during the second half of the twentieth century, with one of the highest degrees of sprawl of South America. Most of the city consists of family houses, normally one or two stories. Lima, the capital of Peru, leads onto the coastal desert. This city is continuously expanding, from south to north, following the coastline, but also from west to east, occupying the mountains and valleys. The climate of Antofagasta is similar to that of Lima, with average temperatures of about 25 °C and small oscillations day–night and seasonal. The city structure is determined by the orography: the coastal mountain leaves only a small corridor in a north–south direction. Valparaíso has a Mediterranean climate, with seasonal and day–night temperature variations that can reach the 10–15 °C. The metropolitan region is composed of the urban clusters of Valparaíso, Viña del Mar, Villa Alemana, and Quilpué, with different morphologies and microclimates. In Valparaíso downtown, high-rise buildings generate more controllable local climates (Carrasco 2008), whereas other urbanization clusters have more dispersed buildings. All of the cities analyzed present serious problems of inequality and social segregation, which historically have been generating risks for public health, especially under extreme events (Antofagasta rainfall 1999; Valparaíso fire 2015). Dwellings in some neighborhoods are deficient in materials and water accessibility. Inostroza et al. (2016) have shown that in these neighborhoods the UHI and heat waves are stronger than in other city sectors. In Lima or Guayaquil, the poverty in some of the very dense emplacements is also very high, and this part of the population is experiences high exposure to heat. In general, it should be noticed that in the cities analyzed, the use of air conditioning is reduced to a very small sector of the population. This fact can be regarded as positive in terms of energy consumption and the resulting forcing function on the greenhouse gas emissions; however, it leads people living under sensitive conditions to face an increase in heat.

3.4 Urban Heat Island Assessment

There are three ways of assessing the intensity of the UHI. The first is monitoring on-site, obtaining very accurate results, but with the inconvenience of requiring many stations right across the cities, restricting the spatial range of the analysis. The second is the use of land surface temperatures obtained by remote sensing. This approach can provide a powerful spatial and temporal coverage with the available sets of images (Fig. 3.5); however, it has to be taken into account that the surface temperature correlates with the air temperature only if all the optical properties of the surfaces are known. The third method consists in the simulation of the urban temperature on the basis of rural data and a parametric interpretation. Simulation of the UHI is possible using a variety of available tools. The scale determines the tool that is most useful to run the simulation. It is possible to distinguish at least three scales of intervention: mesoscale, local scale, and micro scale (Georgatou and Kolokotsa 2016). One option on the micro scale is Envi-Met © (Bruse and Fleer 1998), a computational fluid dynamics software. The restriction is that the micro scale represents only the specific simulated environment. Meso-scale and local-scale simulations could be representative of the entire city or districts. One of the tools available for meso-/local-scale climate generation is

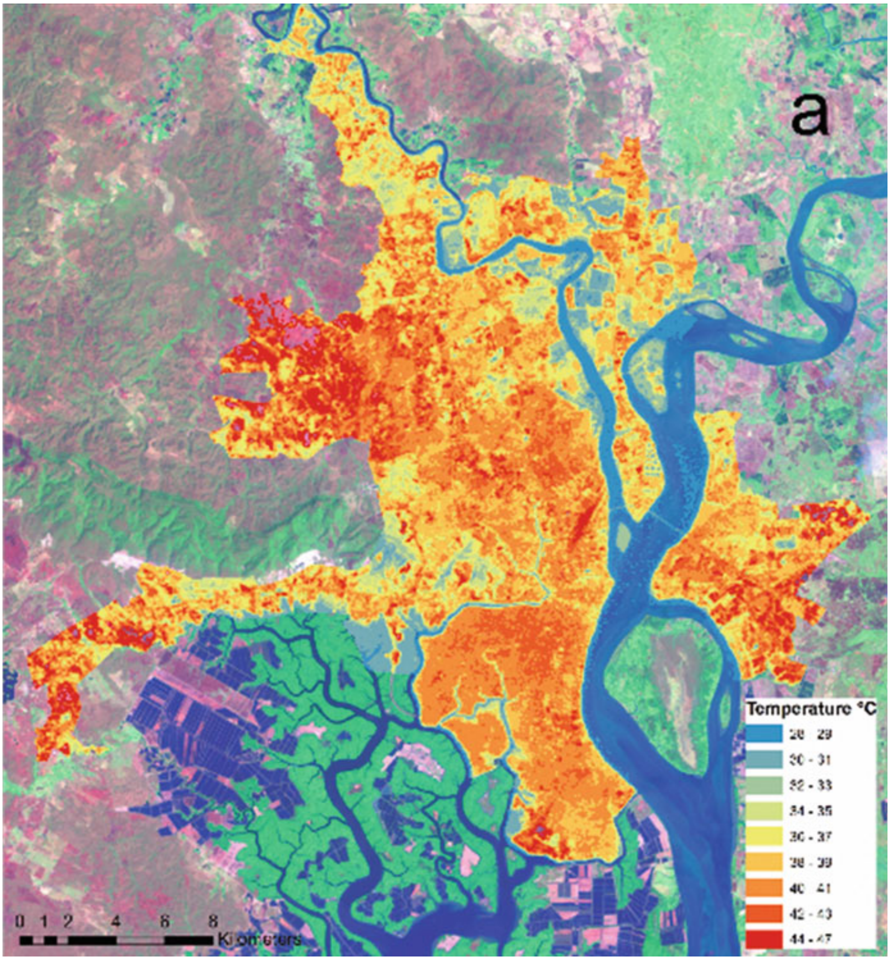


Fig. 3.5 Land surface temperature for the cities of (**a**) Guayaquil and (**b**) Lima

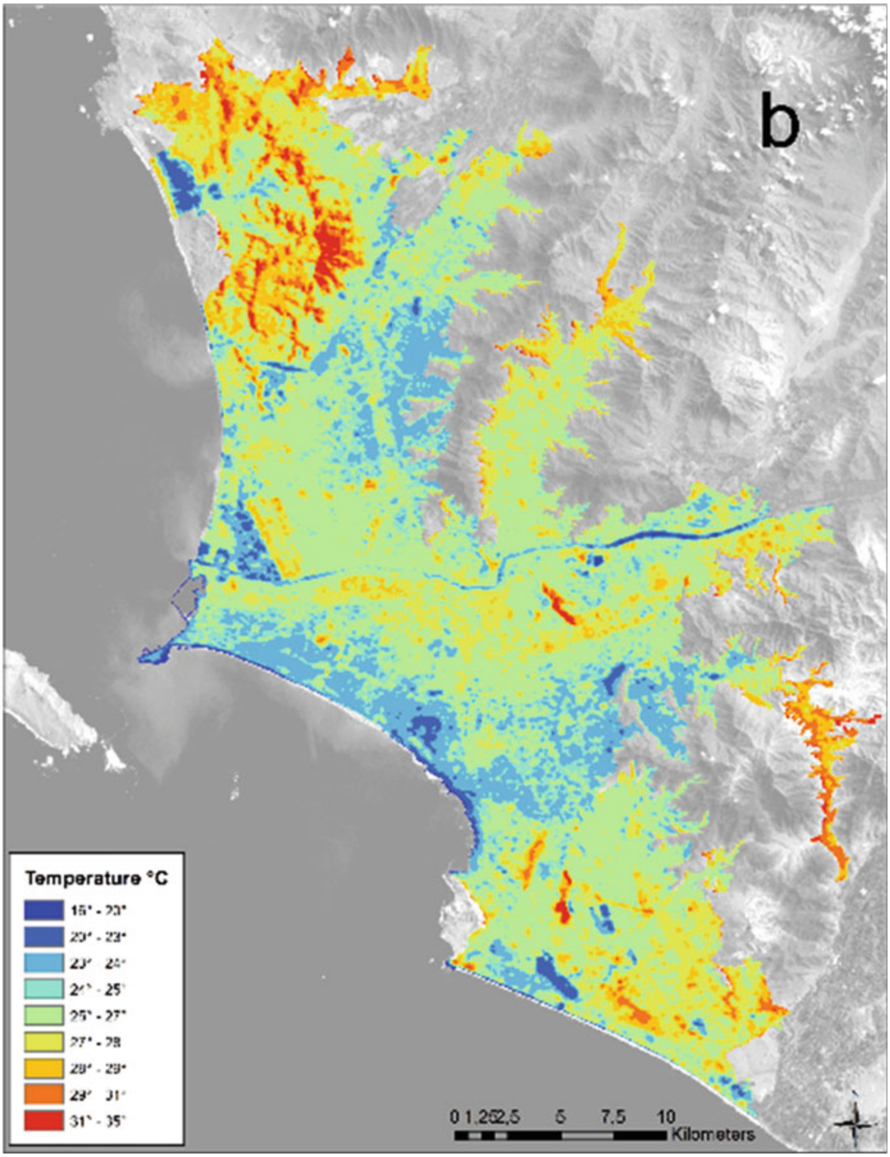


Fig. 3.5 (continued)

the Urban Weather Generator tool (UWG), a software program licensed by MIT in 2008 (Bueno et al. 2012).

This software couples an atmosphere mesoscale model and a building performance simulation model based on Energy Plus© (Crawley et al. 2001), using as input an epw weather file, normally constructed on the basis of data recorded by weather stations. The output is also an epw-modified file that takes into account the UHI effect. The UWG tool requires many parameters to perform the simulation: information about the urban tissue; information about materials; information about the buildings' operations; information about location and simulation data, etc. Sensitivity studies concluded that six parameters are the driving factors of the simulation (Nakano et al. 2015): three parameters related to the urban form (built-up area; green area; façade surface), two parameters related to materials (emissivity and albedo of walls, roofs, and soils), and one parameter related to anthropogenic heat production in the street (basically by cars). In this work, nine values are estimated by using *Google street view* and visual inspections: the three urban parameters, and the emissivity and albedo values for walls, roof, and soils. The heat generated by cars is supposed to be fixed at 25 W/m^2, a value that represents an urban road.

The built-up area or site coverage is defined by Eq. (3.1):

$$\text{site coverage} = \frac{\sum A_{\text{bldg}}}{A_{\text{site}}} \tag{3.1}$$

where A_{bldg} is the footprint of each building on the site and A_{site} is the total site area.

The facade surface or facade-to-site ratio is defined by Eq. (3.2):

$$\text{facade to site ratio} = \frac{\sum \text{Ph}_{\text{wtd}}}{A_{\text{site}}} \tag{3.2}$$

where P is the perimeter of each building on the site, h_{wtd} is the weighted building height (by footprint), and A_{site} is the total site area.

The green area or tree coverage is defined by Eq. (3.3):

$$\text{tree coverage} = \frac{A_{\text{green}}}{A_{\text{site}}} \tag{3.3}$$

where A_{green} is the area covered by trees and A_{site} is the total site area.

In this chapter, samples representing the different urban morphology were selected by using a random sample point generation in ArcGIS 10.1 © (ArcGIS 2017). Then, all nine relevant parameters were measured in each of the 24 samples to perform the UWG simulation. However, high correlation has to be expected between the parameters, positive (for example, between the built-up ratio and the facade ratio) or negative (for example, between the green area and the built-up ratio). A segmentation technique was used to select the spatial location of the urban samples. For this purpose, a set of buffers following the coastline was applied in each city. This criterion considers that urban development of coastal cities follows the coastline on two axes: along and transversal to the coastal line. Several buffer thicknesses were tested to ensure that most types of urban tissues were included in the sample selection, according to the specific morphological and geographical features of each city, such as slope, overall surface, and shape.

To group the results in a coherent set of samples with similar morphology, a principal component analysis (PCA) was run to group the samples. The PCA permits the elimination of correlations between the parameters. A varimax rotation technique was also used to obtain better interpretation of results. Figure 3.10 shows the scatter plot for the 24 samples for each city, after varimax rotation. Principal components are shown in red (vectors) and permits the samples to be grouped into fewer categories representative of the morphology. Figures 3.6, 3.7, 3.8, and 3.9 show the 24 location samples and the morphological groups obtained by PCA (in color). Four urban tissue categories (UTCs) for Guayaquil, Lima, and Antofagasta, and five UTCs for Valparaíso were obtained. These UTCs can be considered representative of the local (or urban) climates zones, where the influence of urbanization remains the same. Local climate zones (LCZs) and urban climate zones (UCZs) are concepts introduced by Stewart and Oke (2012) to map uniformities in the urban climate. UCZs have been included in the guidelines of the World Meteorological Organization (Oke 2004). Table 3.1 shows the average values of the urban parameters for the selected UTCs.

Once the groups were obtained, the Urban Weather Generator tool was used to generate urban weather files that can be compared with the rural weather files obtained by meteorological stations or generated by Meteonorm (2016), a tool that uses station data if present and an interpolation to complete the set of environmental parameters. Urban parameters considered in this study are: the built-up ratio, the green area ratio, and the façade ratio. This last parameter is very relevant because of the influence of the vertical surface on the radiation trapping. One limitation of many studies on the UHI effect is to work only in two spatial dimensions and not include the third dimension in the form of vertical elements, such as facades, or volume in the form of technomass (Inostroza 2014), aspects that more accurately reflect the real quantity of matter that contributes to heat generation and retention. In this study, the use of the facade ratio parameter, allows the third dimension effect to be considered, by generating different UTCs where high-rise buildings dominate (Fig. 3.10).

The epw urban files and the rural data, generated by Meteonorm (2016), a tool that combines meteorological information available and satellite data obtained by NASA, are visualized using TRNSYS 17 Simulation Studio© (Beckman et al. 1994). Differences in temperature are found by analyzing the considered urban tissues for a week in summer and a week in winter. Figures 3.11, 3.12, 3.13, and 3.14 present the rural and urban simulated temperatures for 1 week in summer and 1 week in winter. The UHI intensity is about 2 °C at night, whereas it is near zero during the day. Two types of days can be observed: cloudy and sunny days. During sunny days, the UHI could even be negative at noon. Cloudy days show a positive UHI during the afternoons. Simulated urban tissues show only small differences in UHI intensity, owing to the uniformity in the morphology of the buildings across the

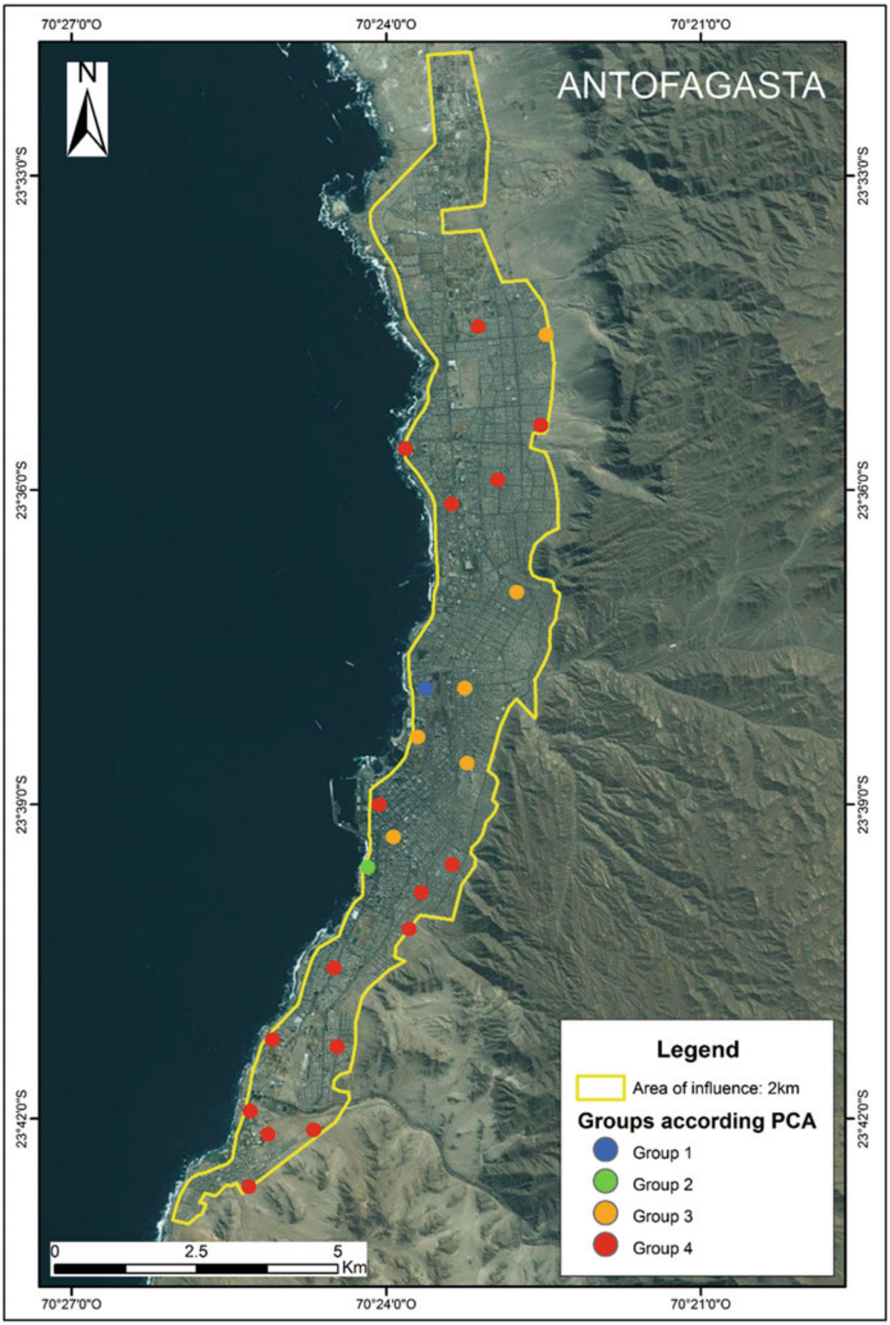


Fig. 3.6 Location of samples in Antofagasta

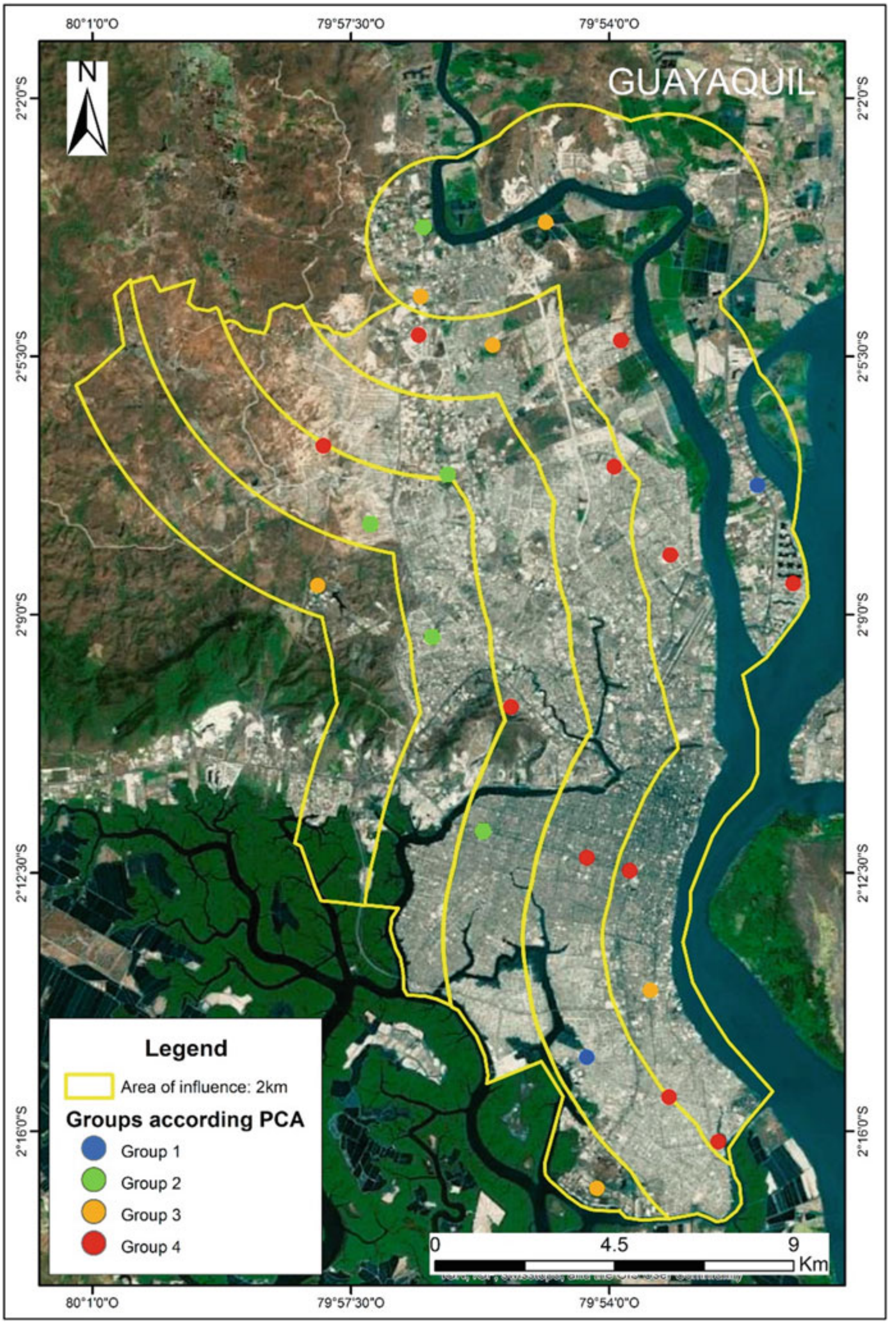


Fig. 3.7 Location of samples in Guayaquil

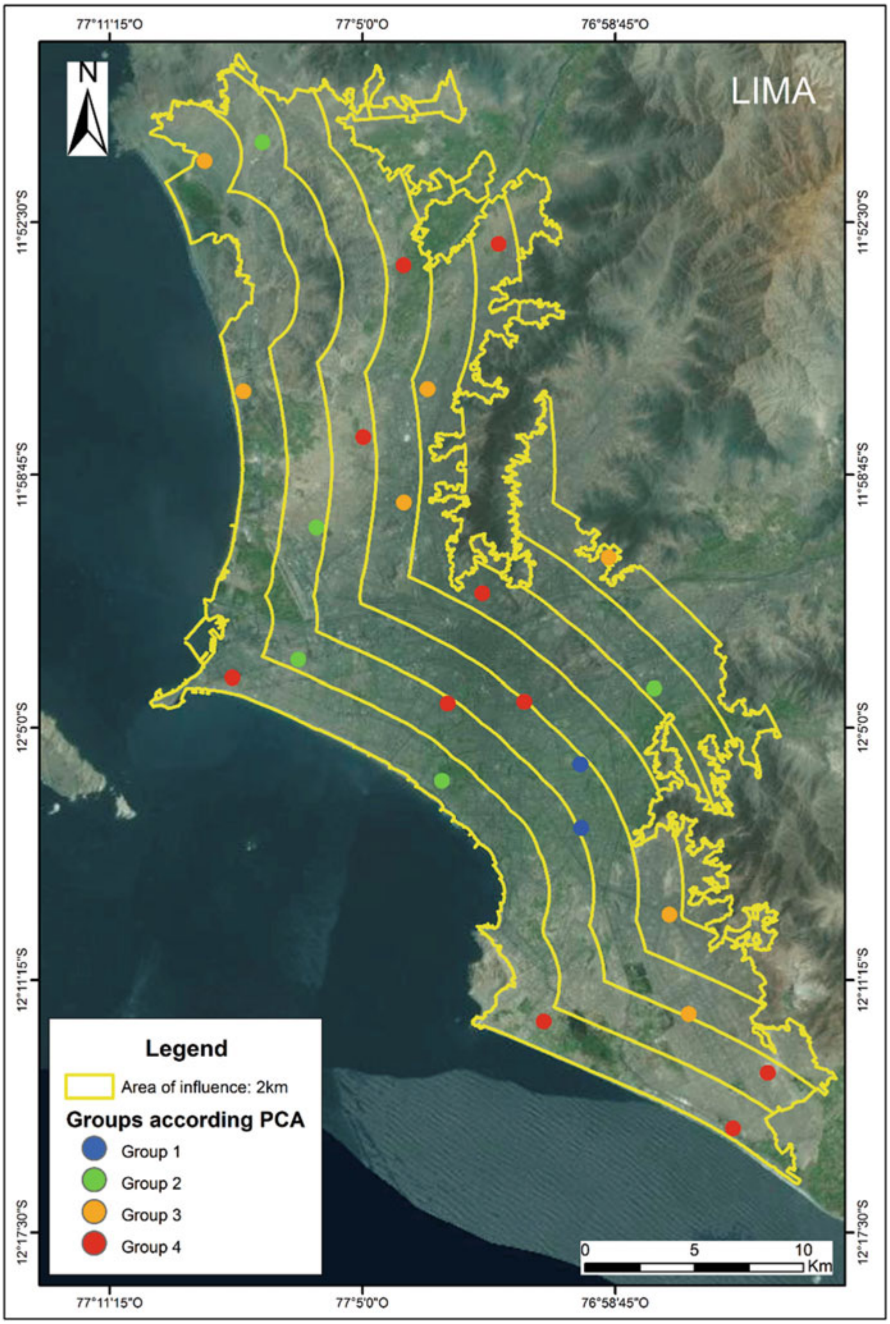


Fig. 3.8 Location of samples in Lima

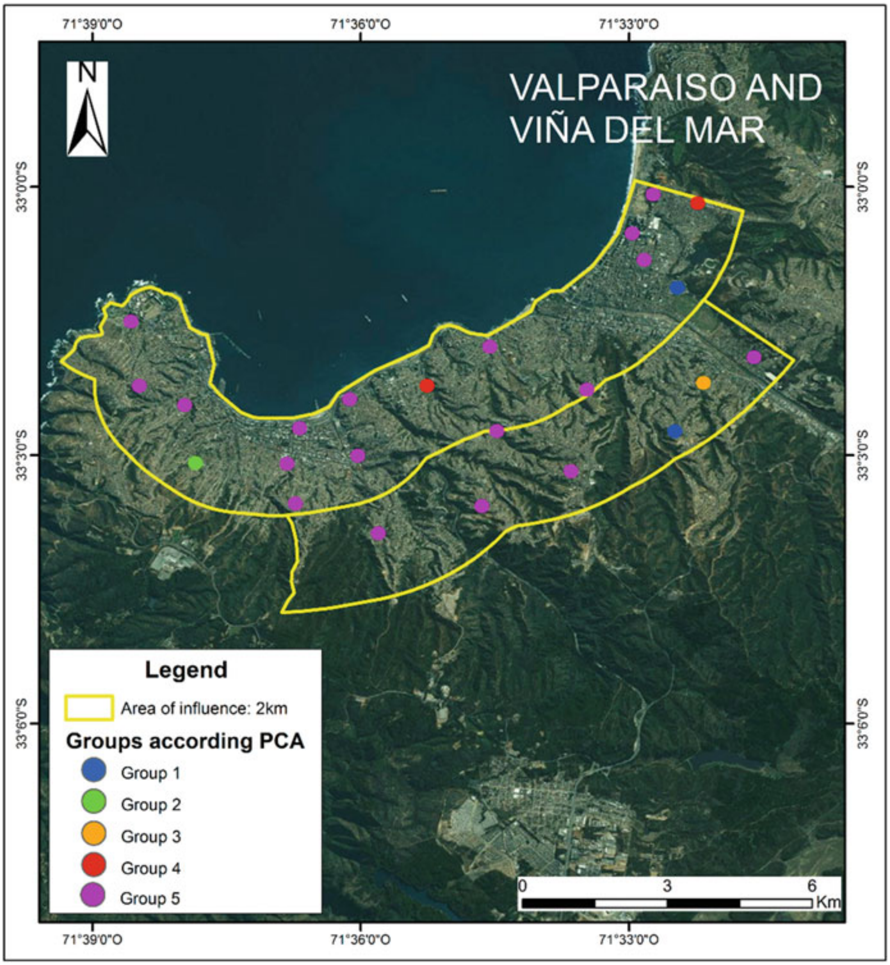


Fig. 3.9 Location of samples in Valparaíso

cities. Like Guayaquil, Lima shows uniformity between the different urban tissues. In summer, UHI intensity can reach around 0.5 °C. In winter, it can increase up to 1.5 °C. Antofagasta shows more differences between the urban tissues analyzed: UHI intensity varies from 0.5 up to 2 °C. Especially at night, some UTCs are more sensitive to heat retention than others. During winter, the UHI is more intense, reaching up to 4 ºC during the night. Valparaíso has a positive UHI intensity at night and negative UHI intensities during the day, probably owing to shadows and wind deviation produced by buildings.

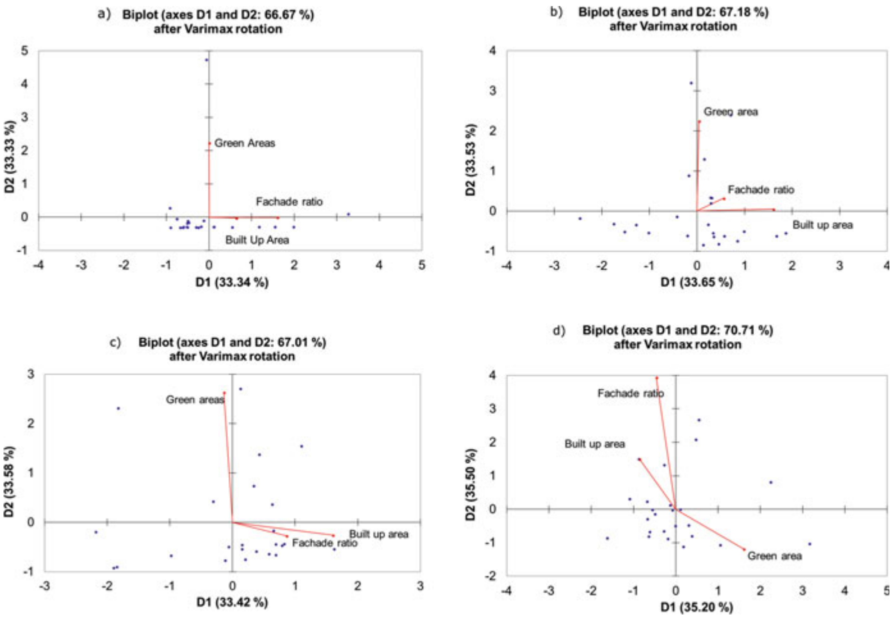


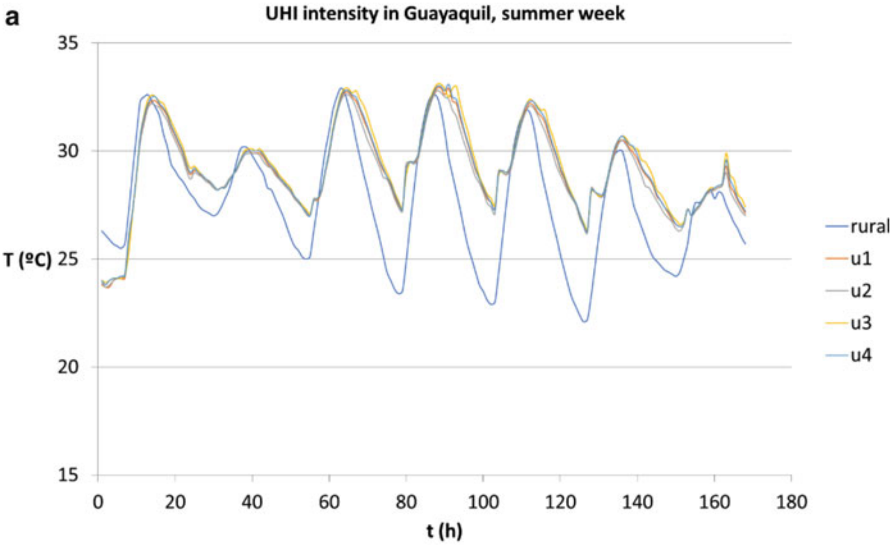
Fig. 3.10 Scatter plots for urban tissue categories (UTCs) in Antofagasta, Lima, Guayaquil, and Valparaíso

The principal difference observed among the four cities is the global UHI intensity (Table 3.2), higher in Guayaquil and in Valparaíso than in Lima and Antofagasta. This result is consistent with the observation that arid climates evacuate the heat better during the nights. The second difference relates to the urban tissues: in Lima and Guayaquil a more homogenous urban morphology is observed. A typical dwelling is a family house of two or three floors, with concrete block walls and a light roof (normally metal decking). In Valparaíso, and especially in Antofagasta, some tissues are much more sensitive to the UHI than others, owing to morphological features: in those cities, medium-sized dwelling blocks and especially tall buildings modify the urban scenario, sometimes drastically.

Differences shown by these experimental results are in line with other results obtained in similar studies around the world. For example, Salvati (2016) found that built-up areas and city density determine the summer intensity of the UHI, whereas the facade ratio and building height influence the winter intensity of the UHI more. Valparaíso and Antofagasta have shown higher intensity of the UHI during the winter nights.

Table 3.1 Urban parameters used in the Urban Weather Generator (UWG) simulation

	Traffic (W/m^2)	A_b/A_s	A_g/A_s	F/A_s	Wall (albedo/ emissivity)	Roof (albedo/ emissivity)	Soil (albedo/ emissivity)
Guayaquil U1	25	0.38	0.15	0.83	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Guayaquil U2	25	0.53	0.15	0.79	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Guayaquil U3	25	0.34	0.01	0.63	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Guayaquil U4	25	0.5	0.01	0.71	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Lima U1	25	0.52	0.27	0.83	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Lima U2	25	0.62	0.16	0.85	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Lima U3	25	0.29	0.02	0.46	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Lima U4	25	0.66	0.01	0.75	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Antofagasta U1	25	0.41	0.20	0.76	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Antofagasta U2	25	0.42	0.01	2.10	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Antofagasta U3	25	0.65	0.00	1.20	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Antofagasta U4	25	0.36	0.01	0.41	0.58 / 0.90	0.51 / 0.28	0.20 / 0.76
Valparaíso U1	25	0.75	0.11	1.62	0.58 / 0.90	0.42 / 0.90	0.20 / 0.76
Valparaíso U2	25	0.25	0.64	0.76	0.58 / 0.90	0.42 / 0.90	0.20 / 0.76
Valparaíso U3	25	0.16	0.85	0.10	0.58 / 0.90	0.42 / 0.90	0.20 / 0.76
Valparaíso U4	25	0.61	0.01	1.30	0.58 / 0.90	0.42 / 0.90	0.20 / 0.76
Valparaíso U5	25	0.56	0.16	0.66	0.58 / 0.90	0.42 / 0.90	0.20 / 0.76



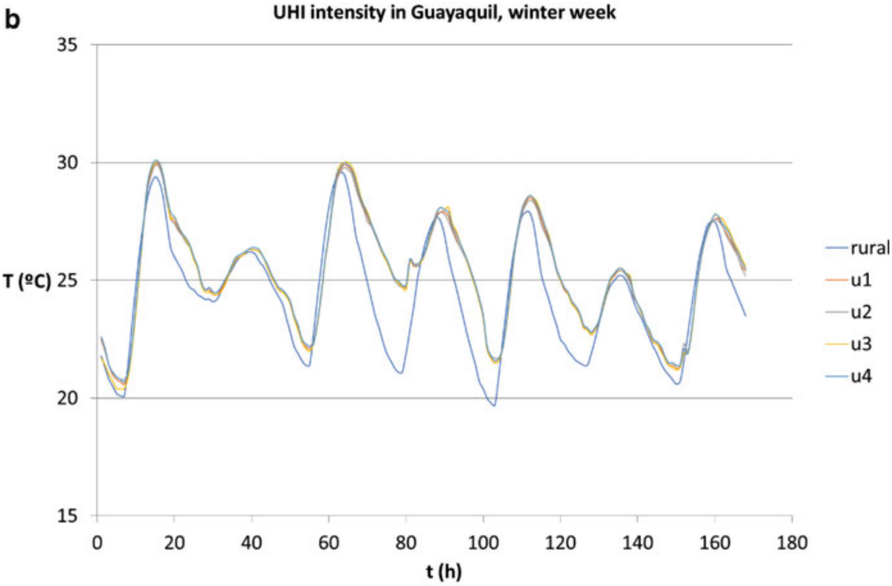


Fig. 3.11 One-week temperature simulation for Guayaquil. (**a**) Caption for summer. (**b**) Caption for winter

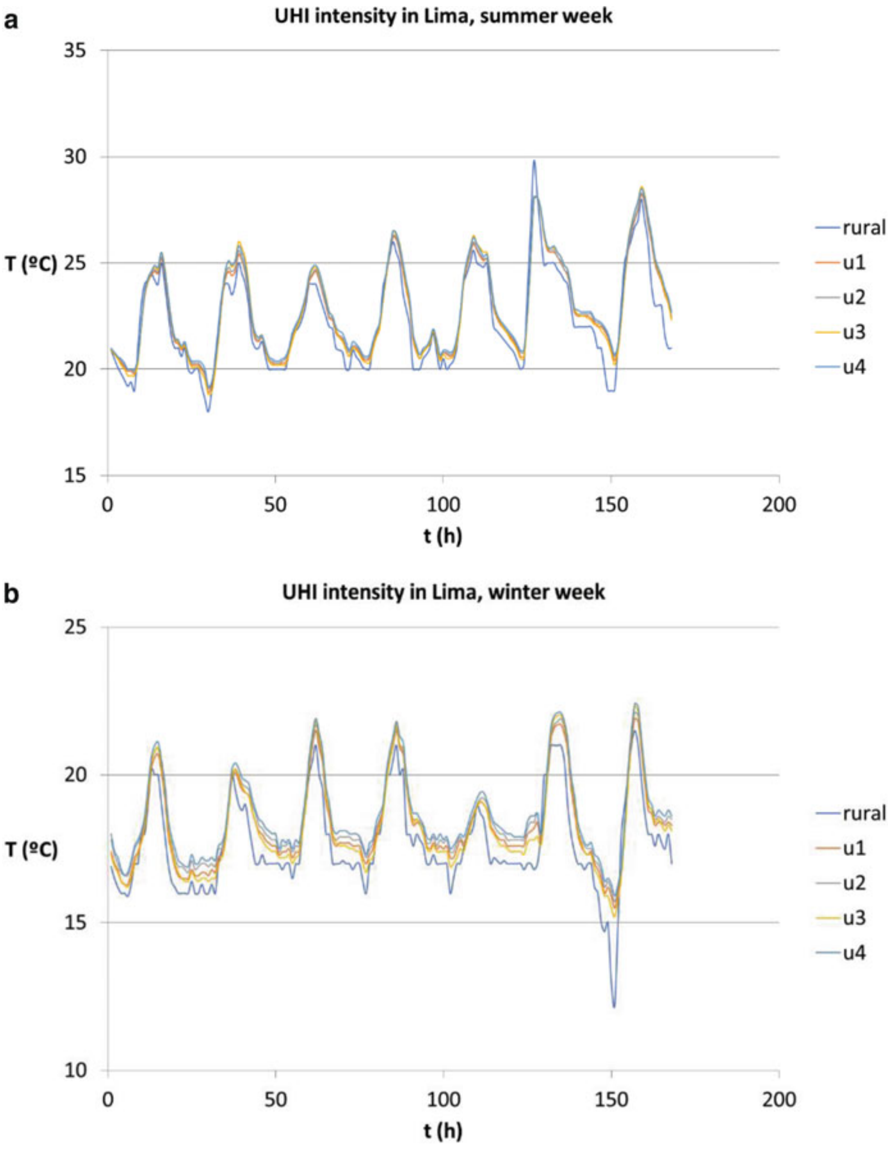
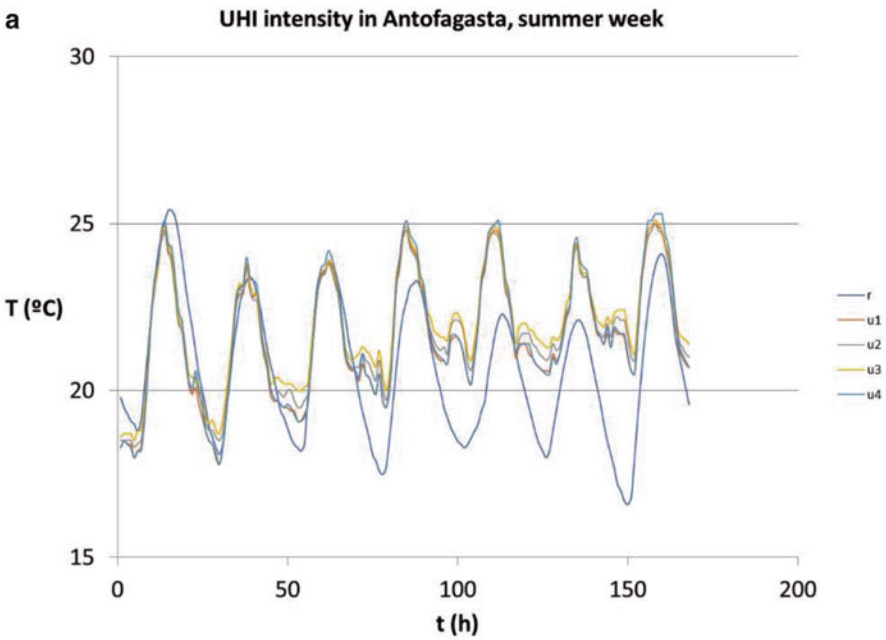


Fig. 3.12 One-week temperature simulation for Lima. (**a**) Caption for summer. (**b**) Caption for winter



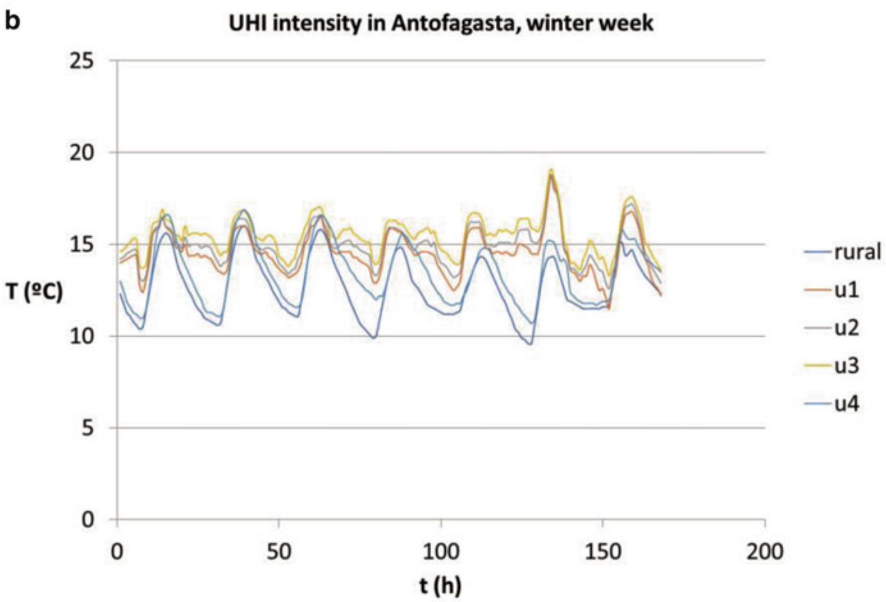


Fig. 3.13 One-week temperature simulation for Antofagasta. (**a**) Caption for summer. (**b**) Caption for winter

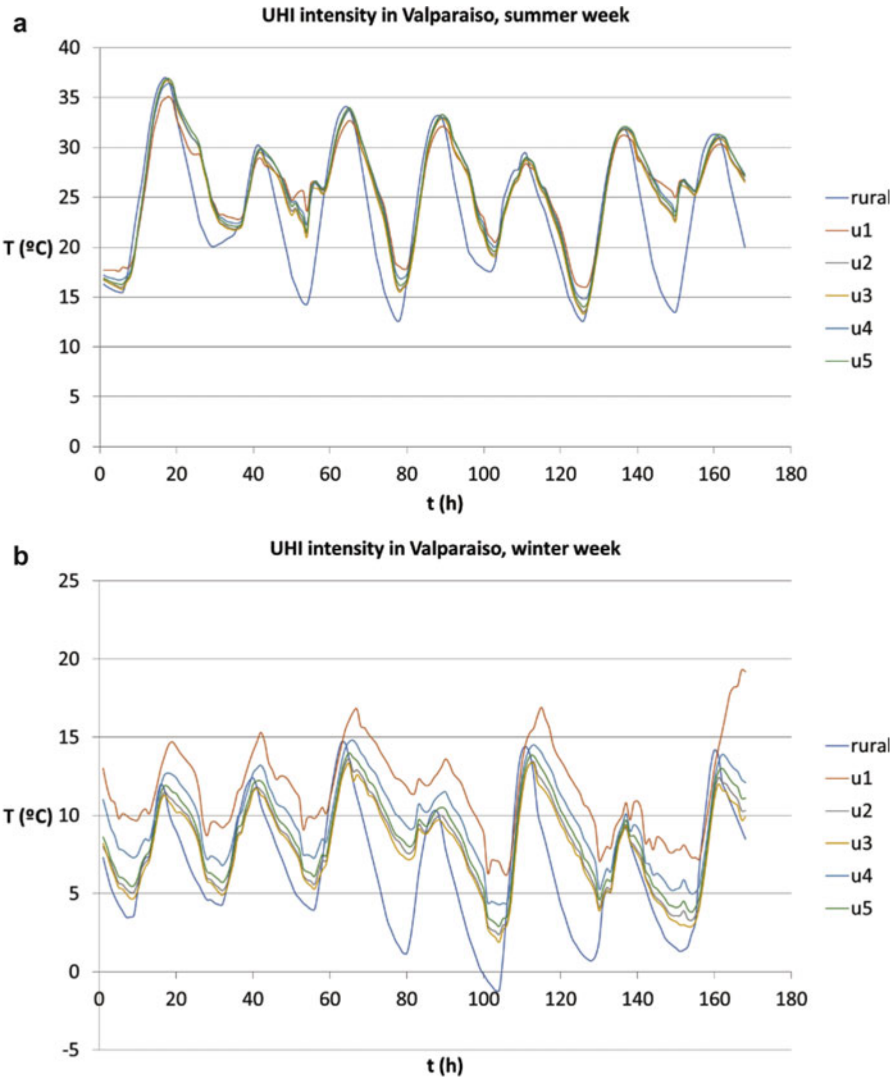


Fig. 3.14 One-week temperature simulation for Valparaíso. (**a**) Caption for summer. (**b**) Caption for winter

Table 3.2 Summary of the diurnal and nocturnal values (UHI intensities) for the cities analyzed

Cities	Diurnal UHI intensity (K)	Nocturnal UHI intensity (K)
Antofagasta	0.59	0.57
Lima	0.02	0.15
Guayaquil	−0.35	1.57
Valparaíso	−1.15	4.87

Intensity of UHI was obtained for an average urban scenario at 14:00 and 2:00

3.5 Urban Heat Island Impacts and Driving Factors

A recent simulation study (Palme et al. 2016a) addressed the influence of some of the generating factors on the UHI in these four cities. Anthropogenic heat generation due to cars seems to be the most important factor, followed by built-up ratio and energy use (especially cooling). Building heights (as geometrical factors) and the presence of green areas normally have the effect of reducing the UHI, especially during the day. This is consistent with results obtained in Asian (Ryu and Bak 2011) and European case studies (Salvati 2016), showing that urban parameters such as facade, the built-up ratio, air-conditioning, and traffic are the driving factors of UHIs.

3.5.1 Impacts on Energy Consumption

The impact of the urban climate on the energy consumption of buildings has been assessed in many studies (Sailor 2014; Bustamante et al. 2011; Santamouris 2014). Santamouris (2016) states that by the middle of the century the average cooling demand for the world would increase up to 500%. In South America, an increase in the cooling demand of residential buildings between 30% and the 200% can be expected (Palme et al. 2016b). The development of thermal regulations under actual rural-biased climatic perception could cause overheating in many places (Palme et al. 2016b; Toledo et al. 2016). For instance, Valparaíso today has a relevant heating demand that could switch to a prevalent cooling demand in the near future. Guayaquil has the highest cooling demands, both with and without the UHI effect.

3.5.2 Impacts on Public Spaces

Street comfort is fundamental for urban planners (Rogora and Dessí 2008; Nikolopoulou et al. 2001). The UHI affects the comfort of public spaces and the people's use of public spaces drastically. Buildings can be used as microclimate regulators, especially if they have a certain height or in the presence of narrow street canyons (Carrasco 2008). However, this microclimate is normally hotter than the rural environment during the night, generating the classical UHI described by Oke.

3.5.3 Impacts on Public Health

Extreme heat events could combine their effect with the UHI. South American cities are threatened by excess heat. In these cities, the level of extreme poverty, although decreasing year by year, was still high (about 20% in Ecuador, 15% in Peru, and 5%

in Chile) in 2010, as reported by the Economic Commission for Latin America and Caribe (CEPAL 2010). Informal urbanization can reach values of the 40% in cities such as Lima or Guayaquil (Clichevsky 2000). Socio-economic urban segregation (Inostroza 2017; Inostroza et al. 2013) suggests that the impact might be tremendous in the poorest neighborhoods, whereas surprisingly, heat vulnerability is driven by inappropriate housing materials and not by a lack of green space (Inostroza et al. 2016). Housing materials and access to water supply have been mentioned as the most important factors in the heat vulnerability of cities such as Santiago in Chile (Inostroza et al. 2016).

3.5.4 Mitigation and Adaptation Strategies

Feasible strategies to mitigate and to adapt to the urban climate under climate change are necessary. Some studies indicate a contradiction between the two strategies (Palme 2015), and others suggest the consideration of new kinds of interventions, named "adaptigation" (Galderisi et al. 2016). Among the mitigation strategies against climate change, the following are considered:

1. Strategies to reduce the fossil fuel component of energy production
2. Strategies to reduce the thermal demand for building conditioning
3. Strategies to change urban transportation models
4. Strategies to reduce the transport flows between the city and the countryside

Climate change mitigation relates to the fuel used for final energy production. In this sense, these strategies do not always generate a more adapted scenario for urban living. In some cases, mitigation and adaptation are both achieved, for example, by changing the transportation system, in other cases they are not, as in the case of the heating demand reduction for buildings, which achieve mitigation, but not necessarily adaptation.

In relation to the urban climate, adaptation and mitigation seem to be much more connected. In fact, adapting to an urban climate means to try to mitigate the urbanization effect on temperatures and other environmental variables (Gartland 2010; Santamouris and Kolokotsa 2016). Among these mitigation strategies, the following should be considered:

1. The use of ventilation to cool the city
2. The city greening
3. The use of evaporative cooling techniques
4. The use of cool materials to reflect solar radiation
5. The use of the ground to cool the air

All these solutions reduce urban temperatures and ensure a more comfortable (or at least supportable) life condition. In this sense, mitigation and adaptation can continue in the same way. The relationship between climate change and the UHI is not totally clear. Some studies suggest that under climate change, the intensity of

UHI should be lower because of the increase in the vertical instability and the consequent heat dissipation (Brazdil and Budikova 1999; McCarthy et al. 2010). However, under extreme heat waves, the UHI is predicted to increase (Li and Bou-Zeid 2013).

Which strategies are the recommended for South American Pacific coastal cities? It is difficult to answer this question; however, some data appear interesting. First, the availability of breezes suggests using them to cool both streets and buildings. It has been indicated that the use of breezes could reduce the overheating of residential houses during the summer season by at least 30% (Palme et al. 2016d). Then, the seasonal and day–night temperature variation of the Mediterranean and of the desert climates should indicate the use of the ground as an interesting solution in Valparaíso, Antofagasta, and Lima. Evaporative techniques could also be useful in the case of Lima and Antofagasta. Guayaquil has a more complicated scenario, with less breeze availability and fewer thermal differences between seasons. Urban greening and cool materials should be considered possible solutions, as in other tropical countries (Jusuf and Hien 2016).

3.6 Conclusion

This study evaluates by simulation the intensity of the UHI, which should be expected in the most significant cities of the South American Pacific coast. All of the cities studied show variable intensity of the UHI between 1 and 5 °C. More intense winter UHIs have been found in Valparaíso and Antofagasta. Both cases also show a greater difference between diurnal and nocturnal intensity of UHIs. This is the result of the different urban tissues, with high-rise buildings in the downtown areas of the cities. The factors generating the UHI effect are the traffic, the built-up surfaces, and the use of air conditioning. With respect to this last factor, it has been found that the location of the specific systems used influences the street temperatures. It is different to place thermal machines (especially heat pumps) at the top of the buildings (a normal solution for centralized systems) or to place individual machines (splits) at the level of each window of a residence. In this case, the UHI intensity increases in 20–40%. Unfortunately, this is the common solution for offices and residential buildings in South American cities. It appears to be very important to develop strategies that avoid the impact of new standards of comfort and lifestyles on the urban climate.

Specific strategies that should be included in the future norms that are developed for the locations studied are at least:

(1) The introduction of environmental urban planning that considers the urban form as a boundary condition for principal environmental factors affecting comfort and energy use.
(2) The development of robust methodologies to assess natural ventilation at both urban and buildings levels.

(3) The development of design guides incorporating concepts such as evaporative and ground cooling.
(4) The introduction of new transportation systems to avoid the overheating component produced by private car transportation.
(5) City greening, avoiding the concentration of green areas in some privileged neighborhoods, as is happening in many cities of the region today.

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Chapter 4
Improving Urban Planning in a Middle Temperate Argentinian City: Combining Urban Climate Mapping with Local Climate Zones

Natasha Picone and Alicia M. Campo

Abstract Promoting the generation of sustainable cities is the main objective of an urban climatologist. To incorporate urban climate knowledge into urban planning, it is necessary to create instruments that summarize the relationship between meteorological parameters and urban form and function. This chapter shows the urban climate of the city of Tandil, Argentina, and its relations with land cover. The main objective is to present an instrument that proposes improvement in urban planning using this information.

The instrument was generated combining two methodologies: local climate zones (LCZs) and climatopes. LCZs are used to characterize the different urban forms and functions. They were created based on construction and population density, the amount of vegetation, location characteristics and temperature, and spatial and temporal distribution. To summarize urban climate information, climatopes were made using seasonal temperature, humidity and precipitation distribution, wind analysis, and comfort. The results are presented in a map and a table.

Tandil is a middle-sized city located in the south east of Buenos Aires province, Argentina. It has a transitional temperate climate and is surrounded by the Tandilia Hill System. The city has a population of 116,916 inhabitants and diversified economic activity.

As a result, 16 LCZs were determined and climatic characteristics were described for each of them. The analysis of each one put into context the need to improve existing urban planning, which does not take into account climatic parameters. The mitigation strategies consisted in three types of intervention: gas emission control, improving urban vegetation, and construction restrictions.

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4.1 Introduction

Urban climate is the modification of meteorological parameters made by human settlement (Landsberg 1981). Its variation depends on several factors: land use, building geometry and materials, green areas distribution, and surrounding conditions. All these combined create a specific mosaic of micro-climatic conditions that affect the comfort and health of people, energy consumption, and air quality (Eliasson 2000). Therefore, it is of great importance to incorporate urban climate knowledge into urban planning.

The use of this knowledge has been a reality from the Romans until the middle of the twentieth century. According to the records, the design of cities and even individual buildings were considered, taking into account climatic variation such as ventilation and insolation. Hebbert and Webb (2012) said that the increase in urban climate knowledge does not imply that it was applied to urban planning. In fact, the opposite tendency occurs. During the 1950s, urban planning started to be less climate-aware, most likely because of the improvement in the technological living conditions.

With the rise of climate change as a global problem and a well-known problem for future generations, urban planning started to take climate knowledge into account. The main problem that this approach generates is that cities prepare for low-frequency hazards that have a huge impact, but they conceal the high-frequency and micro-scale climatic phenomena of the cities, such as changes in the climatic comfort (Hebbert and Webb 2012).

There are several guidelines and tools for urban planning such as climatic maps (Oke 1984; Bitan 1988; Lindqvist and Mattsson 1989; Givoni 1991; Golany 1996; Ng and Ren 2016) and several projects where climatic aspects have successfully been incorporated into the planning process (Balázs 1989; Evans and Schiller 1996; Perera and Emmanuel 2016).

Besides all these examples, as Eliasson (2000) analyzed, in general, there are problems with incorporating climate knowledge into urban planning, basically based on a lack of good communication between urban planners and researchers. As a result, he presents three ways of improving the urban climatologists' intervention, and they are: "improve awareness of urban climate, improve communication and argumentation, and develop tools and courses suitable for urban planners" (Eliasson 2000, p. 42).

A well-developed way of incorporating urban climatology into urban planning has been urban climate mapping. It was first used in Germany during the 1970s and since then, it has been used in more than 40 countries all over the world. This tool is basically made up of two maps: the urban climatic analysis (UC-AnMap) and the climatic recommendation map (UC-ReMap). The first one incorporates and interrelates meteorological (temperature, humidity and mainly wind), land use, topography, and vegetation information, from which climatopes classifications are made. The second one presents the strategies for improving urban planning, presented according to the climatic understanding and evaluation from the previous map (Ren et al. 2012). This methodology exhibits a unique set of climatopes (in name and definition) in each city.

As regards a way of standardizing and reporting site metadata, the development of the local climate zones methodology (Stewart and Oke 2012) for urban heat island studies has made a very important improvement. According to the authors, the local climate zones (LCZs) are defined as:

> Regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale. Each LCZ has a characteristic screen height temperature regime that is most apparent over dry surfaces, on calm, clear nights, and in areas of simple relief (Stewart and Oke 2012, p. 1885).

There are 17 LCZs and they are divided into two groups: the "built types" 1 to 10, where a constructed area prevails over a predominant soil cover; and "land cover types" A to G, classified basically as "natural" covers of forest or crops that can incorporate seasonal cover variations such as snow cover. As Stewart and Oke (2015) state:

> The roles of LCZs and Climatopes in UCMapping are mutually beneficial. The former provides a surface classification that is generic and objective, and that introduces standardized information to an otherwise site-specific database. The latter provides a classification that is inclusive yet detailed, and that highlights the pervasive effects of surface relief on local climate. Together, the two classifications can advance scientific and climatological knowledge in UCMaps (p. 401).

As a result of this discussion, in this work, we present an example of this complementation in a middle temperate city of Argentina. To do so, the LCZ and climatope methodologies were used, in which local areas of the city are presented on a map where the proposals for improving urban planning are incorporated and related to each zone's climatic and construction characteristics. They are also described in a complementary table.

4.1.1 LCZ and UCMapping in Latin America

There are few records of the use of UCMapping in Latin America. The first case study is the application of climatic information to the urban planning of Vicente López, Argentina, during the 1980s (Evans and Schiller 1990/1991). In recent years, the use of this methodology has been applied in two middle-sized cities of Brazil: Salvador (Andrade et al. 2015) and Campinas (Prata Shimomura et al. 2015).

On the other hand, the applications of local climate zones methodology are more significant, but most of them can only be found in the WUDAPT web (www.wudapt.

org). The cities mapped in this web are: Caracas, Lima, Campina, Campeche, Aracaju, Medellin, Mendoza, Mexico, San Juan, Santo Domingo, and Sao Paulo. Besides these cities, Mendoza and San Juan have been mapped with the intention of relating the LCZs to the thermal comfort of the city (Puliafito et al. 2013; Roca et al. 2013). Finally, three middle-sized cities of Argentina, Tandil, Bahia Blanca, and Mar del Plata, have been classified in LCZs using satellite images (Picone 2016).

The importance of taking into account the climatic information in urban planning is crucial for the development of sustainable cities. In the case of Tandil city, before this study, there was little or no information about most of the meteorological parameters and none was incorporated into the urban plan for the city development. The work presented in this chapter is the first systematic work on urban climatology in the city and the complementation of the two methodologies helped to develop an instrument that can be used by the urban planner to improve the current plan for urbanization.

4.2 Study Area

Tandil city is located in the south-center of Buenos Aires Province, Argentina. It takes up the middle basin of Langueyu river and the central area of the north face of the Tandilia Hill System. These hills surround the city and control its growth from south to northwest. The main water flows have been anthropologically controlled, using hydraulic structures such as a dam and enclosures (Fig. 4.1).

The climate of the area is transitionally temperate, with four distinguishable seasons. The mean annual temperature is 13.4 °C and the annual range is 14.5 °C. The precipitation is concentrated between spring and summer (October to March), with an annual amount of 893 mm. There are 46 days with frost between March and October, concentrated during the winter (Fig. 4.2).

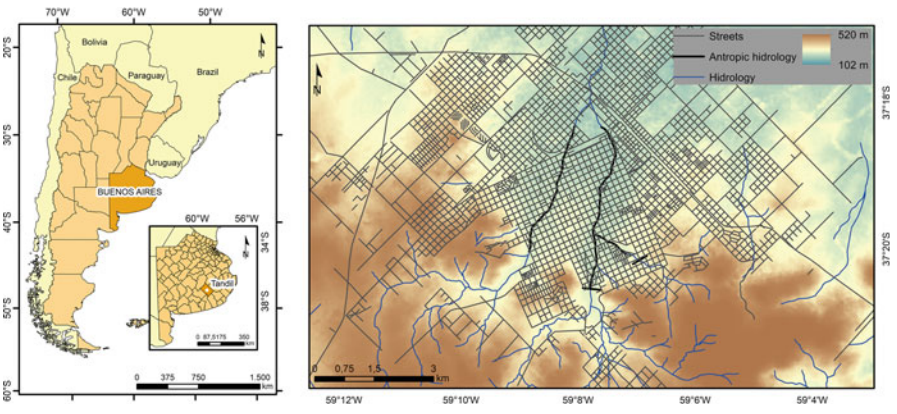

Fig. 4.1 Location of Tandil city, Argentina

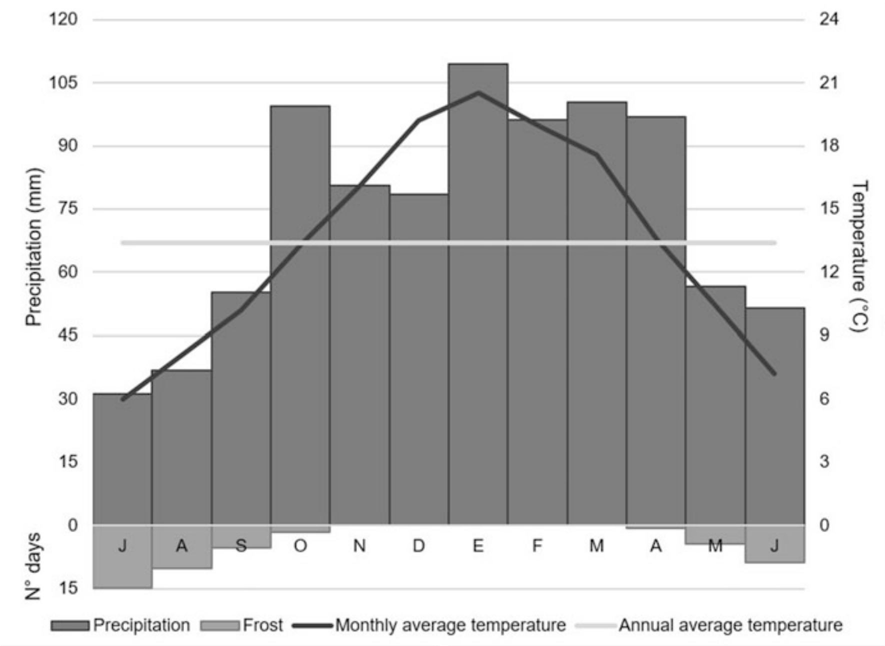

Fig. 4.2 Climatic characteristics of Tandil city. (Source: Climatic Statistics, Servicio Meteorológico Nacional 2001–2010)

Tandil is considered to be a middle-sized city in the Argentinian urban system. This classification is based on the population of each city: it being small if it has between 2000 and 50,000 inhabitants; middle-sized, between 50,000 and a million, and large if it has more than one million inhabitants (Vapñarsky and Gorojovsky 1990). According to the last census, the city has 116,916 inhabitants that represent 94% of the department's population (INDEC 2010).

As a regional center, its economy is basically concentrated on the services sector, particularly education, culture, and agriculture. However, the city has a history of industrial development related to the production of automobile parts and the primary production of rock for construction, an activity that was shut down in 2012.

4.3 Methodology

The LCZs were built up using information on temperature, vegetation, population, and construction distribution and location, to determine the form and function of each zone. The temperature analyses consisted in the study of the spatial distribution and the seasonal variability.

The amount and distribution of vegetation was derived from Landsat satellite images. The normalized difference vegetation index (NDVI) was calculated for different seasons using Landsat 5 TM images (10/02/2011, 15/04/2011, 24/10/2011). The population density was obtained using the last census of 2010. The density is calculated in the most disaggregated spatial resolution of the census information, the radius, that is, a group of blocks whose number varies according to the city area, smaller in the concentrated areas and larger in the dispersed one. The construction density was derived from information from the City Hall dating from 2011. The number of square meters per parcel was obtained and then resampled to the block. A location map was built up to show the influence of the natural environment on the city settlement, particularly the topography. A digital elevation model was generated using the topography chart from the Instituto Geográfico Nacional. The Hydrology Module of the ArcGIS® 10 was used to extract the general hydrological parameters and then incorporate them into the map. Finally, the geomorphology of the area was included on the map using the previous information, field work, and results obtained by geologists in the area (Dalla Salda 1999).

The climatic information was obtained throughout 3 years of measurements. Different analyses were made and the data were collected using various methods. To study the general urban effect, a comparison between two weather stations was made, one located in an LCZ D (Servicio Meteorológico Nacional) and the other in an LCZ 3_4 (IGEHCS, CONICET/UNCPBA). For the whole period, temperature, humidity, pressure, wind direction, wind speed, and precipitation were analyzed and meteorological statistics were calculated.

The methods of mobile transects were used to study the spatial distribution of temperature and humidity. The measurements were made during typical seasonal days with a wind speed less than the critical wind speed for the city (calculated based on Oke and Hannell 1970, the value is 3.6 m/s). We conducted three measurements (8:30, 13:30, and 20:30) in 33 points, which represented different microclimatic conditions of the city. With this information, comfort conditions were calculated for cold and warm seasons. The indexes used for this analysis were: HUMIDEX (Weather Services of Environment Canada 2001), Apparent Temperature (Steadman 1984), and Equivalent Temperature (Quayle and Steadman 1999).

To analyze the precipitation, spatial distribution data were collected in 11-gauge rain stations (IGEHCS, CONICET/UNCPBA) distributed in the city and its surroundings. At each occurrence of rain, the amount and pH of the sample were registered.

The wind pattern analysis was carried out using a re-escalation of the GFS model from the original 36-km resolution to a 1.4-km resolution. Four typical weather conditions of the area were analyzed and the local patterns of wind were extracted.

In this work, we integrated the climatic analysis map (UC-AnMap), the climatic recommendation map (UC-ReMap), and the LCZ map. The integration was based on the LCZ map, over which the proposals were marked for each area. The table sums up the climatic and construction characteristics of each LCZ.

4.4 Results

This section is divided into three major subsections. The first is a description of the spatial distribution of the general information necessary to know the form and function of the city. The second shows the results obtained in the distribution of the meteorological parameters that we analyzed. Finally, we present the map and table where all the information studied is compared.

4.4.1 Analysis of the General Information

The population density of each area of the city was obtained based on the census data from 2010 (Fig. 4.3). The spatial distribution showed a concentration in a U shape from northeast to northwest passing by the city center. In addition, there are some focuses of concentration in the east and in the south of the city.

Using the data from the city hall, the construction density was calculated (Fig. 4.4). The distribution is quite normal, more concentrated in the center and

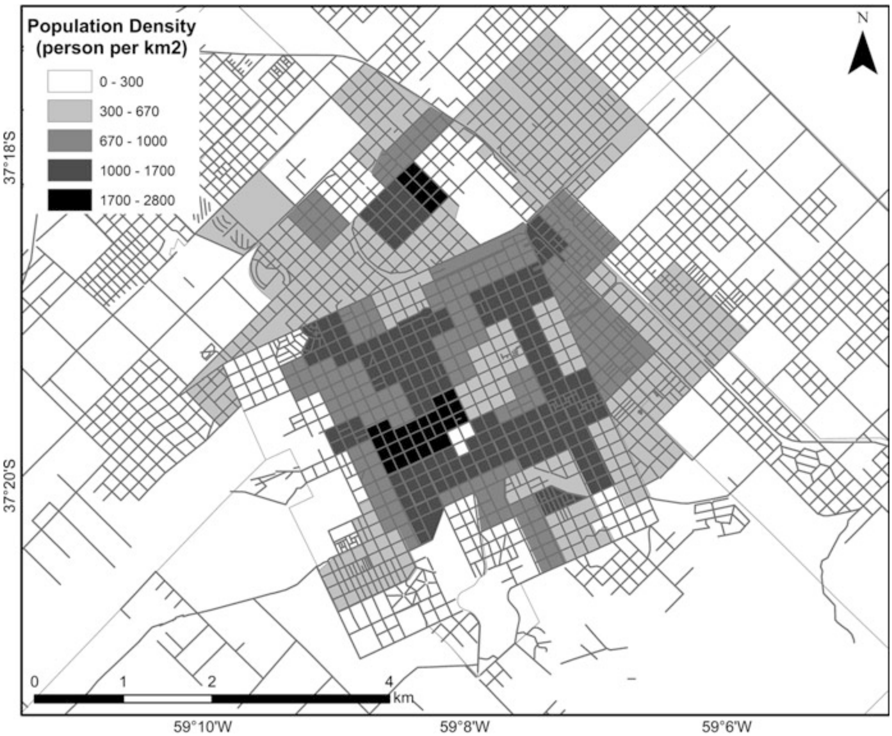

Fig. 4.3 Population density. (Source: INDEC Census 2010)

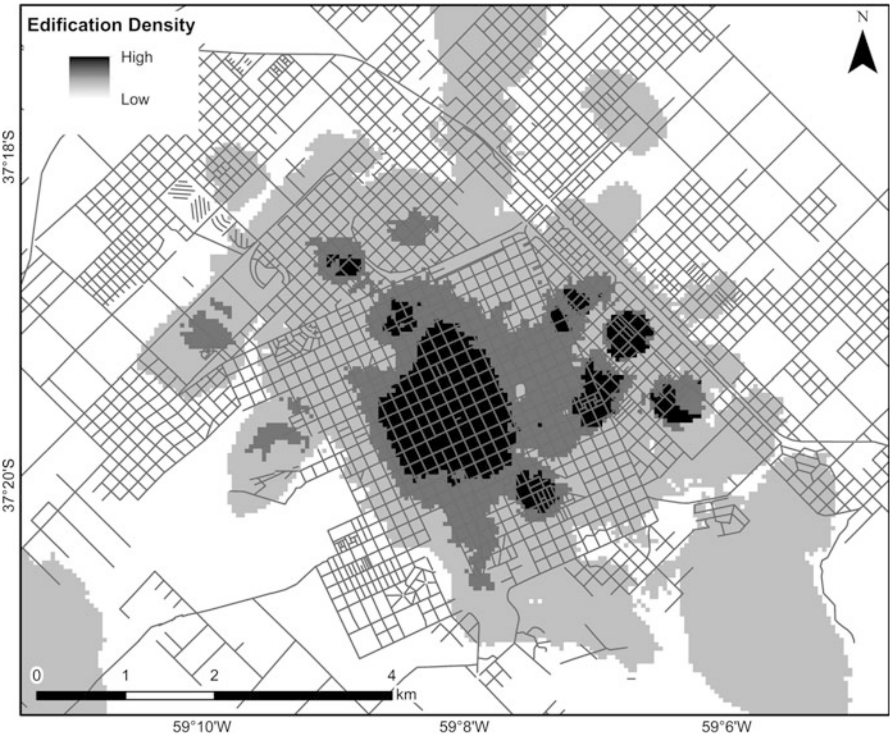

Fig. 4.4 Construction density. (Source: Cadastral Information, Tandil City Hall 2011)

decreasing while moving away from it. There are two areas that are an exception to this normal distribution: the north of the central area, which is related to the railroad station, and the east, which is a commercial area around the bus station.

To analyze the vegetation, the NDVI was calculated (Fig. 4.5). As a general pattern, the vegetation decreases with increasing construction density. However, the city presents several parks and trees by the sides of the streets, except in the city center.

4.4.2 Spatial Distribution of the Meteorological Parameters

Studies of the temperature using seasonal mobile transect measurements presented a varied spatial and temporal distribution (Fig. 4.6). Warmer seasons (spring and summer) showed a cold island during the mornings and a heat island around midday and at night. These changes in the distribution were attributed to the differences in the heat exchange rates of the materials that predominate in the city center (concrete and built-up areas) and its surroundings (vegetation and less dense construction areas). Meanwhile, the autumn presented a cold island during the whole day and

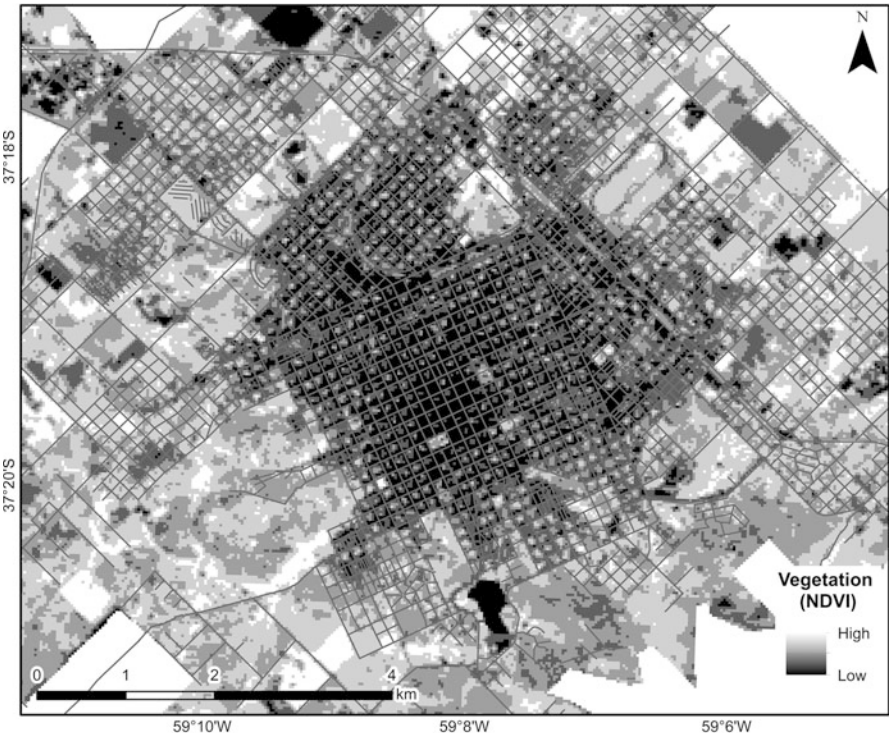

Fig. 4.5 Vegetation (normalized difference vegetation index). (Source: Landsat 5 TM 225086 24/10/2011)

winter had only a cold island during the night. Both cold seasons presented a low temperature range, less than 4 °C, whereas the warmer season had values over 8 °C. Analyzing the urban–rural values, a double pattern was detected. During warmer seasons, the urban effect is more relevant than during cold seasons, particularly in the maximum temperatures, reaching differences of more than 7 °C monthly.

Humidity was closely related to temperature distribution, reducing its values as the temperature rises (Fig. 4.7). The spatial distribution showed that the areas with a lot of vegetation had more humidity and, as a consequence, the temperature varied less during the day. The comparison between urban and rural conditions showed not only the relation with the temperature, but also a connection with the amount of precipitation. When the rainfall was similar, the humidity was determined by the temperature and the urban effect, whereas when the precipitation amount in the rural site was 10% higher than in the urban station, the humidity was higher in the former, changing the general behavior of humidity.

The study of comfort was carried out in two steps. First, the general conditions of comfort were analyzed calculating the HUMIDEX, Apparent Temperature, and Equivalent Temperature indexes using the urban–rural data. The results were that the general conditions of discomfort according to each index, in the urban area, were more likely to occur during the summer when the urban effect was more important.

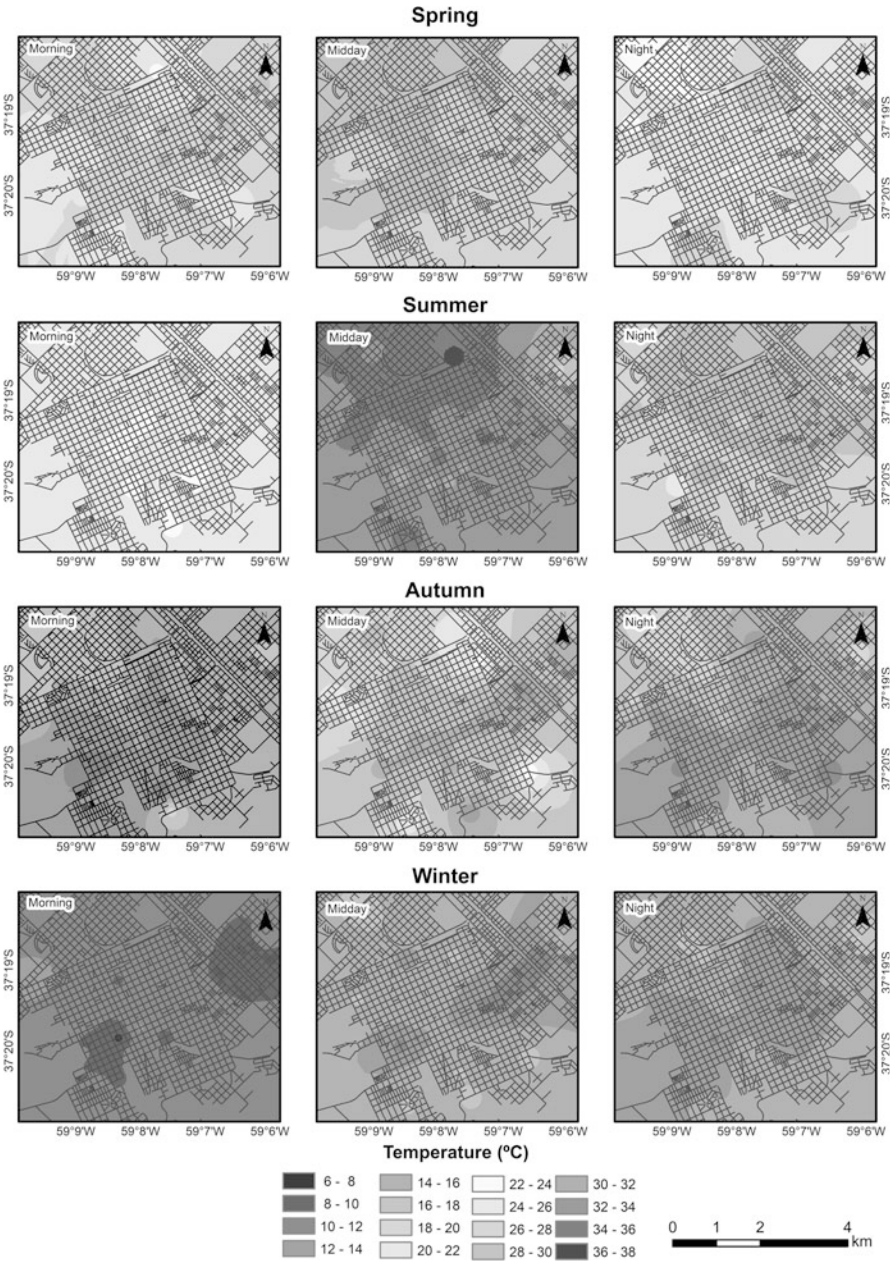

Fig. 4.6 Seasonal and daily information on temperature. (Source: Mobile transect measurements 2011)

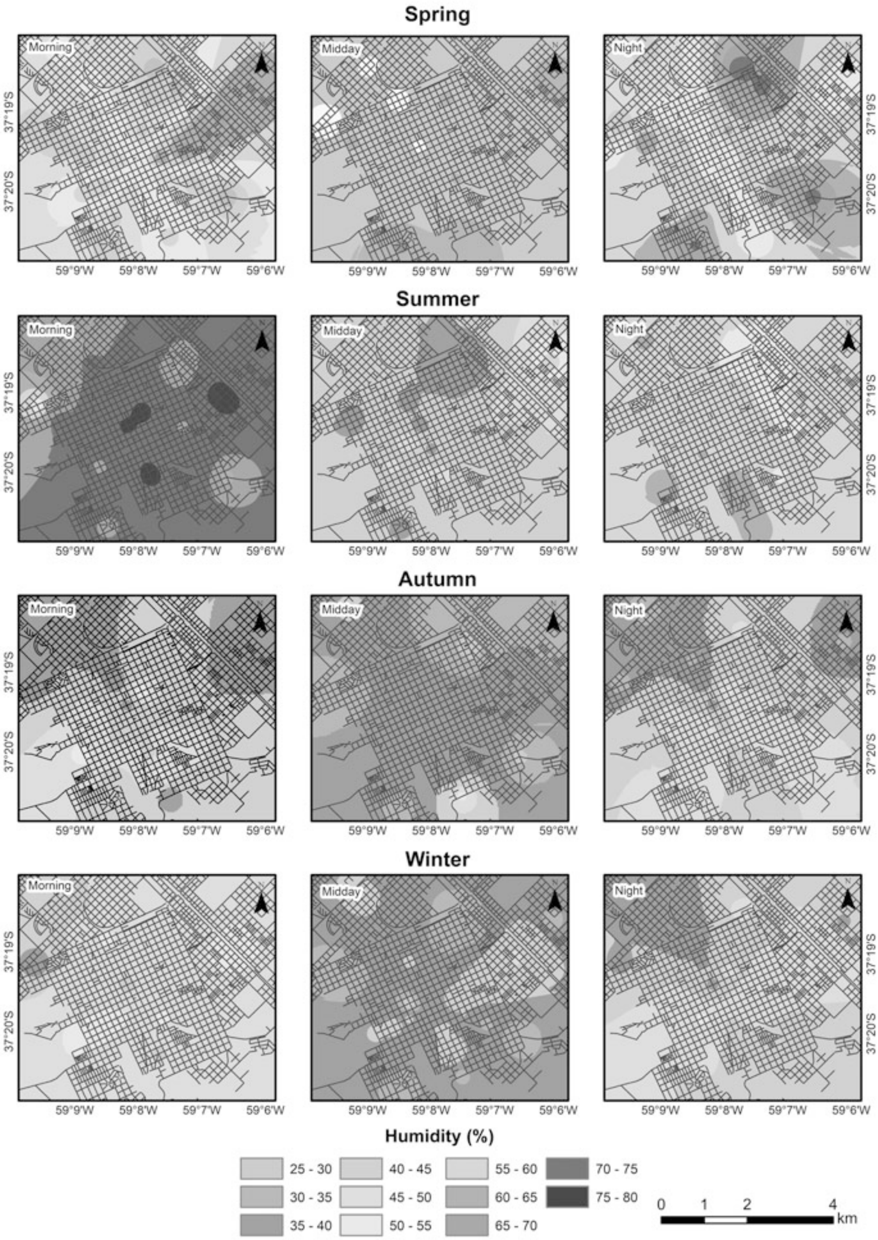

Fig. 4.7 Seasonal and daily information on humidity. (Source: Mobile transect measurements 2011)

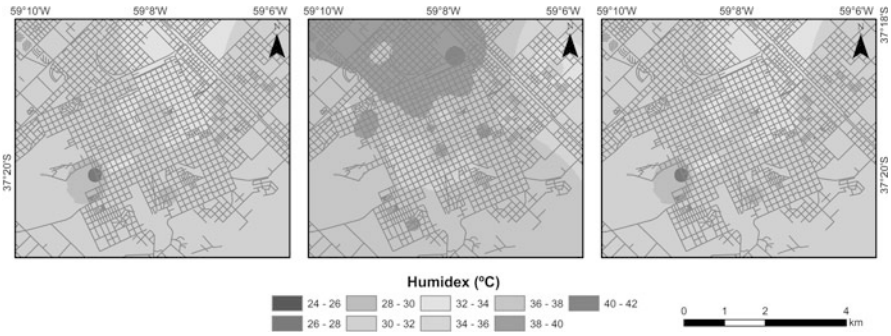

Fig. 4.8 HUMIDEX of summer. (Source: Mobile transect measurements summer, 2011)

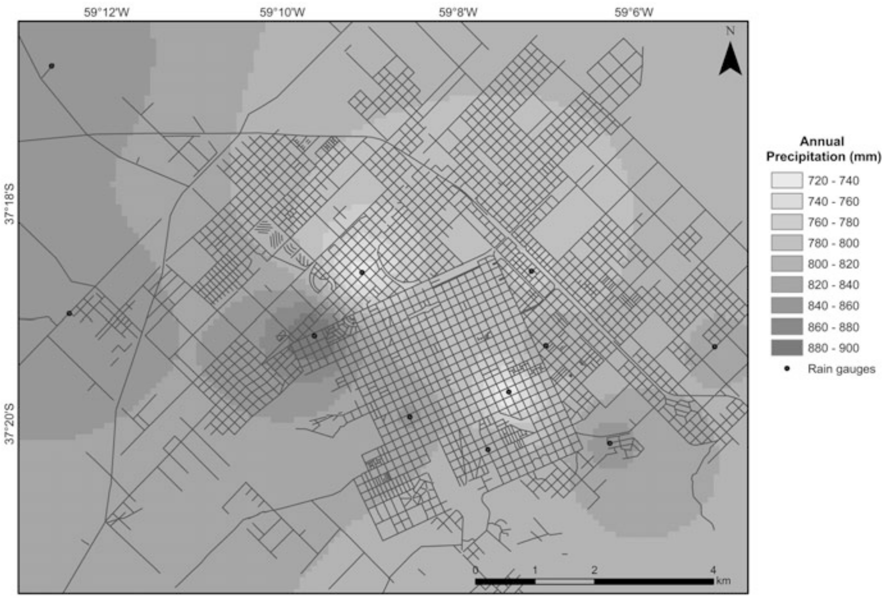

Fig. 4.9 Precipitation spatial distribution. (Source: Rain gauge network, IGEHCS 2008–2009, 2010–2013)

With this conclusion, the spatial distribution in the city was analyzed using the summer measurements from the transect method (Fig. 4.8). As a result, the city center and some parts in the north of the urban area, where large warehouses are located, were the most uncomfortable zones. This effect was particularly great around midday and at night.

Analyzing the spatial distribution of precipitation in the city, two distinctive patterns were discovered (Fig. 4.9). First of all, the higher amounts of rainfall were detected in the hills. Second, a barrier effect is produced by the tall buildings, which

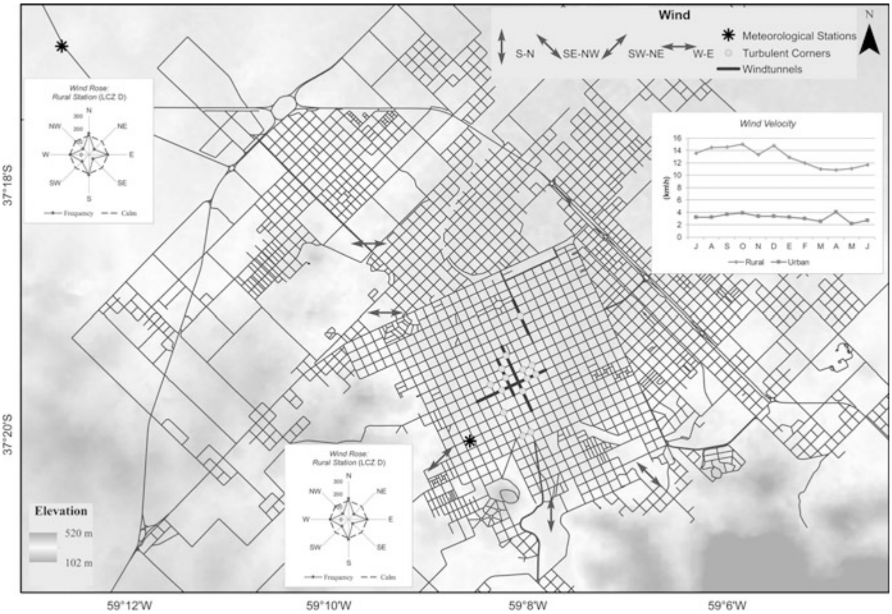

Fig. 4.10 Wind distribution and velocity. (Source: field work, weather station SMN and IGEHCS and wind models)

are reflected in lower precipitation amounts in the northeast of the city, which is downwind of the dominant winds. Considering the pH of the rainfall, as all the values were over the natural pH of precipitation (5.6), they are considered to have alkaline characteristics. Analyzing the spatial distribution, the lower values were found in areas close to industrial activities.

Finally, the wind was analyzed using three different approaches. First, an urban–rural comparison was made, and the results showed that the urban effect is reduced in a 75% wind speed and duplicates the amounts of no-wind conditions. Second, areas in the city that presented high turbulence and wind tunnels were detected, particularly in the city center, where the variations in the arrangement of buildings are greater. Last, wind models were applied to the area of the city to study the general patterns. As a result, a valley-–mountain wind pattern was detected, but only during regional anticyclonic conditions (Fig. 4.10).

4.4.3 The Complementation of LCZ and Climatopes Methodologies

Integrating the information described in the last two subparts, 16 LCZs were determined in Tandil. Figure 4.11 shows the distribution of the LCZs.

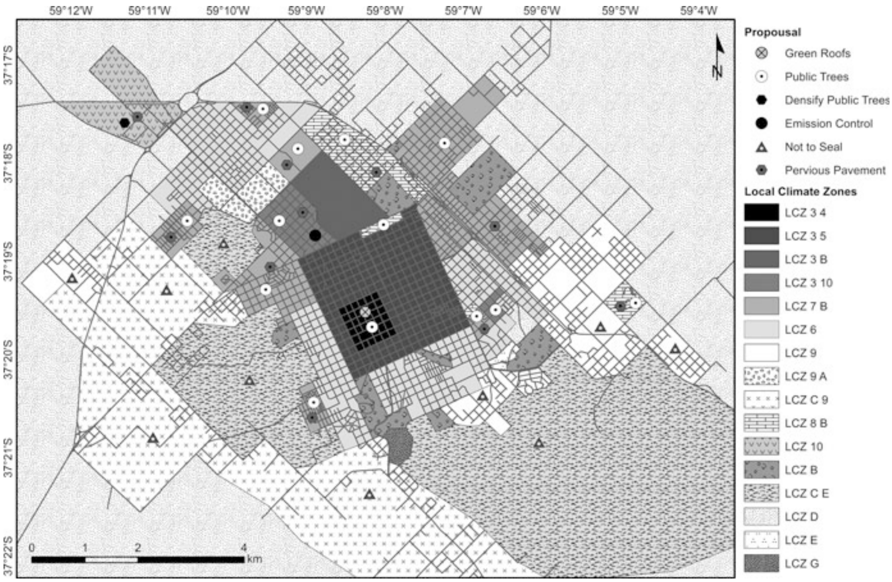

Fig. 4.11 Local climate zone map with the urban planning improvement proposal. (Source: Picone 2014)

In the central areas of the city, low buildings prevail, but among them, there are tall (LCZ 3_4) and midrise buildings (LCZ 3_5), the former particularly found in the city center. Around this area, there are three LCZs, all of them presenting low-rise buildings mainly for residential use. The difference between them is the amount of trees and the arrangement of buildings. LCZ 3_B has dense construction and some trees, LCZ 7_B is denser than the previous ones, and LCZ 6 has more trees and less dense constructions.

LCZs 10, 8_B, and 3_{10} are the three zones with industrial use or warehouses, with an increase in vegetation in the order in which they are presented. The three zones where vegetation prevails over constructions are LCZ 9, LCZ 9_A, and LCZ $C_{9.}$ The first two are the main vegetation; meanwhile, in the third zone, the natural environment of the area (bushes) prevails.

The other four LCZs are the land cover types. LCZ D is the most significant according to its area. LCZ C_E and LCZ E represent the natural environment of the area; therefore, they are the most important ones to be preserved. Finally, LCZ G is a dam made to prevent flooding in the city.

In Table 4.1 there is the name of the LCZ, a picture showing what it looks like, a description of the construction properties, and the climatic characteristics regarding temperature (daily, seasonal, and annual behavior), precipitation, comfort, and wind.

As can be seen, the little differences described above in the construction characteristics generate diversity in the climatic conditions of each zone. The reduction of vegetation generates higher temperature and more variability. In other zones, the topography and building arrangements cause changes in the wind flow and the

Table 4.1 The local climate zones (LCZs) and the corresponding climatopes with the description of the construction and climatic characteristics

Name	Picture	Description	Climatic characteristics
LCZ 3_4 Compact low-rise with high-rise		Dense mix low-rise buildings with arrangement of tall buildings of ten stories.	Variable temperature with great daily and seasonal variability. Low precipitation. Summer discomfort. Wind acceleration: wind tunnels and turbulence in corners.
LCZ 3_5 Compact low-rise with mid-rise		Dense mix of low-rise buildings with an arrangement of mid-rise buildings. Scattered trees.	High temperature with high seasonal variability. High precipitation in the west and low values in the rest of the area. Comfortable. Turbulence in some corners.
LCZ 3_B Compact low-rise with scattered trees		Dense mix of low-rise buildings with a lightly wooded landscape of deciduous and/or evergreen trees.	Seasonal temperature variability. Low precipitation. Summer discomfort. Reduced wind speed.
LCZ 3_{10} Compact low-rise with industrial		Dense mix of low-rise buildings with industrial structures.	High temperature all year. Precipitation lower than normal and pH lower than normal. Summer discomfort. Reduced wind speed.
LCZ 7 B Lightweight low-rise with scattered trees		Dense mix of single-story buildings with lightly wooded landscape of deciduous and/or evergreen trees.	Light high temperature. Normal precipitation. Summer discomfort. Reduced wind speed.
LCZ 6 Open low-rise		Open arrangement of low-rise buildings and abundance of pervious landcover.	Low variability in mean temperature. Normal precipitations. Comfortable in general, except in summer.
LCZ 9 Sparsely built		Sparse arrangement of small or medium-sized buildings in a natural setting.	Low temperature variability. High precipitation. Comfortable. Wind direction change during the day related to the valley and mountain breezes effect.

(continued)

Table 4.1 (continued)

Name	Picture	Description	Climatic characteristics
LCZ 9 A Sparsely built with dense trees		Sparse arrangement of small or medium-sized buildings with heavily wooded landscape of deciduous and/or evergreen trees.	Low temperature variability. Low precipitation. Comfortable. Reduced wind speed.
LCZ C 9 Bush with sparsely built		Open arrangement of bushes, shrubs and short, woody trees. Sparse arrangement of small or medium-sized buildings in natural settings.	Daily temperature variability. High precipitation values. Comfortable. Wind direction change during the day related to the valley and mountain breezes effect.
LCZ 8 $_{B}$ Large low-rise with scattered trees		Open arrangement of large low-rise buildings with lightly wooded landscape of deciduous and/or evergreen trees.	High temperature with mean variability. Lower precipitation. Summer discomfort. Regional winds prevail.
LCZ 10 Heavy industrial		Low-rise and mid-rise industrial structures. Few or no trees. Land cover mostly paved or hard-packed.	High temperature all year. Normal rain. Summer discomfort. Regional winds prevail.
LCZ B Scattered trees		Lightly wooded landscape of deciduous and/or evergreen trees.	Low temperature variability. Normal precipitation. Summer comfort and winter discomfort.
LCZ C E Bush with bare rock		Open arrangement of bushes, shrubs, and short, woody trees with landscape of rock.	Great daily temperature variability. Precipitation higher than normal. Variable comfort. Wind direction change during the day related to the valley and mountain breezes effect.
LCZ D Low plants		Featureless landscape of grass or herbaceous plant cover.	Variable temperatures according to the type of crops. Normal precipitation. Comfortable. Regional wind prevails.

(continued)

Table 4.1 (continued)

Name	Picture	Description	Climatic characteristics
LCZ E Paved surfaces		Featureless landscape of rock or paved cover.	High temperature during the day and low values at night. Normal precipitation values. Comfortable. Reduced wind speed.
LCZ G Water		Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.	Low temperature variability. Normal precipitation. Comfortable.

Source: Picone (2014)

precipitation patterns are modified. Last, the comfort conditions are a result of the combination of temperature, humidity, vegetation, and wind distribution creating important differences in the spatial distribution.

According to the results obtained in each zone, some presented problems concerning their climatic behavior. The main ones are related to: the diurnal variation of temperature, comfort during the summer, the amount of precipitation, and the generation of wind turbulences. Therefore, some proposals were made to mitigate those problems and others to prevent possible future problems. The main proposals are:

- Green roofs in areas to densify. This strategy was implemented to generate more efficient energy consumption and to balance the heating/cooling rates.
- Replanting public trees in areas where they were replaced by concrete areas. In this way, the climatic comfort conditions of these areas will improve, particularly during summer, and turbulence at ground level will be reduced.
- Densify public trees in areas where the amount of cement is high. The main objective is to compensate the energy balance. This strategy should be carried out in conjunction with green roofs on large warehouses and pervious pavement on parking lots.
- Emission control in the areas where pH values are lower than the rest. These areas are the ones that have concentrated industrial activities.
- Pervious pavement to improve infiltration in areas with high values of precipitation or a large number of sealed surfaces.
- Not sealing is a preventive strategy for two main reasons. First, in hilly areas, it will allow natural infiltration of the precipitation in the hill soils, and prevent the surface flow of this water directly to the city. Second, particularly in the valleys between the hills, it will allow the air drainage to bring fresh air and clean it.

4.5 Conclusion

As a general conclusion, this chapter introduced a case study where the complementation presented by Stewart and Oke (2015) is fulfilled. The mutual benefits of using the combination of LCZ and climatopes to generate UCMaps is quite clear, particularly understanding that both represent crucial descriptions for analyzing and presenting climatic information to urban planners. In this sense, the relevance of including urban climatic knowledge in city planning to improve the urban environment must be highlighted, especially considering the urban area as one of the most important areas where people live their lives.

In relation to the case itself, the map and the table must be taken as one. Moreover, they can be seen as an interactive instrument that changes along with the city. In this way, with each LCZ change, the results in climatic conditions can be inferred according to the table and mitigation strategies can be proposed. In the best-case scenario, it would be helpful to plan the city according to the relationship that has been revealed in the actual map and table to improve urban planning for a more sustainable city.

Acknowledgments This work was carried out with a PhD scholarship from the CONICET, Argentina, and it is part of two projects: An environmental conflict analysis on different scales and Studies of Applied Physics Geography in an interaction with Nature-Society. Problems on different spatial and temporal scales. A special thanks to Ian Stewart for suggesting this focus to my research, and to Roland Stull and his research group for running the wind models for Tandil city.

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Chapter 5
Thermal Differences, Comfort/Discomfort and Humidex Summer Climate in Mar del Plata, Argentina

Mónica Cristina García

Abstract The bioclimatic comfort is a state of complete physical, mental, and social well-being of the individual in relation to its environment, relevant in tourists and residents of coastal cities such as Mar del Plata, as its temperate climate contributes to alleviating high temperatures in other corners of the country and generates a feeling of comfort, favorable to rest and the development of various outdoor activities. The Humidex index (sensation of overwhelming or embarrassment perceived by people owing to the lack of evaporation of body humidity) was calculated to evaluate summer comfort/discomfort, based on hourly temperature and relative humidity data recorded on 18 January 2014 and 28 December 2015, identifying the periods of comfort and/or urban discomfort observed on those days. Some spatial differences were also evaluated and explained from data from three meteorological stations in the city. The results obtained, especially those on heat discomfort and its effects on the health of urban dwellers, especially children and the elderly, justify incorporating this index into the daily meteorological information of the media during the summer.

Keywords Comfort/discomfort · Humidex · Coastal cities · Human welfare · Information to community

5.1 Introduction

The city constitutes the humanized space par excellence. Human settlements interfere in the natural dynamics not only through the urban space, but also through the various activities that take place in it. One of the most important changes is the generation of a particular climate, called the urban climate. This climate is related

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directly and indirectly to the well-being, energy, and health of the human being. Its influence can be seen in all manifestations and daily urban activities and in a significant way in the recreational, tourist, cultural, and sports practices developed outdoors (Pérez-Cueva 2001; Gómez et al. 2010).

Jendritzky (1991) and Olgyay (1998) agreed that under certain atmospheric conditions, human activities are stimulated and invigorated, while others depress physical and mental efforts. The most important variables are temperature, duration of isolation, atmospheric humidity, absence of precipitation, and, especially, bioclimatic comfort. The latter is understood as the existence of an energy balance between the human body and its environment, with a minimum of self-regulation. However, other authors define it as the mental state that expresses satisfaction of the thermal environment, whereas the World Health Organization (WHO) points out that it is a state of complete physical, mental, and social well-being of every person in relation to the environment (García 2013).

This sensation of thermal comfort or climatic comfort constitutes a subjective experience and consequently, not everyone has the same opinion about optimal comfort. Different subjective variables, including age, gender, body shape, diet, skin color, metabolic activity, health status, etc., have an impact on human behavior in the face of changes in environmental variables, whereas other influences arise from the time of exposure to thermal history and the expectations of comfort that people have. Therefore, it is a relevant factor in any place, and even more so in coastal areas throughout the year, because it can contribute to mitigating the extreme temperatures that are registered in other cities and areas of the country. This may generate a feeling of well-being and comfort that favors the rest of tourists and residents and stimulates the development of various outdoor activities in Mar del Plata.

5.2 Theoretical Framework

The interest in deepening the analysis of conditions related to bioclimatic comfort has increased in the last decades. Besides, this interest has been focused on different scales in several countries, regions, and cities in addition to green spaces, parks, beaches or urban, peri-urban, and rural assets. Testimony to this is the work of Olcina and Miró (1998) in Alicante, Spain; Vecchia (2000) in São Paulo, Brazil; Scott and McBoyle (2001) in cities of Canada and the USA; Skinner and Dear (2002) in Australia; Givoni et al. (2003) in Japan; Andrade (2005) in areas of Lisbon; Gulyas and Matzarakis (2007) in Hungary; Toy et al. (2007) in Erzurum, Turkey; Lin and Matzarakis (2008); Lin (2009) in parks of Taichung, Taiwan, among others.

In Argentina, Brazol (1954) carried out the first bioclimatic studies and years later Hoffmann and Medina (1971) specified a bioclimatic classification for the country. In the province of Buenos Aires, Piccolo and Capelli de Steffens in 1985 and Capelli de Steffens et al. (2005) studied the conditions of summer discomfort in Bahia Blanca, with possible health compromise for its inhabitants; Marini and Piccolo

(2000) analyzed the climatic comfort summer in different estuaries of the south west of Buenos Aires Province; Diez et al. (2002) researched the thermal sensation of the discomfort winter wind in Ing. White; Rimondi et al. (2000) and García and Rimondi (2002) explained bioclimatic comfort during summer and winter in relation to tourism. In this case, the wind was studied as a relevant factor. García (2009, 2013) analyzed summer/winter bioclimatic comfort/discomfort in the cities of Mar del Plata, Necochea, and Quequén; Bustos and Piccolo (2011) performed a similar analysis in Pehuén Có and Picone (2014) did the same in Tandil.

Previous research has shown that knowing the bioclimatic comfort is of fundamental importance for improving people's quality of urban life in tourist cities, not only for locals but also for visitors. Over the last few years, repercussions for people's health have increased consultations (in children, the elderly, the chronically ill, among others) when the temperature is over 36 °C, but especially in situations of heat waves, as indicated by Díaz et al. (2015) and Tejedor et al. (2016).

Bioclimatic well-being should be understood as a cognitive process that integrates many stimuli influenced by physical, physiological, and psychological factors, among others. For this reason, temperatures and the relative humidity of the air are key basic parameters related to climatic comfort/discomfort. Both determine the environmental stress in the human body. The wind and the radiation are variables modifying comfort: the first increases the cold comfort and the second is able to alleviate the loss of comfort, correcting or alleviating by increasing the temperature respectively. The cooling effect of the wind on this human comfort is perceptible at speeds above 0.3 m/s. The temperature of the skin increases with ambient humidity higher than 70%, especially with high thermal values, as studied by Landsberg (1981); Pérez-Cueva (1994), and Lin and Matzarakis (2008) among others.

The interaction of the human body with the environment is produced by different processes. By convection, heat is transmitted to the air through the skin, and is also influenced by the wind speed. By conduction, the heat of the body is transmitted to the objects that are in contact with the skin, depending on the thermal difference between the surfaces and the thermal conductivity of the material in contact. Both mechanisms are related to sensible heat, for example, heat that can be directly measured with a thermometer (García 2013). Through radiation, heat is transferred between the body and surrounding surfaces through the environment. Evaporation is transmitted as caloric energy, which is dissipated by the processes of breathing and perspiration of the skin (latent heat). As Tuller (1997) and CEPIS (2008) point out, the lower the humidity of the air, the greater the evaporation.

Intervals of thermal comfort are extremely narrow: reduced to a temperature range between 20 and 25 °C and a relative humidity range between 30% and 70%. Other researchers, have reported that the threshold may vary between 13 and 20 °C, with peaks between 16 and 33 °C (Besancenot 1991; Tuller 1997). The smaller the humidity the greater comfort (Fig. 5.1). However, Croiset (1976) noted that the threshold of humidity, should be between 25% and 85%, regardless of the temperature. Low hygrometric values irritate the throat and causes breathing difficulties (Ochoa et al. 2009).

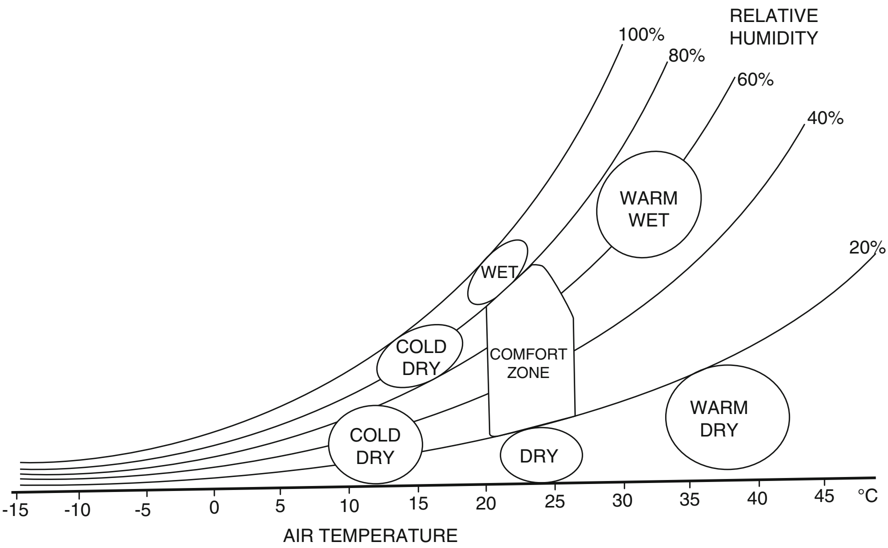

Fig. 5.1 Psychometric diagram and comfort zone. (Source: modified from Corma 2007)

The thresholds mentioned above refer to resting persons or persons with reduced physical activity, wearing light clothing. The strip of thermal comfort is known as the polygon or comfort zone and in the same polygon, most human energy is released and is focused on productivity (Olgyay 1998).

Several authors have studied the different reactions of each human organism to the tensions caused by the prevailing meteorological conditions at a given time and place, using different equations or thermal indices for a long time. Some of them, such as heat indexes, have been used to evaluate thermal well-being in the summer, such as thermal sensation (Siple and Passel 1939), the ITH thermo-hygrometric index (Thom 1959), temperature (Pettersen 1976), apparent temperature (Steadman 1984), Humidex (WSE 2009), among others. On the other hand, some authors measure the sensation of cold – combining low temperatures with windchill (NWS 2001; Marini and Piccolo 2000) or equivalent temperature (Quayle and Steadman 1999).

People's main concerns are related to the performance of outdoor activities and how climate conditions have had an impact on them over their lives has increased in the last 200 years. To provide some solutions, the development of human bioclimatology and the generation of various bioclimatic indexes were addressed (Moreno and Fernández 2003; Bustos and Piccolo 2011). Thus, several comfort indexes were applied in the field of sports activities, as pointed out by Tornero et al. (2006), for example, the thermal stress derived from the practice of surfing (Lyle et al. 1994) or from marathon races has been analyzed, as under a combination of heat and humidity, it can endanger participants (Freitas et al. 1985; McCann and Adams 1997).

The emergence of new environmental problems such as climate change, the urban climate, and especially the heat islands in cities, have shown that thermal extremes cause different physiological disturbances, affecting the health and well-being of the population (Kalkstein and Green 1997; Waters 2001; Jendritzky et al. 2000; Capelli de Steffens et al. 2005; García 2009, 2013). The human being is homeothermic and therefore needs to maintain certain vital parts at approximately constant temperature (Roset 2004). Hence, these studies are important for tourist centers, which should present the best urban adaptations to mitigate the effects of the thermal extremes. In this sense, urban tree vegetation also contributes to the reduction of noise and the circulation of particles and atmospheric pollutants, and modifies the storage and exchange of heat among different urban surfaces. It not only affects local climates, but also attenuates the manifestation of the island per se (Heisler et al. 1995; Nowak et al. 1997; García 2009). It also recognizes its role in the mental health of urban people, their contributions to the psychic balance of people (relaxation, tranquility, rest) and their senses (pleasant aromas, colors, shapes, sounds), improving aesthetics and enjoyment of the urban landscape (Capelli de Steffens et al. 2005).

The presence of the trees then generates a more comfortable space for the pedestrian. This induces people to walk, run, relax or recreate themselves, as streets and paths become more pleasant areas for shade in summer and contrasts of form and color in other seasons, bringing nature closer to the urban environment (Uribarrena 2004).

Therefore, the objective of this work is to analyze the summer comfort conditions in the three sites of the Mar del Plata. Days were selected based on high thermal values and complemented by the analysis of the time distribution of climate conditions and the influence of the vegetation on the thermal comfort. Their knowledge sets on strategic importance when planning designing of residential areas and open spaces, sports practices, tourism–recreational activities, work environments, etc.

5.3 Study Area

The city of Mar del Plata (38° 00′ S 57° 33′ W) is located in the south east of the Province of Buenos Aires, Argentina, the main city of the council of General Pueyrredon and considered the main coastal tourist center of Argentina (Fig. 5.2).

It is an intermediate-sized city including 600,000 inhabitants; however, the population increases during the summer season and public holidays. Mar del Plata has been included in the Inter-American Development Bank's (IDB) Emerging and Sustainable Cities Initiative (ICES) since 2012, along with 24 other Latin American cities.

A survey based on public opinion has shown that Mar del Plata has several problems, like other cities in Latin America, such as safety, transportation, drainage or connectivity. It should be noted, however, that almost all urban satisfaction

Fig. 5.2 Location of Mar del Plata in the Argentine and Latin American territory. (Source: modified from http://www.wikiwand.com)

indices are within or above average. A synthesis of these indices is included in Table 5.1.

According to the last census (INDEC 2010), the population of Gral. Pueyrredon is 618,989 inhabitants, of which 95% of the total belongs to Mar del Plata. The second city of the council is Batán with 15,152 inhabitants. Mar del Plata's masculinity index is 91.2%.

During the summer season, the influx of tourists increases the value by at least 50%, whereas in other periods of the year, 20–25% is added by visitors.

Table 5.1 Mar del Plata Urban Life Satisfaction Index (Argentina) in relation to the average of the Latin American cities included in the ICES[a]

Dimensions	ISVU ICES by city	Security	Inequity	Health	Transport	Job	Public space	Water	Living place	Noise	Sanitation	Climate change	Solid waste	Air quality	Education	Energy	Sewer system	Connectivity
ISVU media ICES by dimension	6.1	4.1	6.6	6.2	6.2	4.7	5.0	7.0	7.1	5.6	7.1	4.9	6.1	6.5	7.3	8.2	8.7	4.1
Mar del Plata	**6.3**	2.5	6.2	**7.2**	5.6	**6.2**	**5.0**	**7.9**	**7.3**	**5.7**	**7.5**	**6.0**	**6.0**	**7.2**	**8.0**	8.1	8.4	3.9

Source: Adapted from Ellis et al. (2016)

Note: Bold values equal to or above average are highlighted

[a]ICES. Emerging and Sustainable Cities Initiative. Inter-American Development Bank (IDB). The countries and cities included in the 2011–2014 report are: Argentina: *Añelo, Las Heras, Mar del Plata, Paraná and Salta*; Bolivia: *Cochabamba*; Brazil: *Florianópolis, João Pessoa and Vitória*; Chile: *Valdivia;* Colombia: *Barranquilla, Bucaramanga, Manizales, Monteria, Pasto and Pereira*; Ecuador: *Cuenca*; Guatemala: *Quetzaltenango;* Jamaica: *Montego Bay*; México: *Campeche, La Paz and Xalapa*; Nicaragua: *Managua*; Paraguay: *Asunción*; Uruguay: *Montevideo*

According to the aforementioned census survey, there are 316,144 houses in the municipality, of which 84,967 (26.9%) are occupied only in summer (García and Veneziano 2012). However, there are 80 dispersed precarious settlements[1] with a very low socioeconomic level, which includes 19.5% of the poor area in the Mar del Plata-Batan conglomerate (INDEC-EPH 2016).

The Mar del Plata activity rate in the third quarter of 2016 is 46% (in Argentina, 45.1%). The level of unemployment in the city reaches 12.1% and underemployment reaches 13.4%, higher than those registered in the country (8.5% and 10.2% respectively) for the same period (Actis Di Pasquale et al. 2016).

Mar del Plata's economic profile is diversified, where 70% of the gross geographic product is made up of commerce and services, especially activities linked to tourism and the production of manufactured goods, which reaches 25%. Of the latter, 47% corresponds to food industries, especially those derived from fishing and horticulture, mainly produced by locals. Textile, metalworking and chemistry complement the industrial spectrum of the city. It is one of the main fishing ports of the country, with a multipurpose port station and an important university and technological innovation center. Almost the whole urban area is residential; in addition, there are green spaces, shops, and services (MGP 2007; García and Veneziano 2010).

The natural surface on which the city is based is very hidden by urbanization. Small elevations (no more than 45 m) are alternated in different parts of the city, mainly along the coastal border and to the south of the city (García and Piccolo 2008).

The coastal edge of the city is sinuous and adopts a general convex form that is exposed to the action of winds of almost all courses, but mainly those coming from NE, E, and SE (Fig. 5.3).

> . . . Due to its location in relation to the masses of subtropical and peaceful air that reach the region of Pampas to which it belongs, it usually suffers alternation of one and another. Consequently, it presents abrupt changes of time, that contribute to identify an area of great meteorological variability. According to Capitanelli (1992, 100) the area of study has as a subtropical marine climate without thermal summer and with extreme precipitations in spring and autumn. . . (García and Veneziano 2012, 32).

Mar del Plata periodically has precipitations that may exceed 100 mm in one day or – during humid periods – there may be values greater than 200 and 300 mm over a month. This has a strong impact on normal runoff in urbanized areas, mainly because of the increased waterproofing of the surface and a lack of a proper storm drain network, which generates urban flooding when extreme events appear. This problem becomes especially critical in those areas with precarious settlements.

[1]According to data released by the provincial government, Mar del Plata is among the first three cities of the Province of Buenos Aires with more precarious settlements, preceded by La Plata and La Matanza. https://10ahora.com.ar/mar-del-plata-la-ciudad-del-interior-de-la-provincia-con-mas-villas-155717/.

Fig. 5.3 Location of the study area and selected meteorological stations. (Source: Modified from Google Earth 2016)

The average winds in the city do not exceed 15–25 km/h and generally decrease between 20% and 40% under the influence of urban roughness. The sea breezes predominate in summer and spring; they start between 1 pm and 6 pm and the average speed is10 km/h. This has an impact on climatic comfort.

The *sudestadas*[2] and storms are a recurrent meteorological phenomenon in the area. There is an average of two *sudestadas* a year, where 40% of them are very strong, with winds over 75 km/h. Only 25% of them exceed 100 mm. Storms[3] are more frequent (about 5 per year) and predominate in summer where 10% of these are severe. Approximately 15% of the total storms presented rainfall of 100 mm and winds over 100 km/h.

Currently, climate change is altering thermal, pluviometric or wind patterns, increasing the intensity and frequency of extreme weather events (heat or cold waves, droughts, storms, etc.) or an increase in the sea level in several parts of

[2]*Sudestada* is a state of bad weather that affects the River of the Silver and the coast of the province of Buenos Aires and therefore, the studied area. It is characterized by the occurrence of regular to strong winds, with speeds greater than 35 km / h SE sector, with persistent, weak or moderate rainfall and relatively low temperatures. It is due to the combined action of the two migratory systems: a high pressure center located on the Patagonian Atlantic coasts, which supplies maritime cold air, and a depression or cyclonic area originated in the NE of the province of Buenos Aires, which transports warm air and damp. When both systems converge, depression deepens and SE winds intensify, causing various urban damages (SMN 1989b).

[3]Storms are produced by the development of convection clouds, in an unstable atmosphere, with strong vertical air movements. Due to their origin, they are classified in convective and frontal storms. In both types of storms, the warm and humid air rises, condenses its humidity and forms powerful cumulonimbus, which then precipitate, accompanied by electrical phenomena and eventually hail. The process of development, maturity, and dissipation of a storm generally does not take more than 1–2 h, except in the case of cluster or multicellular storms (SMN 1989a).

Argentina and the world. The trend can be aggravated and cities and towns will be affected, with various damages and/or economic losses.

Hoffman and Medina (1971) include Mar del Plata in the bioclimatic type of temperate and humid regions (5H). The characterization of the same slogan for the summer: "pleasant time during the day (between 20 and 26 °C); cool to cold nights (below 20 °C) and relative humidity between 65 and 80%." These thermal conditions are generally exceeded during the month of January (SMN n.d., 28–29).

5.4 Methodology

To analyze the summer climatic comfort in the city of Mar del Plata, daily thermal and hygrometric data were analyzed based on three meteorological stations (Fig. 5.3) located in the coastal area (Club Nautico Mar del Plata Station), in the urban area (San Juan Station) and in the peri-urban area (Aeropuerto del Mar del Plata Station). Data evaluated the main thermal and comfort differences that are observed between the meteorological stations reviewed.

To evaluate comfort on a summer day in extreme temperatures, the Humidex index was calculated from recorded temperature and relative humidity data on 18 January 2014 and 28 December 2015 at Aeropuerto Mar del Plata Station, as there were no disaggregated data from the other two. Then, the hourly periods of comfort and/or urban discomfort observed on those days were identified.

The Humidex is an index developed by the Weather Service of Environment (WSE 2009). In fact, it is a calculation that combines air temperature (°C) and relative humidity (%). It represents the warming effect perceived by people due to lack of evaporation of body moisture, making them feel overwhelmed or strained, usually in summer.

Humidex is defined as: Humidex = T + 5/9 * (e − 10), where e is the vapor pressure (6.112 × 10 (7.5 * T/ (T + 237.7)) * (H/100)), T is the air temperature (°C) and H is humidity (%). Heat produces a degree of personal stress that can vary according to the age and physical condition, health status, activity, etc., of each person. Danger ranges, Humidex scales, and possible symptoms are listed in Table 5.2.

Table 5.2 Humidex – index stress caused by heat

Humidex	State	Possible symptoms
<29	Comfortable	Slight discomfort. Possible fatigue on prolonged exposure or physical activity
30–39	Some discomfort	Discomfort growing. Possible heat stroke or exhaustion produced by physical activity or simple exposure to open air
40–45	Great discomfort	Heatstroke likely on continued exposure or physical activity. Avoid activity. Search for a cooler area
> 45	Danger	Imminent heat strike in continuous exposure

Source: modified from Bustos and Piccolo (2011)

Fig. 5.4 Location of measuring points. (Source: Modified from Google Earth, 2010)

To connect the influence of vegetation on the comfort of inhabitants, a transect or urban route was retracted on two residential neighborhoods of the city (Santa Monica and Los Pinos) located approximately in the center of Mar del Plata. This survey covered 23 measurement sites (Fig. 5.4), spaced about 50–60 m each. In each of them was measured temperature and relative humidity of the air by means of a digital thermo-hygrometer, at a height of 1.5 of the soil and without direct exposure to the sun.

The measurement path, made on foot, was made during the time of the maximum temperature (14 h) of the day 8 January 2008 during about 45 min. At that time, the local airport station, used as a reference (Fig. 5.3), recorded 33 °C, 30% relative humidity and wind NNW at 18 km/h.

The field data obtained are entered into a spreadsheet and the Humidex index was determined. The results were interpreted and the techniques implemented were discussed below.

5.5 Results and Discussion

Table 5.3 shows the comfort conditions during January 2014 and December 2015. The first month of the year 2014 included 11 days with temperatures over 30 °C; on 5 of these days maximum temperatures of between 36 and 39 °C were registered. In December 2015, high daytime temperatures above 30 °C were recorded on several days between 24 and 29 December 2015 (6 consecutive days) and between the 10th and 13th days of the same month (4 consecutive days). The heat waves cited above, explain the average high thermal values of these months (Table 5.3).

Table 5.3 also shows similar values in several parameters. The main differences were observed in the maximum thermal records and in the monthly amount of precipitation. Thus, the differences were 2.4 °C and 152.2 mm respectively in January 2014 and in December 2015. The precipitations recorded in January 2014 were distributed in 7 days, some of them with 50 mm and contributed to the increase in humidity. On the other hand, the rains recorded in December 2015 were low, even though they were divided into a similar amount of days, affecting the humidity available in the soil and in the air.

Evaporation is the most important process in the transfer of heat from the body to the environment (Clarke and Bach 1971; Golany 1996; Capelli de Steffens 2000), because it may get rid of sweating from the skin surface – which produces a dermal cooling. The lower the percentage of relative humidity, the faster the evaporation process. If the hygrometric values are high, the evaporation will be slow and difficult and if there are associated high temperatures, the sensation of "discomfort" increases. Under conditions of high humidity, small temperature variations produce perceptible effects (García 2013).

In fact, data from meteorological stations have addressed differences in some selected parameters. Table 5.4 shows that data from 18 January 2014 were analyzed to verify spatial changes under comfort climate conditions in residents and tourists. Data show thermal variations from 0.1 to 0.5 ° C of maximum records among stations (Table 5.4).

Calm conditions in winds recorded in San Juan station, located in the urban inland, are different than other values (20 km/h) obtained from the rest of the meteorological stations located in the coastal area and at the periphery. It is inferred that the different situation is related to site conditions in relation to the dominant wind that comes from NW.

The Humidex index was calculated for each station based on related maximum temperatures and hygrometric data (Table 5.5). Results varied from 46 to 47 °C. This means that not only local residents, but also tourists perceived on their skin the sensation that the temperature was over 45 °C, at least, 6 °C higher than the real value.

These results are similar to those observed on 6 February 2007, when an island of urban–coastal heat of 7.5 °C was verified at 4 pm going north. Then, more spatial variations ranging between −0.5 and 5 °C were calculated (García 2009, 2013).

Table 5.3 Meteorological parameters in selected months in Mar del Plata

Month	Maximum Temperature	Average Temperature	Minimum Temperature	Relative Humidity	Atmosphere Pressure	Wind	Precipitation
January 2014	39.5 °C	27.9 °C	6.0 °C	68.0%	1,010.2 hPa	18.0 km/h	165.2 mm
December 2015	37.1 °C	27.2 °C	6.0 °C	66.6%	1,010.8 hPa	16.8 km/h	13.0 mm

Source: National Weather Service, Aeropuerto Mar del Plata Station

Table 5.4 Selected meteorological parameters for the day 18 January 2014 in Mar del Plata

Station	Maximum Temperature	Average Temperature	Minimum Temperature	Relative Humidity	Atmosphere Pressure	Wind
Club Náutico Mar del Plata	39.1 °C	31.8 °C	24.5 °C	32.0%	1,004.9 hPa	19.2 km/h
San Juan	39.0 °C	29.4 °C	19.8 °C	35. 0%	1,006.8 hPa	Calm
Aeropuerto Mar del Plata	39.5 °C	30.7 °C	22.0 °C	31.0%	1,005.5 hPa	21.0 km/h

Source: Weather data from www.pwsweather.com and SMN, 2016

Table 5.5 Degree of comfort–discomfort as a Humidex index for 18 January 2014 in Mar del Plata

18-01-2014	Temperature (°C)	Relative Humidity (%)	Humidex Index (°C)
0:00 Hour	29.0	51.0	34.8
1:00	27.0	58.0	32.9
2:00	26.0	65.0	32.6
3:00	25.0	69.0	31.6
4:00	24.0	73.0	30.5
5:00	25.0	74.0	32.4
6:00	24.0	78.0	31.4
7:00	24.0	83.0	32.2
8:00	24.0	83.0	32.2
9:00	27.0	65.0	34.3
10:00	31.0	52.0	38.4
11:00	33.0	43.0	39.4
12:00	33.0	43.0	39.1
13:00	36.0	37.0	42.6
14:00	38.0	29.0	43.1
15:00	39.0	29.0	44.7
16:00	39.0	29.0	44.7
17:00	37.0	32.0	42.6
18:00	30.0	48.0	35.7
19:00	24.0	83.0	32.2
20:00	24.0	83.0	32.2
21:00	22.0	83.0	28.6
22:00	21.0	78.0	26.2
23:00	20.0	78.0	24.6
References			
<29	Comfortable		
30 -39	Discomfort Some		
40 -45	Great discomfort		
> 45	Danger		

Table 5.2, shows that these perceived temperatures by people are considered to lead to a feeling of discomfort.

For this reason, and for the purposes of verifying variations in a climate of comfort/discomfort throughout the days selected with high temperatures, scheduled temperature behavior was calculated by a Humidex for 18 January 2014. On that day, wind came from variable directions, with alterations from NW to E between 0 am and 6 pm, and from S-SSW after a storm event. The sky was clear and cloudy before the storm event occurred.

From observation of Table 5.5, it can be seen that only night hours (after 9 pm; 12.5% of daylight hours) generated some comfort for people, perceived when the temperature was below 30 °C. Table 5.5 also shows that most of the day led to discomfort (87.5% of the hours of the day); perceived temperatures were between 30 and 39.9 °C, which produced a feeling of discomfort.

This situation increased more between 1 pm and 5 pm (23.8% of hours without climate comfort); in fact, when people felt temperatures 5–6° higher than the actual. These conditions of thermal stress could eventually produce exhaustion during physical activities. Therefore, it is desirable to avoid activity and seek cooler areas, ensuring proper hydration and appropriate dress.

A similar analysis was performed on 28 December 2015. Data from meteorological stations were summarized in Table 5.6. The increase in spatial disparity can be seen in thermal values during the day. They were at a maximum of 5.9 °C between stations located in the coastal and peri-urban sectors and a minimum of 3.1 °C between the Club Nautico Mar del Plata and San Juan stations. The hygrometric variations between the three stations were lower than 10%. During the morning before 7 am the wind was calm and then it increased to 20 km/h, from N and NW.

The linking of the maximum temperatures of the above-mentioned stations (Table 5.6) with the hygrometric data, the Humidex index was calculated for each one. Results ranged from 35 to 43 °C, which is the perceived temperature on the skin that people felt, about 4 to 6 °C higher than the real temperature.

To verify the climatic comfort/discomfort variations the Humidex schedule was calculated. During the day, the winds alternated from NNW to NNE, with two short lapses, one between 12 pm and 1 pm. Wind blew from SSE between 4 pm and 5 pm. Sustained sea breeze was observed. The sky was clear until the afternoon and then the cloudiness increased until 6 pm.

Table 5.7, shows that 20 of the 24 h of the day (83.4%) were uncomfortable, due to high relative humidity registers, especially during the night hours. Only during the early morning hours, between 3 am and 7 am (16.6% of the hours), when the air had already cooled, was the thermal comfort acceptable according to the Humidex index. The time of day where the discomfort was most pronounced was between 11 pm and 6 pm (40% of the hours without climatic comfort); the index showed that people perceived on their skin a temperature between 5 and 6 °C higher than the actual thermal register. It should be noted that when humans are exposed to thermocontrol physiological mechanisms are activated to maintain normal body temperature, e.g. sweating. When this process is intensified, it can lead to dehydration, heat exhaustion, and circulatory collapse (CEPIS-OPS 2000). This increases medical

Table 5.6 Selected meteorological parameters 28 December 2015 in Mar del Plata

Station	Maximum Temperature	Average Temperature	Minimum Temperature	Relative Humidity	Atmosphere Pressure	Wind
Club Nautico Mar del Plata	31.2 °C	27.0 °C	22.7 °C	37.0%	992.5 hPa	14.3 km/h
San Juan	36.9 °C	28.3 °C	19.6 °C	33.0%	1,002.2 hPa	14.7 km/h
Aeropuerto Mar del Plata	37.1 °C	28,5 °C	19.8 °C	30.0%	s/d	14.5 Km/h

Source: Weather data from www.pwsweather.com and SMN, 2016

Table 5.7 Degree of comfort–discomfort as a Humidex index for 28 December 2015 in Mar del Plata

28-12-2015	Temperature (°C)	Relative Humidity (%)	Humidex Index (°C)
0:00 Hour	24.0	73.0	30.5
1:00	24.0	78.0	31.4
2:00	23.0	83.0	30.4
3:00	22.0	88.0	29.3
4:00	21.0	88.0	27.6
5:00	20.0	94.0	26.6
6:00	21.0	88.0	27.6
7:00	23.0	88.0	31.2
8:00	26.0	74.0	34.2
9:00	29.0	58.0	36.3
10:00	32.0	46.0	38.6
11:00	34.0	41.0	40.5
12:00	32.0	55.0	40.9
13:00	36.0	34.0	41.1
14:00	36.0	37.0	42.6
15:00	36.0	34.0	41.6
16:00	36.0	37.0	42.6
17:00	35.0	39.0	41,6
18:00	36.0	34.0	41.6
19:00	34.0	38.0	39.6
20:00	32.0	46.0	38.6
21:00	30.0	58.0	38.1
22:00	29.0	51.0	34.8
23:00	27.0	61.0	33.5

consultations due to heat stroke, hospitalizations, and even mortality in vulnerable population groups.

Figure 5.5 summarizes the hourly variation of the Humidex during selected days. Most of the hours of 18 January 2014 were very uncomfortable; this may become dangerous because people may be exposed to the maximum sunshine (3–4 pm). Only a certain amount of comfort was achieved after 9 pm.

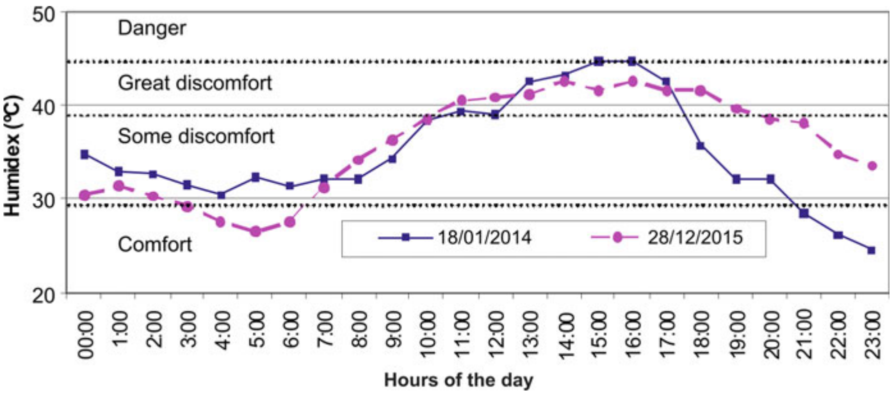

Fig. 5.5 Average variation time Humidex for 18 January 2014 and 28 December 2015

Fig. 5.6 Some heat regulation mechanisms. (Source: Diario Clarín, 2013 and 0223 Diario Digital, 2015)

On the other hand, on 28 December 2015 there were uncomfortable conditions for most hours. Humidex registered a great number of hours of the day with less comfort. Just before the dawn of this day a certain thermal well-being was reached.

To avoid the undesirable effects of the heat and to enjoy bioclimatic comfort during peak temperatures, the influx of residents and tourists to beaches for shade and fresh and open water increased (Fig. 5.6). When this was not possible, physical activity was reduced and supplementation or correction of the usual ventilation or cooling in the homes increased.

This situation is also substantially improved when the urbanized area has adequate tree cover, because trees have a great influence on the solar radiation that reaches the surface, sometimes reducing it by 90% or more. Some of the radiation absorbed by tree cover leads to the evaporation and transpiration of water from leaves.

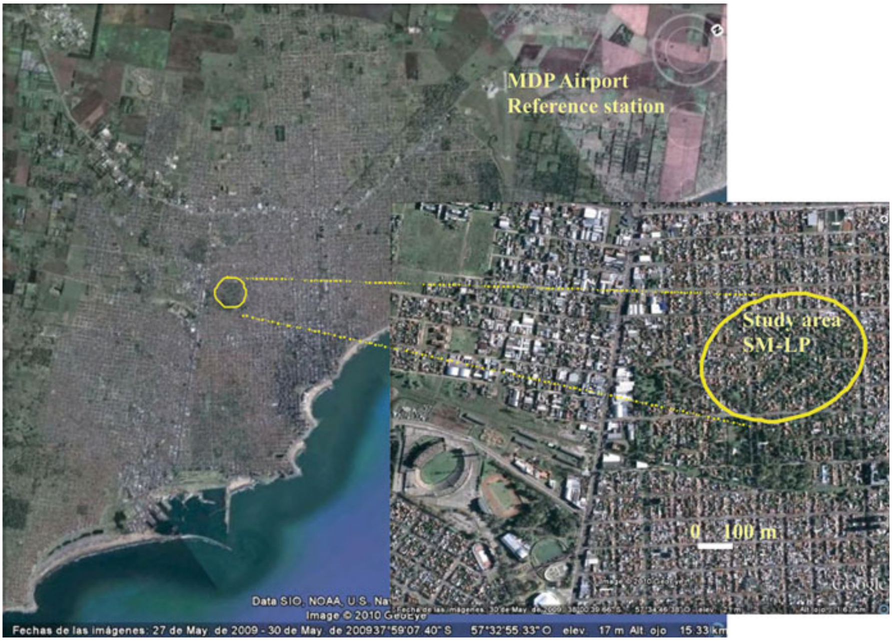

Fig. 5.7 Location of the neighborhoods Santa Mónica (SM) and Los Pinos (LP) of Mar del Plata. (Source: Modified from Google Earth 2010)

For example, an analysis of summer climatic comfort was included. This study was carried out in an area of Mar del Plata (Santa Monica and Los Pinos near the center of the city, Fig. 5.7). This urban area is about 22 hectares, with a deliberately irregular layout and low building density, characterized by its medium and medium–high socioeconomic status.

Both suburbs have a well-developed residential area, gardens, and green spaces predominate in plots with single-family homes. The streets are flanked by trees, although a significant percentage has been lost because of the intensity of wind storms in the 1990s (April 1990, June 1991, April 1993, May 1994, among others.

It is importantly its tree cover, consisting of pines and cypresses (*Eupressus lambertiana*), eucalyptus (*Eucalyptus globulus Labill*), bananas (*Platanus x hispanica Mill*), linden (*Tilia platyphyllos Scop*), and other species of high ornamental value, such as *ombués* (*Phytolacca dioica*, *Chorisia speciosa*), which gives it a distinctive residential character. With the advance of the urbanization in the sector, part of the arboreal vegetation has been eliminated, although the trees have been replaced by others of a lower height, foliage, and root development.

In Santa Mónica and Los Pinos, the temperatures were higher than the measurements in the referenced meteorological station (33 °C). They fluctuated between 35.9 and 34.4 °C in 19 of the measurement points, denoting the existence of a moderate urban heat island reaching 3 °C (Fernández 1995). Humidity had values between 31 and 19% (lower than those measured in the reference station

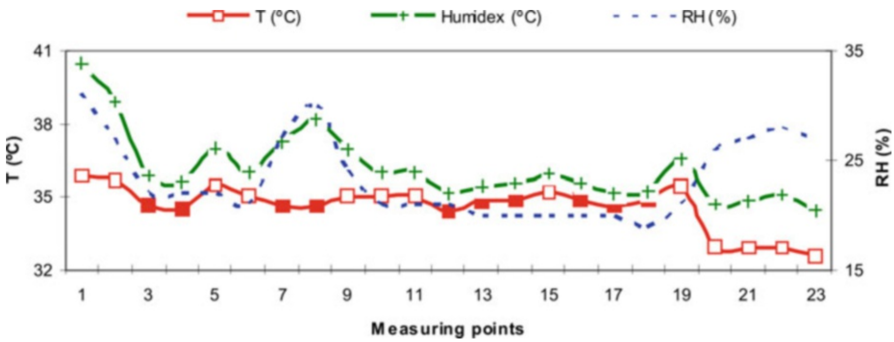

Fig. 5.8 Temperature, relative humidity, and Humidex at the measuring points. Reference: the filled squares identify more sites of leafy tree vegetation transect

30%). The sudden rotation of the wind from SSW modified the thermal conditions and, consequently, the moisture content in the atmosphere on the last four points of the route (Figs. 5.4 and 5.7).

The presence of wooded sites and dense foliage is identified in Fig. 5.8, which represents 43.5% of the measurement points (full squares). Taking into account the temperatures recorded along the transect, differences of up to 1.5 °C were observed between the maximum value (35.9 °C at point 1, with low shade) and the minimum 34.4 °C (at site 12, with trees of great foliage) before wind rotation and variation in hygrothermal data occurred. These differences were similar to those observed by Capelli de Steffens et al. (2005) in Bahia Blanca and lower than 7 °C observed in California by Moffat (1979) and 3.5 to 4 °C measured in a shaded area of Michigan (Haskell 1971).

The highest values of Humidex in Santa Monica and Los Pinos were observed at the sites where there was a lack of arboreal vegetation or of smaller sized foliage (Fig. 5.8). This showed differences of up to 5 °C higher than the temperatures registered in the most shaded areas and increased the thermal discomfort of the inhabitants. Similar thermal values were analyzed in the city of Valencia between two nearby sites, although with different vegetation cover (Ballester-Olmos 1991).

Several of the sites with higher temperatures in Santa Monica and Los Pinos were not the driest, in spite of site conditions (wetter soils, water in gutters, nearby sewers, increased vehicular traffic, etc.). An example of this is the Humidex peak between points 7 and 8, which recorded relative humidity at least 10–15% higher than others nearby. Similar situations were observed in other places in the city when studying the island of urban heat and of summer humidity in Mar del Plata (García 2009, 2013).

The Humidex index calculation based on the data gathered determined that a walker who circulated on the site felt perceived a temperature of 35 to 40.5 °C on the skin; hence, there was little pedestrian presence. This revealed the warming effect perceived by people due to a lack of evaporation of body moisture, which gives signals regarding burden or embarrassment. It is known that heat causes discomfort and stress, with the chance of heatstroke for the most vulnerable of the population (children, the elderly, the chronically ill).

Moffat (1979) and Salvador Palomo (1990) have also demonstrated the influence of vegetation on human well-being. This helps to mitigate the rigors of high summer temperatures and generates a sense of wellbeing and comfort that promotes relaxation and stimulates the development of different outdoor activities (Svensson et al. 2003; Capelli de Steffens et al. 2005).

The function and ecological value of urban trees are not always properly understood. Their role relies on mitigating the urban heat island and ensuring comfort conditions for urban areas. Furthermore, the gradual elimination of many tree species should be avoided.

The loss or degradation of urban trees must be re-evaluated because vegetation carries social and environmental benefits provided especially those that relate to the comfort and quality of life (Fiorentino 2008). These notions are linked to the feeling of well-being that provides this vegetation, which moderates extreme situations (pollution, noise, excessive radiation by aridity, CO_2 consumption, and even coldness aesthetics constructions) (Gómez 2005).

This problem should be included in the strategic plan of cities to minimize the loss of trees. Besides, it is necessary to encourage reforestation, as a preventive measure to reduce generation of urban heat islands and the emergence of areas of thermal discomfort. These latter points are particularly important, because they increase the impacts of global warming, the possibilities for improving urban comfort are linked to the existence, maintenance, and expansion of forested areas in the city.

The heat discomfort and health effects of citizens, especially children and the elderly, justify the notion that the Humidex index should be incorporated into the daily weather information for the media during the summer. This is common practice in several cities, such as Toronto, Canada, which reports a heat alert when the forecast for the next day is above 40 °C. An emergency is declared when the forecast indicates a Humidex at or over 45 °C in the next 24 h (Basrur 2002).

5.6 Conclusions

The presence of urban woodland is one of the mechanisms of regulation and mitigation of the heat islands in the city and consequently, of the greater or lesser comfort for those who live in it. Real thermal differences of 1.5 °C were observed between points with shade from those who did not have such condition. Similar results were observed in Bahia Blanca and lower in California and Michigan for similar studies. Nevertheless, the thermal sensation felt by inhabitants on their skin was 5 °C superior those felt on wooded sidewalks.

The results obtained allowed the objectives of this study to be corroborated and showed that the high values of the Humidex of high temperatures in the city of Mar del Plata are associated with the conditions of moderate or strong discomfort of people. For this reason, the need to ensure conditions of well-being or climatic comfort during heat waves, owing to their effects on health, for locals and tourists, should be addressed.

Likewise, the relationship between the presence of vegetation and the climatic comfort of the citizens was demonstrated. Besides, the presence of trees and green spaces in the city works as an alternative to the mitigation of urban heat islands and the consequent bioclimatic discomfort.

The knowledge of meteorological parameters is fundamental in tourist coastal cities dedicated to tourism activities. The bioclimatic features of the city and the feelings of well-being or thermal discomfort of its inhabitants are important aspects when making decisions or forecasts for local or regional management, urban design, public health, tourism, recreational activities planning, organization of outdoor sports and cultural events, etc.

The hourly fluctuations of the Humidex showed that 83.4% of the hours of the days were uncomfortable because of high humidity values, especially between 11 and 6 pm when people perceive on their skin a temperature between 5 and 6 °C higher than the real one. The most comfortable time of day was recorded in the predawn hours.

The implementation of various technological proposals for the continuous updating of weather information at all times of the day will be another important contribution to alerting the population about the precautions required to prevent or avoid an impact on health and associated medical pathological conditions, reducing the exposure and risks for vulnerable groups and, additionally, the related economic and social costs.

The deepening of studies of applied climatology such as the one presented, allows us to take advantage of the potential of the urban–coastal area, reduce its restrictions or climatic weaknesses, and improve the knowledge of factors associated with the climate. They can contribute to the optimization of urban management in the search for greater human comfort in coastal Latin American cities such as Mar del Plata and others with similar problems.

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Chapter 6
A Comparative Study of Thermal Comfort in Public Spaces in the Cities of Concepción and Chillán, Chile

Pamela Smith, Cristóbal Lamarca, and Cristián Henríquez

Abstract One way of evaluating the impact of urban climate on human health and the quality of life is through the sensation of thermal comfort, which depends on a series of parameters, such as the physiological, psychological, meteorological, and morphological factors of the city. In this context, this chapter focuses on evaluating and integrating the measurement of instrumental comfort, perceptual comfort, and urban morphology in public spaces for two Chilean cities. For this purpose, pedestrian urban canyons representative of the city centers are selected: the pedestrian walkway Arauco in the city of Chillán and the pedestrian walkway Barros Arana in the city of Concepción. The survey was carried out during the months of January 2016 and February 2014 and included meteorological parameter measurements of atmospheric temperature, relative humidity, wind speed and direction, in 2-h intervals. The comfort indicators of Olgyay, the Temperature–Humidity Index, and the Actual Sensation Vote were calculated. In addition, a survey of comfort perception was conducted according to an adaptation of Cheng's proposal. For the purposes of urban morphology, three-dimensional constructions and vegetation were modeled. A significant correlation is observed between instrumental indicators and perceived comfort; this is clearly demonstrated by the greater discomfort declared by permanent residents of Chillán. The importance of planning the structure and urban morphology of the canyons stands out as it regulates heights; materiality and green

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spaces that help to reduce the causes of discomfort in the summer. More studies are needed to determine winter comfort.

Keywords Climate comfort · Urban canyons · Pedestrian walks · Mediterranean and coastal cities

6.1 Introduction

The study of the climate in the city can be understand from multiple nested scales. In spatial terms, a scalar differentiation is observed both at a vertical and a horizontal level, covering different distances that can sometimes be very small and also present at different altitudinal levels (Gómez and Ferrer 2010; Erell et al. 2011). Horizontal variations can be explained according to soil water content, soil slope, height and vegetation type, optical and thermal characteristics of the material covering the ground (Ochoa de la Torre 2009), and the amount of radiation, urban morphology, and human activities developed. Although vertical variations can occur on a meso-scale level, such as the Urban Boundary Layer or on a micro-scale level such as the Urban Canopy Layer defined by energy balances and the urban feather effect at different altitudinal levels in the atmosphere (Oke 1987; Erell et al. 2011). This latter zone is characterized by rapid changes within a few meters of distance owing to the friction coefficient of the land, the type of soil type, the proportion of occupied space, the thermal properties of the materials, the orientation and slope of the surface, plant cover, soil moisture content, solar incidence, among other factors (Ochoa de la Torre 2009).

The literature on the study of urban climate is in agreement in indicating that this has a direct or indirect influence on human health; comfort, quality of life, efficiency, and maintenance of buildings, use of public spaces, among other aspects. Hence, the importance of considering the local climate in urban planning to have more sustainable cities and to generate conditions of greater comfort for its inhabitants (Nikolopoulou and Lykoudis 2006).

One way of evaluating the impact of urban climate on quality of life and quality of the environment corresponds to the study of the sensation of thermal comfort, which depends on a series of parameters, such as the physiological, psychological, meteorological, and morphological conditions of the city. In this context, this chapter focuses on evaluating and integrating the measurement of instrumental comfort, perceptual comfort, and urban morphology in public spaces in two Chilean cities.

The importance of studying thermal comfort and its health implications can be highlighted through the review of extreme events of heat waves that have affected different cities at an international level. The cases of France in 2003 (Schar et al. 2004) and Spain (Fernández and Rasilla 2008) demonstrate that this is an issue that has become increasingly important in public policy, which requires more research, especially in Latin American cities.

In the Chilean case, public policy toward extreme temperature values is becoming increasingly important, for example, by means of the warning announcements made by the Chilean National Weather Service (DMC in Spanish) to the population and the media in the face of ever more intense heat waves. Thus, understanding the behavior of comfort levels in public spaces is of great interest, especially in a context of natural climatic variability and climate change-associated impacts.

In the last decades, the metropolitan areas and mid-sized cities, between 100,000 and 300,000 inhabitants, have been the most dynamic in Latin America. Along with the sustained process of urban growth, mid-sized cities are gradually reproducing the structure and functioning of large cities, and decreasing their high quality of natural environment and the level of socio-spatial integration (López 2008; Bellet and Llop 2004). The spatial and social distances in the cities are increasing because the wealthier inhabitants commute to the peripheries. This social group produces a segregated and closed urban core, with low densities and extensive green areas. In contrast, the poor groups present a “desertified” and degraded landscape, whereas historic centers must make significant efforts to remain in force (Romero et al. 2003). The medium-sized Latin American cities, such as Chillán in Chile or Marilia in Brazil, are examples of the above, as they observe the previous changes, and present the verticalization of the buildings in the center of the city, strong peri-urbanization growth and at the same time as maintaining its traditional centrality of commercial and service activities (Henríquez et al. 2012). In these cities, the Central business center (CBD) fulfils an articulating role and provider of goods and services, which is why they receive large numbers of people every day.

Within the above framework, urban canyons are forming in the public spaces in the city centers. Their geometry is composed of a street delimited on its sides by buildings that define its opening toward the sky, which modifies the atmospheric conditions of the urban environments (Oke 1987; Santamouris et al. 2001; Erell et al. 2011).

Fintikakis et al. (2011) investigated the urban micro-climatic conditions of the historic center of Tirana, Albania (Mediterranean climate), for their integration in the process of the urban rehabilitation of public spaces. The main conclusions of the study were that the inclusion of more vegetation, the creation of shaded areas, and the use of materials with optical and thermal characteristics can improve the comfort conditions of urban canyons during the summer period, reducing air temperatures by up to 3 °C, which contributes to improving the environmental conditions of the city and the life of its citizens.

This chapter is structured in five parts: first, a brief theoretical review of the concept of thermal comfort and its relationship with public space, then follows the study area, which corresponds to the cities of Concepción and Chillán, Chile, the methodology, the results, and finally the conclusions.

6.2 Latin American Public Spaces

In a complete review of the history and current situation of Latin American public spaces, Arango (2013) distinguishes two types of public spaces: concentrated spaces, designed for the permanence of users, and linear spaces, which are places of passage, mainly associated with a chance encounter. Among the linear spaces are the street, avenue, boulevard, and the pedestrian walkways.

Since pre-Hispanic times there has been evidence for the creation and use of streets and sidewalks. For example, Tenochtitlan was composed of an orthogonal network of canals and roads that formed an island in Lake Texcoco, and served as a base for México City. Later, during the mandate of the Spanish crown, in this and other Latin American cities different walks began to be implemented, which, because they were surrounded by trees, were called *alameda*. This is the case of the Alameda de los Descalzos in Lima, the Alameda Vieja and Nueva in Bogotá, or the Alameda de las Delicias in Santiago, which was very popular during the colonial period (Arango 2013), and is now a busy commercial and transport service, surrounded by tall buildings and connecting the Plaza de Armas and Avenida Libertador Bernardo O'Higgins or Alameda.

In Latin American cities, pedestrian walks and malls were transformed into so-called public gardens or promenades with a clear hygienist intent that sought to bring the citizen benefits such as breathing fresh air, enjoying the vegetation and landscape, and recreational activities. At the end of the nineteenth century and the beginning of the twentieth century, avenues emerged, and in these, and in the pedestrian walkways, pedestrians, horses, bicycles, animal traction trolleys, trams, and an occasional car circulated in peaceful coexistence. Later, with the increase in use of the car, the streets lost their pedestrian conditions (Arango 2013).

During the second half of the twentieth century Latin American cities grew, experiencing transformation processes, deterioration or disappearance of many of its significant places. Avenues of intense traffic crossed some of the linear public spaces and intense urban speculation built buildings and densified what were previously residential neighborhoods (Arango 2013).

However, in recent decades, public space recovery processes have been activated, such as the Anhangabaú Valley Walk in Sao Paulo, or the Princesa Walk in San Juan de Puerto Rico, the recovery of which was undertaken in the 1990s by the municipality. Other significant projects are the Boulevard of the Zona Rosa in Salvador, restoration of the port in Porto Alegre or the coastal strip in Asunción (Arango 2013). In the case of Chile, it highlights the urban recovery project of the north bank of the river Biobio.

At the end of the nineteenth century and the beginning of the twentieth century, the Latin American city underwent a process of modernization that followed two streams of European urbanism. For example, in Chile, urban planner Karl Brunner carried out "hygienization" processes, generating large urban canyons to improve the health of the city. His work is also distinguished by the emphasis he placed on the public space for mass leisure and on the hierarchical notions of the road systems that satisfy the functional demands and have value for symbolism, the landscape, and the sense of connection of the city.

Despite the peculiarities, such as the difference in historical tendencies toward verticalization and compaction (Brazil), or expansion with low density (México), this characteristic is repeated in several Latin American cities (Ferreira 2012).

During the last few decades, the re-structuring of the urban space in the context of neo-liberalization has implied that the already integrated areas and the central areas of the cities are articulated with processes of privatization of the urban public (shopping center); changes in the location of urban activities (land uses), determined by the processes of de-industrialization and tertiarization, and the new verticalization processes undertaken by real-estate capital, which substantially change the functioning, amount of people, and social distribution (Cobos 2014). This has been implemented not only in the large Latin American metropolises, but also, gradually, in some fast-growing medium-sized cities, with a juxtaposition of modern processes with traditional urban elements. Many of these processes of creation and recovery of pedestrian spaces have also begun to appear in Latin American middle-sized cities, especially in the central zones, such as the two cases analyzed in this chapter.

6.3 Thermal Comfort and Public Space

The sensation of thermal comfort is defined as a mental state that expresses satisfaction with the environment surrounding a given person, without requiring an ambient temperature increase or decrease (Vanos et al. 2010; Parsons 2014). Thus, the sensation of comfort can be considered a subjective, spontaneous, and real-time assessment of climatic conditions (air temperature, relative humidity, air velocity, and solar radiation temperature) (Perico-Agudelo 2009), measured through individual sensations or by a group of people.

Increased temperatures cause discomfort in both interior and exterior spaces. The study of thermal comfort has been approached mainly for enclosed spaces (Brager and de Dear 1998; Hôppe 2002) such as offices, schools and homes, where conditions are often controlled by active climatic conditioning systems, such as air conditioning. In developing countries, this aspect may involve considerable costs, especially for the poorest populations. On the other hand, outdoor spaces have a greater climatic variability than interior spaces; however, there is less control of the climatic conditions. In this ambit, urban planning and design play a very important role as a public response to the challenges imposed by the local urban climate.

The sensation of thermal comfort depends on a series of objective and subjective parameters; in the first group, the main ones relate to the people themselves (physiological) and the rest have to do with environmental and meteorological conditions. Subjective parameters are associated with cultural behaviors and psychological factors.

From the earliest studies dealing with climatic well-being (late nineteenth century) to the present day, numerous indices have emerged to evaluate the thermal sensations and the person's response to climatic conditions (Fernández García 2001). More recently, Nikolopoulou et al. (2004) have proposed a direct measurement index of outdoor comfort, based on environmental variables, called the Actual Sensation Vote (ASV), which includes atmospheric temperature, relative air humidity, wind speed, and solar radiation.

The low correlations between micro-climatic variables and the sensation of comfort perceived outdoors found in research carried out under the Urban Realm and Open Spaces project suggests that thermo-physiology alone might not fully describe these relationships (Nikolopoulou et al. 2004). Without diminishing the importance of the human thermoregulatory system in the process of attaining thermal comfort, we must go further improve their understanding. Thus, it is increasingly more common to find studies that move toward the consideration of perceived comfort through surveys and rating scales, comparing them with micrometeorological data (Pearlmutter et al. 2014). The work of Nikolopoulou (2011) on external thermal comfort shows that other factors, such as climatic or thermal history, expectations and other non-physical parameters, strongly influence thermal perception.

Over time, the number of investigations that deal with the effects of microclimatic conditions on the use of public spaces has increased. Despite the lack of information that still exists in this area (Nikolopoulou and Lykoudis 2006), authors agree that environmental conditions and in particular, climatic conditions imposed on people using open spaces may affect their experience in a positive or negative way (Perico-Agudelo 2009; Nikolopoulou and Lykoudis 2006; Guzmán and Ochoa 2014; Zeng and Dong 2015). Precisely in exterior spaces, where the thermal well-being of a pedestrian can be evaluated, understanding the relationships among the form, space, and microclimate to intervene and make a city more livable and sustainable is invaluable (Cárdenas 2012). According to the aforementioned European project Rediscovering the Urban Realm and Open Spaces, the most important parameters that determine the use of public spaces are air temperature and solar radiation (Nikolopoulou and Lykoudis 2006), with differences according to the time of day.

To achieve better thermal comfort in public spaces, the climate of a particular place offers positive and negative aspects, according to the different times of the year or different times of day. Sun exposure may bring warmth in the winter, which can be considered positive, but could also overheat this same space during the summer. Knowledge of the complex relationships between psychological adaptation and external thermal comfort should provide an orientation toward designing better spaces. The effect of experience and expectations, the importance of environmental stimulation and other personal parameters can improve the diversity of the environment and, therefore, the experience of open spaces within the urban fabric (Nikolopoulou 2011).

In the context of urban climatology and in particular of the studies of thermal comfort, urban canyons are highlighted as a unit of analysis. These are understood as the void space delimited by the walls of buildings and the street (Grimmond et al. 2001). On this scale, urban geometry is one of the most important factors that contribute to temperature variation and therefore comfort (García-Cueto et al. 2007; Mayer et al. 2008; Krüger et al. 2011). However, there are only a few canyon studies in Latin American cities, highlighting research on the impact of forested canyons and different construction densities on the local climate: in Sao Paulo, Brazil (Chebel et al. 2012); in Mendoza, Argentina (Correa et al. 2012); and the study of thermal comfort in nine canyons of Concepción, Chile (Lamarca et al. 2018).

6.4 Study Area

This work deals with thermal comfort on a micro-climatic scale for the summer period, through the case study of public spaces in two Chilean cities: Chillán and Concepción, located in the Biobío Region. These two cities are at a similar latitude (36° 36′ and 36° 49′ S respectively), but in a different geographic location. Concepción is located on the coast and Chillán about 100 km inland, which explains why their climates differ in nuances, yet still belong to the same Mediterranean domain with winter precipitations that annually reach 900 and 700 mm respectively (Sarricolea et al. 2017). In Concepción, the annual average temperature is 12.9 °C, whereas the summer average reaches 16.5 °C, in Chillán these values are 13.7 °C and 19.5 °C respectively. The maximum temperatures reached in Chillán are much greater than those of Concepción, in fact, the former city has a higher number of summer hours in which the temperature surpasses 35 °C and for this same reason displays a greater recurrence of heat wave events, registering four during the summer of 2015–2016.

According to population estimates for 2016, both cities account for 25% of the regional urban population (Fig. 6.1) (INE 2016) and represent two different types of cities. Chillán corresponds to an average sized city that has expanded by more than 1,000 hectares in the last 20 years and Concepción is located at the core of the Metropolitan Area, which has experienced urban growth of nearly 5,000 hectares in two decades.

The rural and peripheral environment of the two cities is also different: Concepción is dominated by forestry activity, whereas Chillán is agricultural activity prevails. In their interior, the cities also differ with respect to their public spaces: Chillán displays a greater deficit and a very small amount of public green area per inhabitant, only 1.7 m, whereas for Concepción the Figure is 5.5.

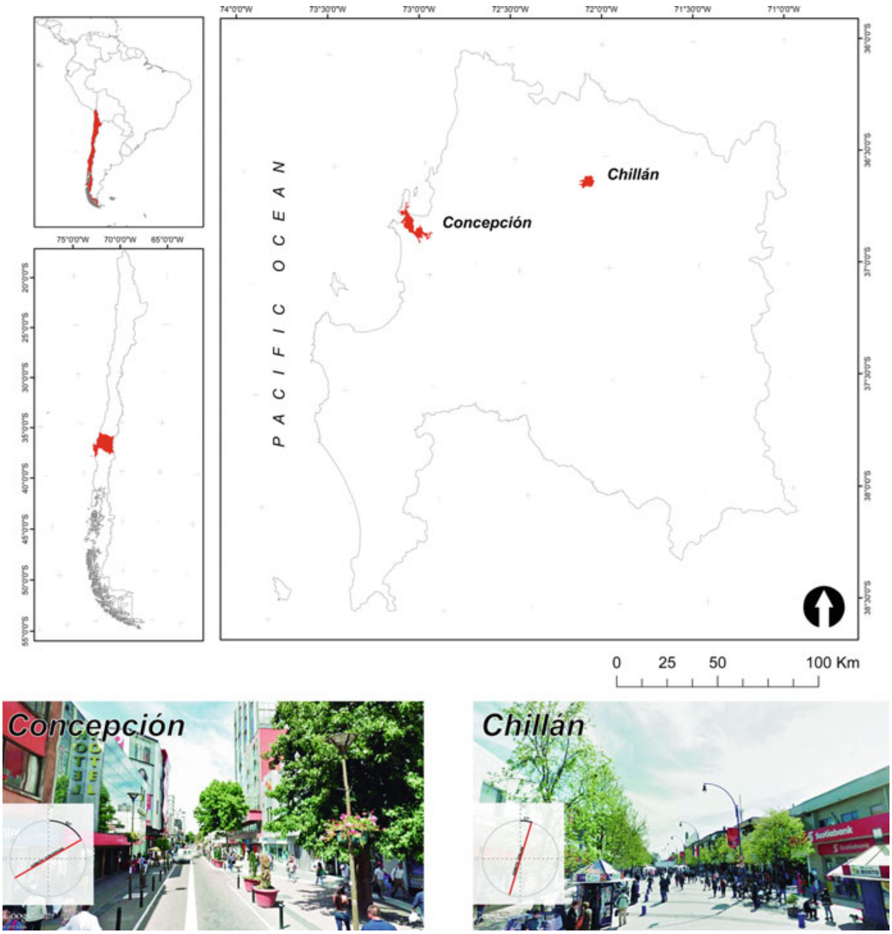

Fig. 6.1 Study area

6.5 Methodology

In the first place, a cadaster of the public spaces of both cities was done. Two representative public spaces then selected in the center of both cities; the pedestrian walk Arauco in the city of Chillán and the pedestrian walk Barros Arana in the city of Concepción, located in the center of the city, which concentrates the local climate zone "compact high rise" defined by Stewart and Oke (2012). Two pedestrian urban canyons were analyzed from each public space (see Fig. 6.2). The gathering of information was carried out during the month of January–February 2016 and February 2014 respectively. This included measurement of meteorological parameters of atmospheric temperature, relative air humidity, wind speed, and wind

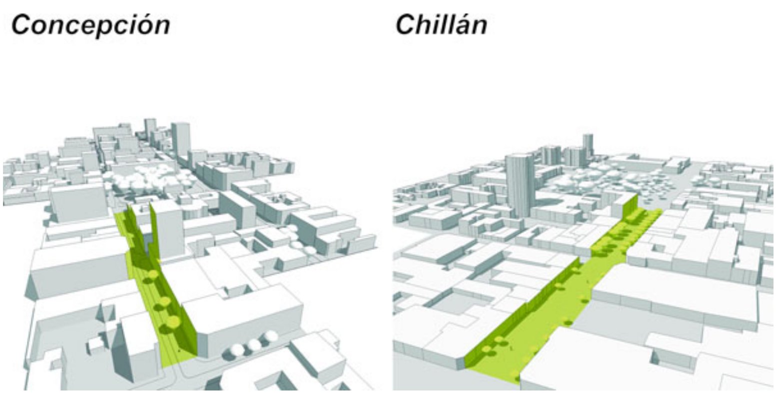

Fig. 6.2 Urban canyons modeled in 3D

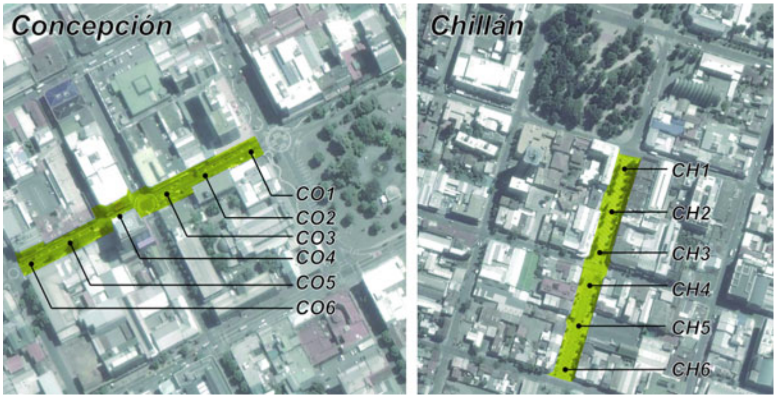

Fig. 6.3 Control points for the urban canyons of Concepción and Chillán

direction using mobile mini thermo-anemometers (VETO), at 2-h intervals, between 10:00 h and 20:00 h local time.

In each canyon, three-dimensional constructions and preponderant vegetation modeled to determine the orientation of its longitudinal axis with respect to the north (azimuth), the sky view factor (SVF), the H/W ratio, which determines the proportion of the canyon between its height and width, the solar radiation and finally the shadow factor given by the volumetric in the space studied. The methodology proposed by Lamarca et al. (2018) was applied. Shade and solar radiation were calculated for the 13 h. Six control points considered in each city, distributed along the longitudinal axis of each canyon (Fig. 6.3).

To measure the SVF, the technique of generating a hemispheric graph of the open public space was used, measured at a height of 1.5 m from ground level. Once the images were obtained from the fisheye photographs and 3D models, the image for calculating using the Sky View Factor Calculator in the MATLAB program selected.

The instrumental thermal comfort was calculated as follows using three indices:

1. The comfort zone proposed by Olgyay (1963)
2. The Temperature–Humidity Index (THI) (Thom 1959)
3. The Actual Sensation Vote (ASV) constructed by Nikolopoulou et al. (2004)

The comfort zone of Olgyay extends between 21.1 and 26.7 °C and between 20 and 80% of relative air humidity. The temperature limits are adjusted depending on latitude in accordance with the author's proposal, which extend between 21.1 °C and 27.02 °C in the cities of Concepción and Chillán.

The THI, like Olgyay, integrates relative humidity and atmospheric temperature through the following equation:

$$\mathrm{THI} = \mathrm{Tair} - (0.55 - 0.0055 \times \mathrm{HR}) \times (\mathrm{Tair} - 14.5)$$

where: Tair = air temperature (in degrees Celsius) and HR = relative humidity (in percentage; source: Jáuregui and Tejeda 1997).

The THI results range from 1.7 to 30; the optimal comfort level is between values 15 and 20 of the index. By means of empirical testing of THI values for humans, comfort limits for the summer season have been defined as follows (Nieuwolt 1977): $21 \leq \mathrm{THI} \leq 24 = 100\%$ of people feel comfortable, $24 < \mathrm{THI} \leq 26 = 50\%$ of people feel comfortable, and $\mathrm{THI} > 26 = 100\%$ of people experience heat discomfort.

Finally, the ASV delivers thermal comfort on a scale of −5 and +5 from data on atmospheric temperature, relative air humidity, wind speed, and overall radiation. Thermal comfort is associated with values between −1 and +1. Authors propose 10 different surveys built from data from 10 different European cities. This research considers the equation made for the city of Athens, Greece, which lies at a similar latitude to the cities of Chillán and Concepción. Although the three cities have significant differences with respect to their size and number of inhabitants, they have similarities in climate. The city of Athens, in addition to the cities of Chillán and Concepción, are within the domain of Mediterranean climates, presenting a marked seasonality, characterized by dry and hot summers.

$$\mathrm{ASV} = 0.034\mathrm{T}_{\mathrm{air}} + 0.001\mathrm{Sol} - 0.086\ \mathrm{V} - 0.001\mathrm{HR} - 0.412$$

Where: $\mathrm{T}_{\mathrm{air}}$ = air temperature (in degrees Celsius); Sol = solar radiation (in $\mathrm{W.m}^{-2}$); V = wind speed (in m/s) and HR = relative humidity (as a percentage).

Source: (Nikolopoulou et al. 2004).

The constants of the equation were calculated by Nikolopoulou et al. (2004) based on the relationship between the thermal comfort perceived as a dependent variable and the data of atmospheric temperature, relative humidity, wind speed, and solar radiation, as independent variables, in ten European cities.

In all three cases, the meteorological parameters used correspond to those measured on the field in public spaces. The global radiation, necessary for the ASV, was modeled in the Autodesk Ecotect Analysis program based on the 3D model of constructions and the weather data file of each city.

Table 6.1 Survey of urban canyon users

Canyon N°						Body	Thin, normal, robust		
Control point N°:						Gender:	Male, female		
Hour:						Clothing:	Little, normal, plenty		
Age:						User:	Neighbor, citizen visitor, tourist		
General comfort: How do you feel about the temperature?									
1	2	3	4	5	6	7	8	9	10
Thermal discomfort by cold			Thermal comfort			Thermal discomfort by heat			

Together with this modeling, a survey was carried out that included general data from those surveyed, public space users aged over 18 years old, and climate perception information, considering a scale of ten points, ranging from −2 (cold, very uncomfortable) and +2 (hot, very uncomfortable); values between −1 and +1 were associated with comfort. The survey was built based on Cheng's 2008 proposal (Table 6.1).

6.6 Results

This section comprises three main parts. The first consists of morphoclimatic modeling of the four pedestrian urban canyons, two for the Arauco pedestrian walkway in Chillán and two for the Barros Arana pedestrian walkway in Concepción. The second presents the instrumental comfort indices results and their relationship with morphological canyon modeling. Finally, we show the results of the surveys applied to passers-by in public spaces.

6.6.1 Modeling the Morphology of Urban Canyons

First, the Barros Arana pedestrian walkway architecture in Concepción is of a continuous façade, eclectic style, mainly emphasizing the architecture of the modern movement in Chile and the contemporary commercial architecture. Some buildings are of neoclassical style. The average height of the buildings is 17 m, the highest building being 45 m, the average width between façades is 16.5 m and takes into consideration urban furniture such as benches, garbage cans, lighting, planters, telephone booths, and kiosks.

The pavement goes from façade to façade and is composed of concrete grey tiles with white stripes; one-way vehicular access is allowed in both canyons with reduced speed.

The morphology of the Arauco pedestrian walkway in Chillán has the same characteristics to the one in Concepción. The average height is 6.3 m, the highest building being 18 m, the average width between façades is 26.5 m and it has street

Table 6.2 Values for the morphoclimatic variables for each control point

Control Pt	SVF	H/W ratio	Azimuth (°)	Radiation (W/m^2)	Shade (%)	ASV (comfort calculation)	Average comfort perception
CO1	0.280	1.40	60	322.66	100	−0.28	2.2
CO2	0.410	0.86		296.58	0	−0.04	2.8
CO3	0.450	0.79		303.80	0	−0.02	2.5
CO4	0.430	1.10		270.86	100	−0.2	2.0
CO5	0.405	0.52		339.31	0	−0.1	1.4
CO6	0.437	0.84		351.52	25	0.21	2.8
CH1	0.510	0.43	17	352.20	0	0.56	1.0
CH2	0.504	0.22		334.75	0	0.71	3.75
CH3	0.515	0.24		296.77	100	0.67	0.5
CH4	0.729	0.23		395.47	0	0.89	3.6
CH5	0.761	0.07		402.50	0	0.92	3.3
CH6	0.750	0.22		398.51	0	0.92	3.25

SVF sky view factor, *ASV* actual sensation, *H/W* height/width

furniture similar to that of Concepción. The pavement goes from façade to façade and is a cream colored cement tile with grey and ochre lines, and one-way vehicular access allowed in only one canyon with reduced speed.

With urban structure modeling (Fig. 6.3), the aim is to measure the spatial characteristics of public spaces, particularly pedestrian walkways, considering their proportions and also their orientation in the urban fabric, and thus define positive and negative conditions of urban design with respect to climate (Table 6.2). In both cities, the canyons studied are characterized by low vegetation, distributed in an isolated and heterogeneous way.

According to the climatic morph modeling results of the canyons, both public spaces are oriented north–east/south–west. The most significant differences in their urban design are the SVF and the ratio between the height of the buildings and the width of the streets (H/W). The previous indicators show differences in the urban canyon configurations in both cities; on the one hand, the pedestrian walkway Barros Arana in Concepción is narrower, closed to the sky, with taller buildings, and a homogeneous situation along the whole pedestrian walkway. Meanwhile, the Arauco pedestrian walkway includes two urban canyons that coincide with the streets that make up the walkway. The sky opening is greater, and increases with its distance to the square, from CH1 to CH6. The buildings are lower and the canyon is more open.

The above indicators relate to radiation, as they influence the amount of insolation. The radiation is consequently greater in Chillán than in Concepción. The results of the SVF, shade factor, and solar radiation models are shown in Figs. 6.4, 6.5, and 6.6 respectively.

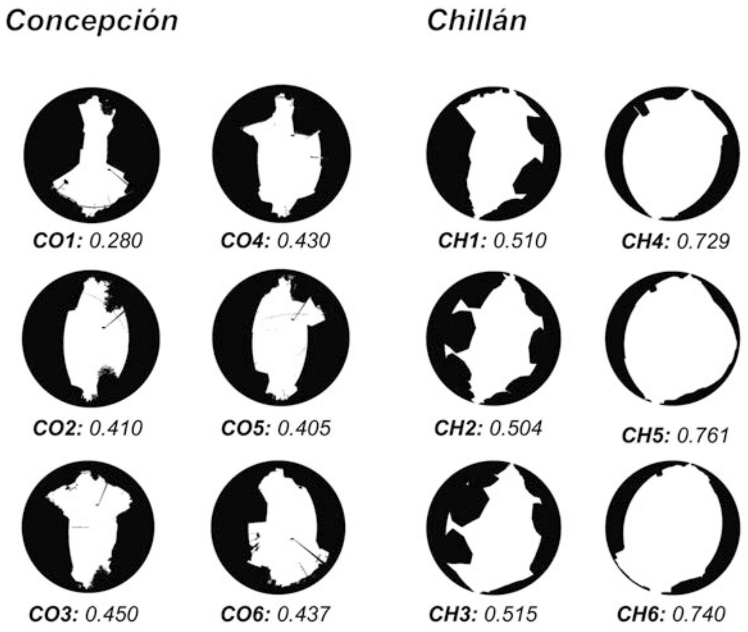

Fig. 6.4 Sky View Factor for each control point

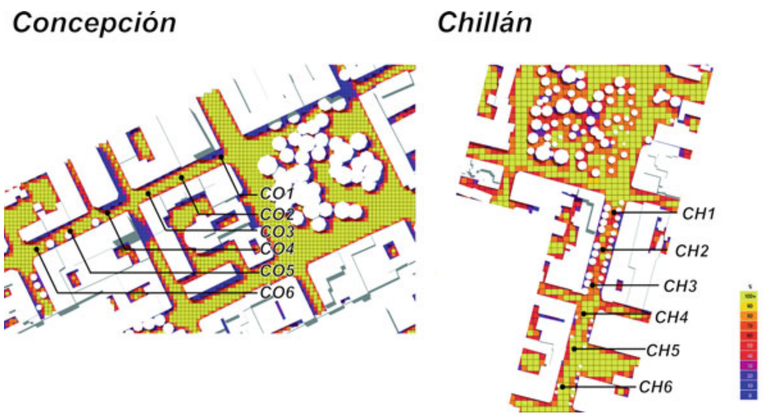

Fig. 6.5 Shade factor for Concepción and Chillán

6.6.2 Instrumental Thermal Comfort

First, although the study concentrates on the urban micro-scale, general thermal comfort has been calculated for both cities, taking into consideration the daytime hours of comfort and thermal discomfort according to the comfort zone defined by

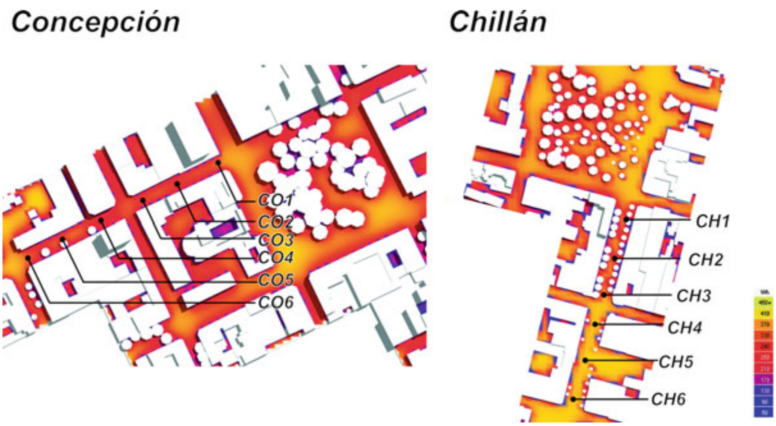

Fig. 6.6 Radiation for Concepción and Chillán

Olgyay (1963) and adapted according to the latitude of the cities. Olgyay's proposal defines the limits of the comfort zone using atmospheric temperature and relative air humidity data, between 21.1 and 27.4 °C and between 20 and 80% humidity respectively. The author states that for every 5° drop from latitude 40°, 0.5 °C should be added to the upper comfort zone limit. This scale used information from HOBO temperature recorders installed at different urban land uses and from the available meteorological stations of the DMC. Thus, Chillán is observed to have a higher percentage of daytime hours in a thermal discomfort situation during the summer (12%), whereas thermal comfort hours reach only 18%. This contrast occurs in Concepción, where 30% of its hours are considered "comfortable," whereas the temperature exceeds 27.02 °C for less than 5% of its hours. The remaining hours are below the lower limit, i.e., temperatures lower than 21.1 °C (Fig. 6.7).

On the canyon scale, according to Olgyay (1963), five of the six points evaluated in the Barros Arana pedestrian walkway in the city of Concepción are located under the lower limit (21.2 °C). The CO6 point is the only one that is located in the comfort zone (atmospheric temperature above 21.1 °C and below 27.02 °C) according to these criteria.

In contrast, in Chillán, five of the six points evaluated are in the discomfort zone (atmospheric temperature above 27.02 °C); only CH1 is located within the comfort zone (closest to the square).

On the other hand, the THI has two interpretations. First it defines the thermal condition; in the case of Concepción, the values go from 18.6 °C at the point CO1, closest to the city's arsenal, to 21.3 °C in CO6, which corresponds to the one furthest from the square of arms, to 250 m approximately. All points (from CO1 to CO5) are defined in a pleasant/comfortable situation, with the exception of CO6, which enters the hot category.

On the Arauco pedestrian walkway located in the city of Chillán, the values of THI go from 23.2 °C, next to the city square (CH1), to 25.5 °C (CH5), which coincides with the point that is most open, with a greater SVF and consequently has

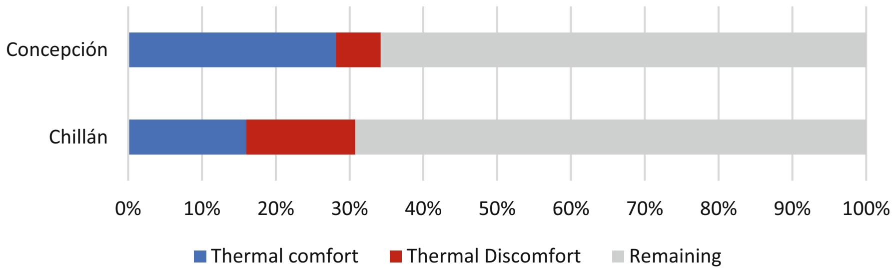

Fig. 6.7 Hours of thermal comfort and discomfort in the cities studied. (Source: Authors' own elaboration)

Table 6.3 Weight of the morphoclimatic variables to explain the instrumental comfort

	Sky View Factor	H/W ratio	Global radiation	Orientation (azimuth)	Constant
Both cities	0.771	−0.191	0.001	−0.011	0.107
Concepción	3.067	0.273	0.005		−3.060
Chillán	0.937	−0.395	0.001		0.328

more insolation. Despite differences in the value of the indicator, all points are defined as hot.

In a second interpretation, the THI values are associated with the proportion of comfortable users. According to the data presented in Table 6.3, it is possible to establish the ratio of the proportion of comfortable users according to the indicator and the results of the perception survey applied along both pedestrian walkways. In neither case does it coincide; at all points the proportion of users who declare themselves to be in discomfort by heat exceeds 50% and does not adjust to what is determined by the index, even less in those cases where 100% of users should feel comfortable.

At all points, the ASV result corresponds to a situation of comfort, with values ranging from −0.3 to 0.95 (Fig. 6.8). There are marked differences between the results obtained for Chillán and Concepción. All the points evaluated for the city of Chillán are over 0.4, and canyon 2, corresponding to the segment of the Arauco pedestrian walkway between Maipón and El Roble streets, is the highest, approaching the value of 1, which marks the lower limit for heat discomfort. All values in Concepción are negative, except for point 6 of canyon 1 (CO6).

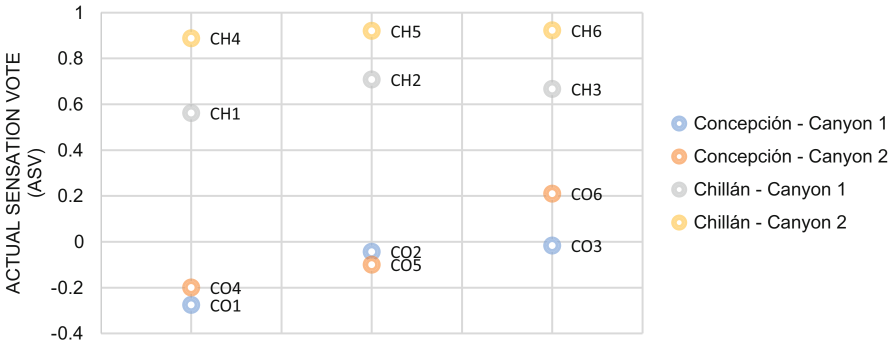

Fig. 6.8 Instrumental comfort indicator (Actual Sensation Vote) calculated for each control point

6.6.3 Relationship Between Thermal Comfort and Canyon Morphology

The results are interpreted first by integrating data from both cities and second, independently. The analysis of the aggregate data, Concepción and Chillán together, showed significant correlations between the morphological and instrumental comfort indicators from the ASV index, a direct relationship with SVF (0.892**[1]) and radiation (0.73**), and inverse with H/W (−0.905**) and azimuth (−0.945**). Unlike ASV, the results with perceived comfort do not have significant correlations.

When analyzing only the city of Concepción, the ASV correlates directly with the SVF (0.652) and inversely with the shade factor (−0.636); in the third place, H/W would also be inverse (−0.562). Unlike the ASV, the results with perceived comfort do not have significant correlations.

When relation the results of Chillán, a direct statistically significant correlation is shown between the ASV and SVF (0.947**), and between SVF and radiation (0.793), and inversely with H/W (−0.773). Although not statistically significant, when assessing perceived comfort, a direct relationship is detected with radiation (0.677) and SVF (0.599), and an indirect relationship with the shade factor (−0.709) and H/W (−0.574).

In an exploratory way, the weight of the climatic variables is evaluated to explain the instrumental comfort. If the data of both cities are evaluated, it is recognized that both the SVF and the global radiation have an effect by increasing the value of the ASV and thus decreasing thermal comfort. On the contrary, the proportion of H/W and azimuth increase comfort, as, by having a negative sign, they reduce the value, until reaching a certain threshold that would then be observed as discomfort by cold.

[1] **The correlation is significant at the 0.01 (bilateral) level.

On the other hand, when observing the above for each city, in Chillán the same signs are observed in these variables, and therefore the effect they have on the instrumental comfort value are in the same direction. However, in Concepción the H/W index is positive.

Table 6.4 presents a summary of the results of the three indices of instrumental comfort and its relationship with the comfort perceived in the pedestrian walkways of Chillán and Concepción.

6.6.4 Perceived Thermal Comfort/Surveys

A total of 56 surveys were conducted on the pedestrian walkway Barros Arana in Concepción and 72 on the Arauco pedestrian walkway in Chillán during the summer days of 2014 and summer of 2016 respectively, as indicated in the methodology. According to the users of the selected public spaces, the perception of thermal comfort in both cities is very different. On the one hand, in Concepción, 60% of users are comfortable users compared with 40% who declare themselves to be in a situation of discomfort, whereas in Chillán, the proportion is 20% and 80% (Fig. 6.9). Differences between the public spaces of each city are observed only in Concepción, where urban canyon number 1 is perceived as comfortable by more users, reaching 70%, 15% more than in canyon number 2.

From the differences observed between the comfort/thermal discomfort results obtained from the instrumental calculation and the response of the users of the public spaces studied in the cities of Concepción and Chillán, some relationships are explored that deal with variables that could modify the expectations and as a consequence modify the tolerance level of the meteorological parameters, mainly atmospheric temperature.

In the first place, the perceived comfort is related to the users' age, grouped into four categories: under 20 years, between 21 and 40 years, between 41 and 60 years, and over 60 years. In both cities, the highest proportion of users in discomfort is found in those users younger 20 years (Fig. 6.10). However, in the remaining categories, no similar pattern is observed. In Concepción, the greater proportion of comfortable users is between 21 and 40 years old, and there is an increase in users who are in discomfort as age increases, contrary to what occurs in Chillán, whereas when age increases, the proportion of comfortable users is greater.

Then, to evaluate the type of users of public spaces, three categories were defined based on their distance and frequency of use. The tourist is someone who lives outside the city and visits the public space for recreational walking or for some specific activity. The citizen lives in the city, but not in the center, more than a 1 km away from the public space analyzed, and visits this space sporadically. Finally, the user defined as a resident neighbor is someone who lives or goes to the center regularly, knows the streets well, the weather conditions, and therefore the climate (Fig. 6.11).

Table 6.4 Instrumental and perceived comfort per point

Point	Comfort zone (Olgyay)	THI value (Thom)	THI categories (Thom)	ASV Value	ASV categories	Perception of users			
						Number of users in heat comfort	%	Number of users in heat discomfort	%
CH1	Thermal comfort	23.2	Hot	0.56	Comfort	3	27.3	8	72.7
CH2	Heat discomfort	23.6	Hot	0.71	Comfort	1	10.0	9	90
CH3	Heat discomfort	24.2	Hot	0.67	Comfort	4	36.4	7	63.6
CH4	Heat discomfort	25.2	Hot	0.89	Comfort	1	12.5	7	87.5
CH5	Heat discomfort	25.5	Hot	0.92	Comfort	1	9.9	10	90.1
CH6	Heat discomfort	24.9	Hot	0.92	Comfort	1	9.9	10	90.1
CO1	Low	18.6	Comfortable	−0.28	Comfort	5	45.5	6	54.5
CO2	Low	18.8	Comfortable	−0.04	Comfort	2	18.2	9	81.8
CO3	Low	19.1	Comfortable	−0.02	Comfort	5	45.5	6	54.5
CO4	Low	19.1	Comfortable	−0.20	Comfort	5	41.7	7	58.3
CO5	Low	19.4	Comfortable	−0.10	Comfort	7	63.6	4	36.4
CO6	Low	21.3	Hot	0.21	Comfort	3	25.0	9	75

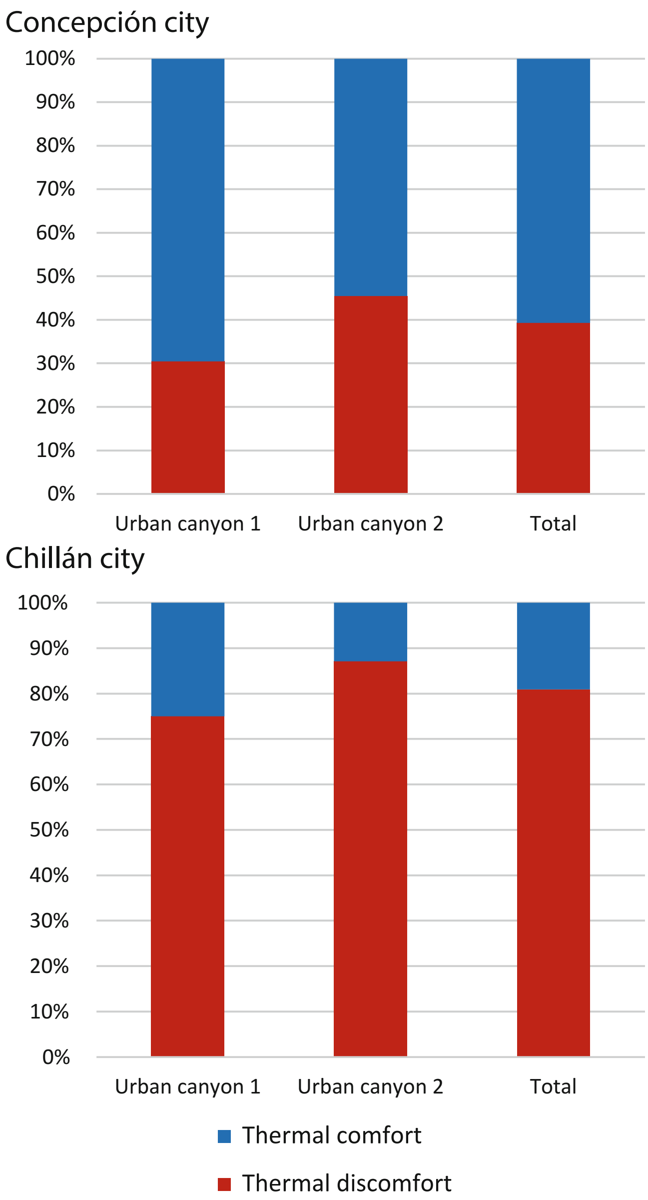

Fig. 6.9 Thermal discomfort perceived by users of the canyons studied

There are no significant differences between the types of users and the proportion of those in a situation of comfort or discomfort. In Concepción, the discomfort is slightly higher: approximately 5% for those defined as neighbors compared with the

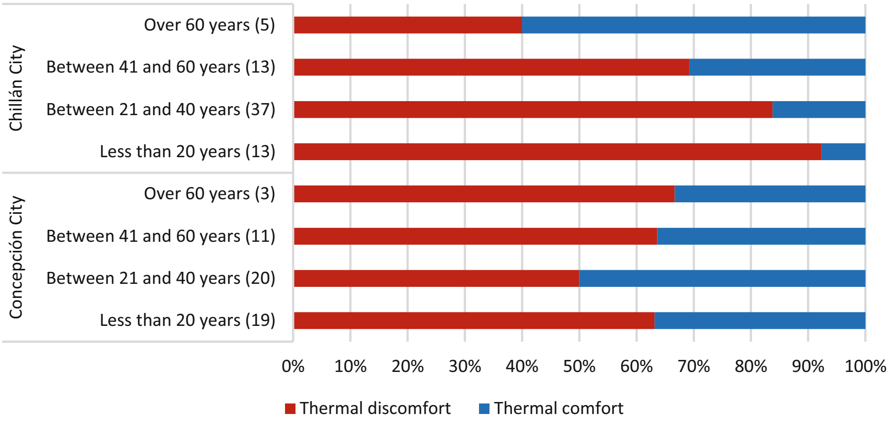

Fig. 6.10 Perceived thermal comfort for age ranges

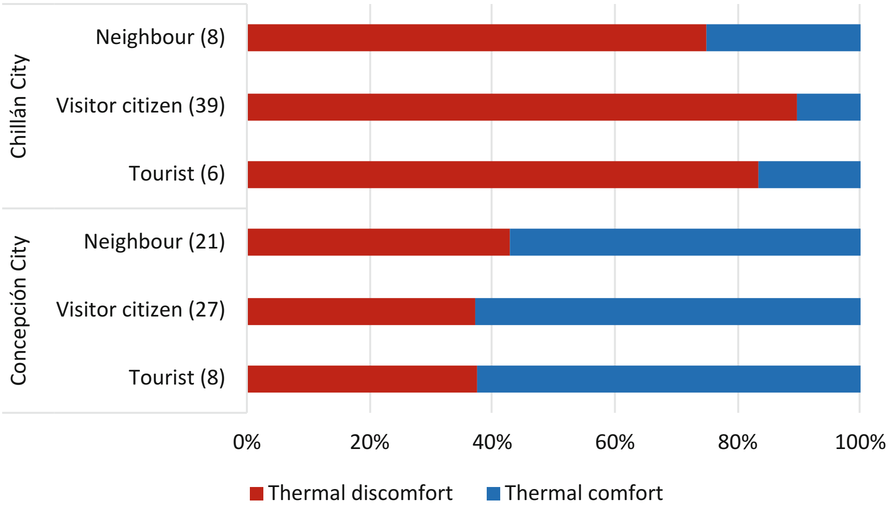

Fig. 6.11 Thermal comfort perceived by the type of users

peripheral citizens and tourists. The results in Chillán are a little different, as there is a greater proportion of comfortable neighbors, which may account for a greater adaptation to the meteorological conditions, and second, the tourists, when associated with a sporadic use mainly related to recreation can tolerate high temperatures better.

6.7 Conclusions

In general terms, it can be concluded that Chillán has greater conditions of discomfort than Concepción in the summer season due in large part to the background climatic conditions. It is characterized by a temperate interior climate with greater radiation and temperatures, unlike Concepción, whose climate is tempered by its proximity to the coast (the Pacific Ocean and the cold Humboldt current). The morphoclimatic factors of the canyons are very relevant in understanding the levels of thermal comfort in the pedestrian urban canyons studied, especially the H/W and SVF. In Chillán, there is a significant correlation between instrumental indicators and perceived comfort; this is clearly demonstrated by the greatest discomfort being declared by the permanent inhabitants of that city.

Considering that the formulas used to calculate instrumental comfort mainly include variables associated with meteorological parameters, the crossing of climatic variables with thermal comfort, mainly with that perceived by users, is very important. The incorporation of the perceived comfort allows deepening in the direction and intensity with which the objective parameters affect the thermal comfort. Morpho-climatic variables, such as SVF or the presence of vegetation, can be modified to improve climatic conditions in the city.

The use of the SVF indicator versus the H/W allows for the adaptation of new and existing public spaces by increasing or decreasing vegetation to reach the ideal ranges mentioned in the previous paragraph. The use of vegetation distributed in public spaces allows the comfort sensation to be improved during the summer. When using the vegetation to increase the thermal comfort in summer, it must be considered not to diminish the thermal comfort of winter. For the above, it is necessary to establish antecedents regarding the relationship between the insolation and the comfort during that specific season of the year. The use of deciduous species could increase comfort during the winter, allowing a greater insolation in the surfaces, if it is demonstrated that a greater insolation in winter is related to greater thermal comfort.

The results show that if the ASV and perceived comfort values increase as the SVF value increases, then this verifies that urban canyon designs should limit their proportions to be in SVF ranges between 0.45 and 0.55. On the other hand, and in relation to what is particularly observed in Concepción, it is shown that a drop in the SVF to values below 0.28 works negatively, as it passes through the discomfort threshold toward the sensation of cold.

With respect to the orientation of the canyons in the urban plot, we can estimate that the higher the azimuth, the better the instrumental comfort and perceived comfort; however, it is imperative to expand the sample of analysis to obtain more meaningful values that provide indications of the urban plot orientation in the urban planning stage.

The importance of planning the urban structure and morphology of the canyons is emphasized in terms of the regulation of building heights, materials, and green spaces that help to reduce the causes of thermal discomfort in summer. Many physical characteristics of urban canyons may be regulated by communal regulatory plans and urban designs.

We can conclude that both the proportion of the urban canyons and their orientation are related to the feeling of thermal comfort that pedestrians experience; therefore, urban design regulations can be drawn up that require and monitor the SVF values of each space to create more sustainable urban spaces in Chilean cities. Finally, carrying out these studies in the winter season is recommended to adjust the ideal ranges of SVF and azimuth and thus design urban spaces and pedestrian walkways that respond to climatic variables in the best way possible throughout the year.

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Part II
Air Pollution and Urban Climates

Chapter 7
Urban Air Pollution

Héctor Jorquera, Lupita D. Montoya, and Nestor Y. Rojas

Abstract Air pollution is currently the most serious environmental risk worldwide. Air pollution is the result of different driving forces (demography, economic growth, consumption patterns, energy options, cultural traditions, etc.) constrained by climate conditions, urban shapes and development patterns, distance to industrial or mining activities, air quality regulations and plans, etc. Air quality has been improving in some of the largest cities in Latin America, yet in most of them ambient air quality standards are not attained. In Brazil, Chile, Ecuador, and Mexico, the most polluted city is not the country's capital, emphasizing the relevance of sustainable local governance. In countries that report air quality just for their capital cities, most of their pollution levels are above the respective national ambient air quality standards. There is less information for mid-sized cities, and the available results are mixed. We present case studies from several countries that show serious air quality exposure for millions of inhabitants, especially the low-income segment. We discuss environmental justice, urban governance, and citizen participation in decision-making processes, sustainable urban transport options, and gender issues throughout those case studies.

Keywords Air pollution · Health impacts · Receptor modeling · Air quality management · Environmental justice · Sustainable urban development

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7.1 Introduction

The World Health Organization (WHO) estimates that, in 2014, as much as 92% of the world population was living in places where the WHO air quality guidelines levels were not met. Furthermore, around three billion people cook and heat their homes using open fires and simple stoves burning biomass (wood, animal dung, and crop waste) and coal. The WHO has estimated that in 2012 ambient and indoor air pollution caused 6.5 million premature deaths, an 11.6% of total global deaths; thus, it is the largest single environmental risk that society faces (WHO 2016a).

We present in Fig. 7.1 a conceptual framework (United Nations Environment Program [UNEP] 2016) to understand the linkages of air pollution with society. First, drivers such as population and economic growth produce pressures on the environment (increases in motor vehicles and fuel consumption, etc.) that constitute

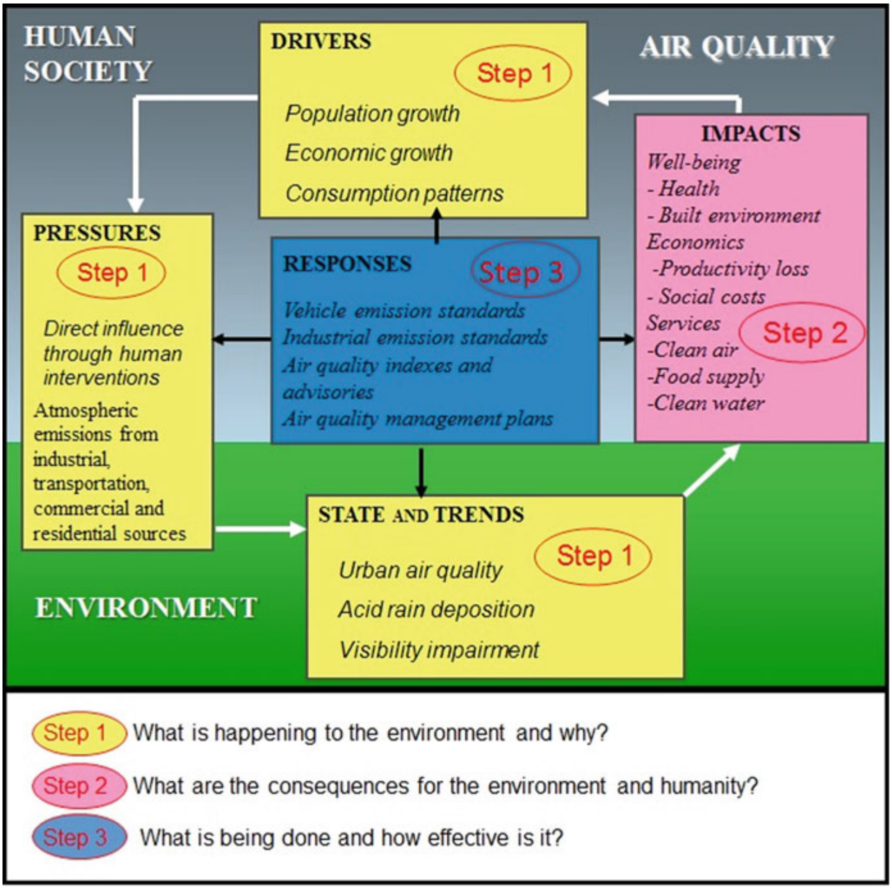

Fig. 7.1 The Driver Pressure State Impact Response (DPSIR) conceptual framework of the United Nations Environment Program (UNEP) (2016)

emissions of pollutants into the atmosphere by transport, industrial, commercial, and residential sources (Step 1).

Then, local and regional features (topography, meteorology, land uses) control the fate (state and trends) of those emissions, that is, ambient concentrations of air pollutants, deposition of dust and gaseous species (including acid rain), and visibility impairment (Step 1). This state of the atmosphere then determines the impacts on human health, ecosystem services, and the built environment, usually expressed in terms of social and economic damage (Step 2). Society's response to this problem comes in the form of policies oriented toward improving air quality; these policies may include the promotion of energy efficiency, sustainable urban transport, stricter emission standards for industrial, mobile, and residential sources, etc. (Step 3). The overarching goal is to maximize society's wellbeing, subject to natural, socioeconomic, and technological constraints.

In the following sections, we present the current state of air quality in Latin American cities and the major sources of ambient air pollution therein. Then we discuss three case studies: air quality management in Colombia, wood burning pollution in southern Chile, and indoor air pollution in Latin America. We summarize the major results in a conclusions and recommendations section.

7.2 State of Air Quality in Latin America

The first step in the conceptual framework laid out in Fig. 7.1 is to measure air quality. Historically, Latin American countries started air quality monitoring programs in the 1980s as a response to clear indications of high levels of air pollution in the major cities and industrial zones of several countries (Romieu et al. 1991). Currently, most Latin American countries monitor urban air quality to assess the state and trends of air pollution, to estimate population exposure and health impacts, and to evaluate the cost-effectiveness of regulatory measures.

According to the WHO's Global Urban Ambient Air Pollution Database (WHO 2016b) there are 122 cities in 16 Latin American countries that routinely report ambient concentrations of particulate matter $(PM)_{10}$ and $PM_{2.5}$, PM with an aerodynamic diameter below 10 and 2.5 μm respectively. We show a summary of those data in Table 7.1 below. Nine countries only report air quality in their capital city, and only six countries report seven or more cities.

Most of the cities with better air quality (i.e., annual PM_{10} below 30 $\mu g/m^3$) correspond to mid-sized cities (population less than one million inhabitants) or coastal cities with good ventilation conditions – such as Buenos Aires and Montevideo. The exception is Curitiba (Brazil), long known for its pioneering urban planning and sustainable urban transport. The picture for the most polluted cities (i.e., annual PM_{10} above 50 $\mu g/m^3$) is more complex and includes large cities (Santiago, Lima, Bogota, Mexico City) and mid-sized cities throughout South and Central America as well. In some of the largest cities (Mexico City, Sao Paulo, and Santiago), significant improvements in ambient PM_{10} and $PM_{2.5}$ concentrations

Table 7.1 Available annual ambient air pollution data for Latin American cities

Country (# cities)	PM_{10} summary, μg/m^3				$PM_{2.5}$ summary, μg/m^3			
Argentina/Buenos Aires			26				14	
Bolivia (2)	60	82	71	15.6	32	44	38	8.5
Brazil (45)	12	95	34	14.0	5	44	15	6
Chile (23)	12	75	46	15.5	5	64	24	12
Colombia (18)	18	52	40	9.7	9	41	20	7
Costa Rica (7)	20	47	29	8.7	14	30	22	6
Ecuador (9)	18	69	36	18.8	9	33	17	10
El Salvador/San Salvador			77				41	
Guatemala/Guatemala City			56				41	
Honduras/Tegucigalpa			59				36	
Mexico (9)	32	86	56	17.7	19	36	26	6
Panama/Panama City			31				14	
Paraguay/Asuncion			34				18	
Peru/Lima			88				48	
Uruguay/Montevideo			26				8	
Venezuela/Caracas			47				25	

WHO (2016b)
When four entries appear, they correspond to minimum, maximum, mean, and standard deviation of urban annual data for a given country

have been achieved since 1990. Hence, those cities' urban transport systems have reached more sustainable pathways.

The availability of ambient $PM_{2.5}$ concentrations is lower than for PM_{10}. In fact, most of the data compiled by the WHO (2016b) are estimates based on PM_{10} measurements, which means that ambient $PM_{2.5}$ is less frequently measured throughout the region. One way of estimating the spatial distribution of ambient $PM_{2.5}$ is to use satellite information. Several satellite missions orbit the Earth and provide estimates of the aerosol optical depth (AOD), a quantitative measure of how atmospheric particles attenuate light throughout the atmospheric column. Van Donkelaar et al. (2016) have collected available satellite information for AOD and combined it with ambient monitoring data and a global circulation model to obtain a global estimation of ground level $PM_{2.5}$. Fig. 7.2 shows their results for the Latin American region in 2015; the estimated spatial variation shows higher values at large metropolitan areas and desert regions, low values at coastal regions and remote zones (such as Patagonia). However, it should be remembered that those estimates involve uncertainties brought about by the estimation process.

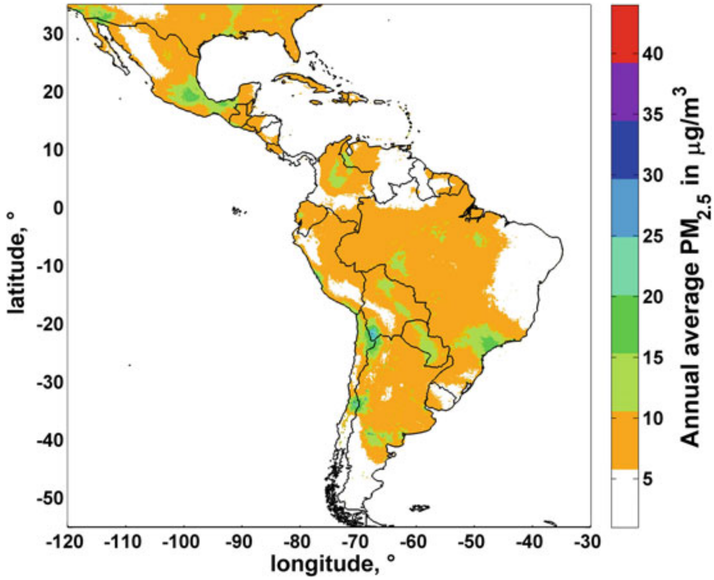

Fig. 7.2 Spatial distribution of ground level $PM_{2.5}$ ($\mu g/m^3$) in Latin America. (Data downloaded from: http://fizz.phys.dal.ca/~atmos/martin/?page_id=140. Accessed: November 2016)

7.3 Where Does Air Pollution Come From?

This question usually arises once air pollution has been measured. Answering this question requires obtaining a list of air pollution sources (traffic, industry, commercial, residential, natural) and the amount of air pollution that each of them contributes to the total burden at a given city; in this way, all relevant sources can be ranked according to their contributions. Following the conceptual framework depicted in Fig. 7.1, that answer completes step 1, identifying the sources to be regulated in step 3. Likewise, knowing how source contributions change with time allows for assessing how effective current air quality initiatives are; this also contributes to step 3 in the framework of Fig. 7.1.

There are two different methods of estimating the contribution of air pollution sources to air quality: dispersion models and receptor models. Dispersion models, also known as chemical transport models, simulate the meteorology in a given area (urban, regional, continental or global) and how the atmospheric emissions (coming from natural, residential, commercial, industrial, and transport sectors) are transported and physically and chemically processed in the atmosphere (Seinfeld and Pandis 2006). The result is a prediction of the spatial and temporal distribution of pollutants over a city or region, and estimates of how much each sector contributes to the air quality therein. However, this approach requires spatially (~ 1 km) and temporally (~ 1 h) resolved atmospheric emissions inventories, which in turn require substantial resources to be compiled. Because of that, few dispersion model results have been published for Latin American cities, especially those that predict source contributions to air pollution concentrations.

7.3.1 Receptor Models

Receptor models are statistical models that identify and quantify the sources of ambient air pollution and their effects at a site (receptor), using concentration measurements at a receptor site without using emission inventories or meteorological data (Belis et al. 2013; Hopke 2016). Therefore, receptor models are independent of and complementary to the above-described dispersion models.

The approach to obtaining a data set for receptor modeling is to determine a large number of chemical constituents such as elemental concentrations in a number of ambient PM samples. As some chemical species (denoted as tracers or markers) are only emitted by one (or a few) sources, a solution can be obtained, provided we include enough tracers/markers to constrain the solution sought. Any solution corresponds to a minimization of the differences between ambient data X and model data, which can be expressed as a mass balance equation:

$$X_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \tag{7.1}$$

where X_{ij} is the j-th species mass measured at the i-th sample, g_{ik} is the PM mass concentration from the k-th source contributing to the i-th sample, f_{kj} is the j-th species mass fraction from the k-th source, and p is the total number of independent sources (Hopke 2016). Finally, e_{ij} is an uncertainty term introduced to facilitate a statistical solution of the mass balance as opposed to an analytical mathematical solution to Eq. (7.1).

The number of sources (p) that can be resolved from Eq. (7.1) is highly dependent on the number of samples (n) and the properties of the m species considered above. The two most commonly used methods of solving the above equation are (Hopke 2016):

1. In the chemical mass balance (CMB) approach, the F matrices are known source profiles; thus, a system of linear equations is solved on a sample-by-sample basis using effective variance least squares, which is the basis of the United States Environmental Protection Agency's CMB model (US EPA 2016a). Here, the number m of chosen tracer species should be equal to or greater than the number of factors sought.
2. The F matrices are unknown, so they are iteratively estimated; thus, they are denoted as factor profiles. The most frequently used receptor model of this kind is Positive Matrix Factorization (PMF), which minimizes the following objective function (US EPA 2016b):

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\left(X_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj} \right) / \sigma_{ij} \right]^2 \tag{7.2}$$

where σ_{ij} is the estimated uncertainty in the j-th species at the i-th PM sample. There are two main assumptions for the mass balance in the above methods:

1. That source profiles do not change significantly over time or do so in a reproducible manner so that the system is quasi-stationary for CMB depends on them not changing.
2. That receptor species do not react chemically or undergo phase partitioning (solid/gas or solid/liquid) during transport from source to receptor (i.e., they add linearly). Metals are excellent receptor species with respect to assumption 2 and they have been used from the very beginning of receptor modeling. They are truly "tracers" because they preserve their identity as they are transported from a source to a given site (receptor). As the measurement of chemical source profiles is expensive and requires significant experimental facilities to conduct the tests, most of the reported studies from Latin America have been carried out using the PMF framework or similar techniques; the number of published applications of CMB is smaller. Once the source apportionment solution is generated, the contributions of each source are estimated, on a daily basis, by using the following multiple linear regression:

$$\mathrm{PM}_i = \sum_{k=1}^{p} \beta_k g_{ik} + e_i \tag{7.3}$$

where PM_i is the daily concentration of PM (PM_{10}, $\mathrm{PM}_{2.5}$, etc.) on day "*i*," g_{ik} are the source contributions (normalized, so that their average is 1 for each source *k*), e_i is an uncertainty term on day "*i*" and β_k is the average contribution of source "*k*" to ambient concentrations of PM. It is a customary assumption that all major PM sources have been identified (except perhaps biological sources and secondary aerosols); thus, the above regression coefficients $\{\beta_k\}$ should be positive and statistically significant (for instance, its p value <0.05). A negative value in $\{\beta_k\}$ means that too many sources are included in the receptor model; therefore, the receptor model should be run again with *p-1* sources, etc.

7.3.2 Source Apportionment Results in Latin American Cities

We summarize here the results published by Karagulian et al. (2015), who compiled available source apportionment studies worldwide and classified the identified sources as sea salt, dust, traffic, industry, biomass/residues burning, and other anthropogenic sources. This uniform source classification allows for meaningful

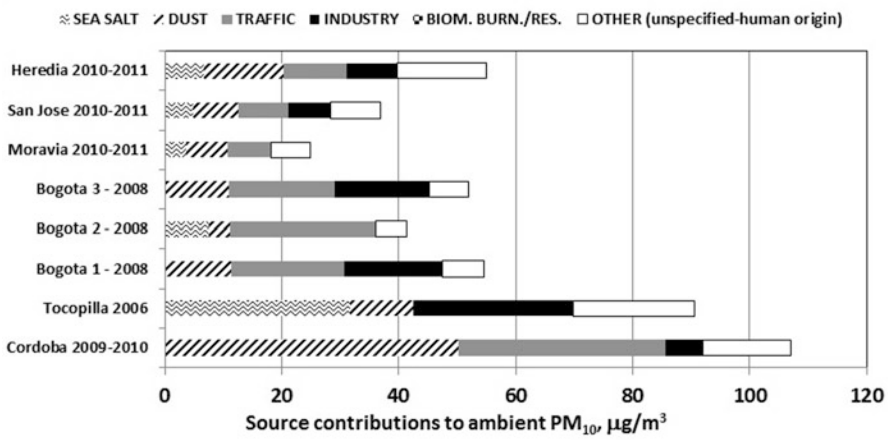

Fig. 7.3 Summary of source apportionment results for ambient PM_{10} in Latin American cities. (Source: WHO (2016a, b, c))

comparisons among countries, cities, and study years. The database released by the WHO (2016c) includes studies published up to 2014, and we have added one study published for Santiago (Villalobos et al. 2015).

Figure 7.3 shows the results for ambient PM_{10} concentrations. Almost all cities exceed the annual value of 25 μg/m^3, the WHO recommended guideline (WHO 2005). Sea salt (marine aerosol) is relevant at coastal cities such as Tocopilla (Chile) and the three Costa Rican cities at the top of Fig. 7.3. Traffic is greater in the larger cities (Bogota, Colombia, and Cordoba, Argentina). Dust is present in all cities, usually as a mixture of surface soil suspended by wind (natural contribution) and urban dust, the result of road dust abrasion and resuspension by traffic. Industrial contributions are highest at Tocopilla, a port city with several coal-fired power plants, and lowest at Moravia, Costa Rica, a small city away from major industrial activities. The biomass/residue burning contribution is not present, although it may be included within the "Other" classification. At Bogota, three sites were analyzed in 2008, two of them are residential sites and one is an industrial part of the city; it is clear from the Fig. 7.3 that only one of the residential sites is far enough from industrial sources. This shows that source receptor analyses may diagnose environmental justice issues.

Figure 7.4 shows source apportionment results for ambient $PM_{2.5}$ concentrations. For ease of visualization, we prioritize studies at the same city in different years instead of showing all results. None of the cities meets the WHO guideline of 10 μg/m^3, as a long-term average (WHO 2005). Coastal cities (Rio de Janeiro and Recife in Brazil) have better air quality than continental cities in valleys surrounded by mountains (Cordoba, Mexico City, Santiago). In Rio de Janeiro, Sao Paulo, and Santiago, ambient $PM_{2.5}$ has increased, with traffic sources on the rise, but industrial contributions decreasing. The first trend may be a result of an increase in motor vehicles (ECLAC 2016), whereas the second trend may be due to more regulations

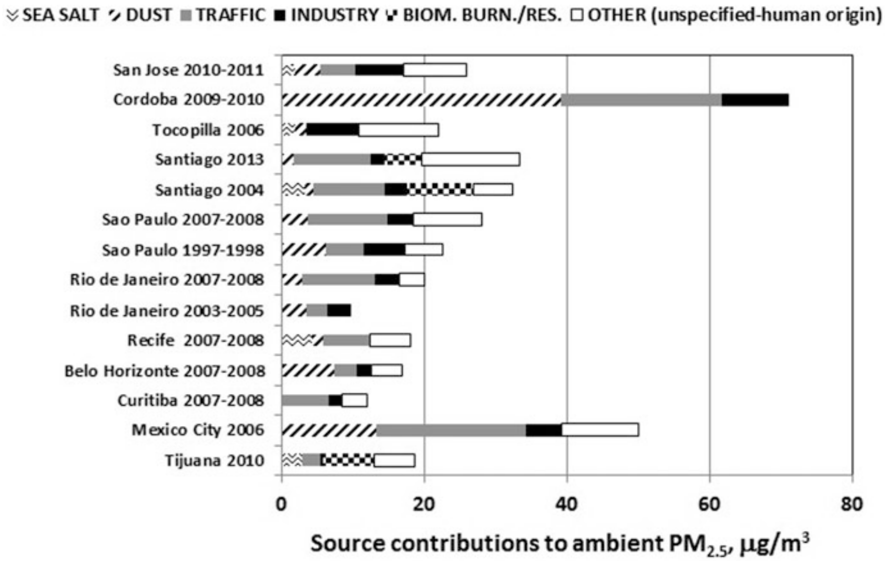

Fig. 7.4 Summary of source apportionment results for ambient $PM_{2.5}$ in Latin American cities. (Source: WHO 2016a, b, c)

upon industry. Owing to climate conditions, wood burning is only relevant at Santiago and Tijuana, Mexico; the trend at Santiago is downward.

7.4 Air Pollution Monitoring and Management in Colombia

7.4.1 Introduction

In January and early February 2016, unusually dry conditions over Bogota – the capital and largest city of Colombia with nearly eight million inhabitants – associated with a long El Niño period, caused strong thermal inversions and a critically stable atmosphere. Dust resuspension increased because of a soil that was drier than usual. Because of drier vegetation, forest fires started in the region and on the mountains along the Eastern border of the city. For more than 3 weeks, as a result, airborne PM concentrations reached alarmingly high values (82 μg/m^3; AQI = 165), considered unhealthy for sensitive groups or unhealthy according to the air quality index scale (SDA 2016). On 1 February, the strongest and closest forest fires produced emissions that infused the city with heavy smoke, causing several institutions at the historical town of La Candelaria and its surroundings to be evacuated. On 4 February, the city celebrated one of its two annual car-free days. The event promoted sustainable urban transportation by reducing light-vehicle emissions significantly, but slightly increased PM emissions from its diesel-powered bus-only transit system because more buses were in service. Many citizens used their bicycles to go to work, but unfortunately, they exposed themselves to air that was much more polluted than usual. Although local health and environmental agencies declared an orange alert, communications to the public through social media were scarce and unclear about the risk that such high PM concentrations posed to people's health. The authorities issued no special communication to bicycle users or pedestrians regarding air pollution and how to use respiratory protection on the car-free day.

One month later, still under the effect of the dry conditions of El Niño and the incidence of forest fires on the North of Colombia, strong atmospheric stability conditions occurred at the Aburra Valley, where Medellin – Colombia's second largest Metropolitan Area – home of nearly 3.5 million inhabitants, is located. Between 5 March and 3 April, $PM_{2.5}$ concentration levels were deemed unhealthy for sensitive population groups, with an average of 68 $\mu g/m^3$ – AQI = 157 and a maximum daily average of 103 $\mu g/m^3$ – AQI = 176 (Universidad Nacional de Colombia 2016). The episode was unusually severe and long, and triggered a determined, though late, response from the Mayor of Medellin and his government collaborators. On 18 March, a set of risk communications was issued to the public and emission reduction measures were taken, focusing on diesel-powered trucks and buses, in addition to motorcycles and scooters. Authorities ran an air quality model to evaluate mitigation measures and decided to celebrate two car-free days on 2 and 3 April, promoted working from home, and invited private companies to join the government in their efforts to reduce emissions. In addition, emergency response protocols were revised.

These two episodes are examples of the many contrasts found in Colombia's air quality management. In these examples, both cities have strong air quality monitoring networks, but responses from the authorities to high air pollution episodes were utterly dissimilar, despite the existence of a set of National Air Quality Policies that includes air quality standards and emission regulations, in addition to air quality monitoring and emission testing protocols. Differences are even stronger when other cities and smaller towns are considered. This is because of the way in which the national environmental system is designed. Decisions about the number and type of monitoring stations, in addition to enforcement strategies, are taken autonomously by regional or city-level agencies, following a nonbinding set of air quality monitoring and management guidelines, according to their own budget and technical capacity.

Of the 20 largest cities in Colombia, 16 have at least one air quality monitoring station (IDEAM 2016). However, nearly 40% of people living in urban areas in Colombia are not covered by the ambient air quality monitoring network. In addition, existing systems are highly heterogeneous. Costly automatic stations are used in large urban areas such as Bogota, Medellin, Cali, and Bucaramanga, and some towns with important high-emission activities such as mining and brick production. Other cities and towns rely on inexpensive, manual stations that do not provide continuous information. Most of the ambient air quality monitoring stations in Colombia (88%) focus primarily on PM_{10} monitoring. $PM_{2.5}$ and gaseous pollutants are measured at only ~20% of the stations, mostly in the largest cities;

however, the number of $PM_{2.5}$ monitors is increasing, given its significant impact on human health. Measurement quality is also a concern with the existing air quality monitoring systems. Around 23% of the installed monitoring capacity does not produce data that can be considered of high quality, defined as providing at least 75% valid measurements (IDEAM 2016). This is associated with deficiencies in structural capacity, such as the number or performance of personnel in charge of air quality monitoring, and the operation and maintenance of the monitoring technology.

The highest PM_{10} concentrations, consistently exceeding the annual-average Colombian Air Quality Standard of 50 μg/m^3, occur in the following areas:

1. The southwestern area of Bogota
2. The Cesar open-pit coal mining-influenced area
3. Small towns influenced by brick kiln production
4. The southern part of the Aburra Valley – Medellin Metropolitan Area. These areas are, roughly, the same as those that show consistent exceedances of the $PM_{2.5}$ Colombian Ambient Air Quality Standards (25 μg/m^3 as the annual average and 50 μg/m^3 as the 24-h average).

The southwestern area of Bogota has the highest number of the PM_{10} 24-h average exceedances, reaching 100 in 2015. It is a highly populated area, with a density of 25,000/km^2. Therefore, it constitutes the highest public health concern related to air pollution in Colombia.

7.4.2 Bogota, An Unfinished Success Story

Air quality records at Bogota show that the most concerning pollutant is PM (IDEAM 2016; Secretaria Distrital de Ambiente [SDA] et al. 2010). Figure 7.5 shows that PM_{10} concentration levels increased from ~50 μg/m^3 in 1998 to 75 μg/m^3 in 2005 and were reduced after 2007, to levels around or below 50 μg/m^3 after 2012 (Observatorio Ambiental de Bogota 2016), which can be considered successful for an economy that was growing steadily during the same period. After 2014, however, PM_{10} concentrations seem to be leveling off. Ambient $PM_{2.5}$ monitoring started in late 2013, showing an annual average of 23 μg/m^3 in 2014 and 20 μg/m^3 in 2015, about twice the WHO guideline (WHO 2005).

Concentrations of PM_{10} and $PM_{2.5}$ are highly heterogeneous across the city. Figure 7.6 shows (a) PM_{10} and (b) $PM_{2.5}$ monthly averages between January 2014 and April 2106 for the following four areas of the city: north east, east–south east, north west, and west–south west, each one grouping a subset of air quality monitoring stations (shown in Fig. 7.7). It is evident that there is a strong west–east difference, between 17 and 39 μg/m^3 during this period. This difference is explained by the high concentration of industrial sources in the western and south western areas. There is a significant number of small and medium-sized industrial manufacturing facilities, many of which use coal or fuel oil and are not equipped

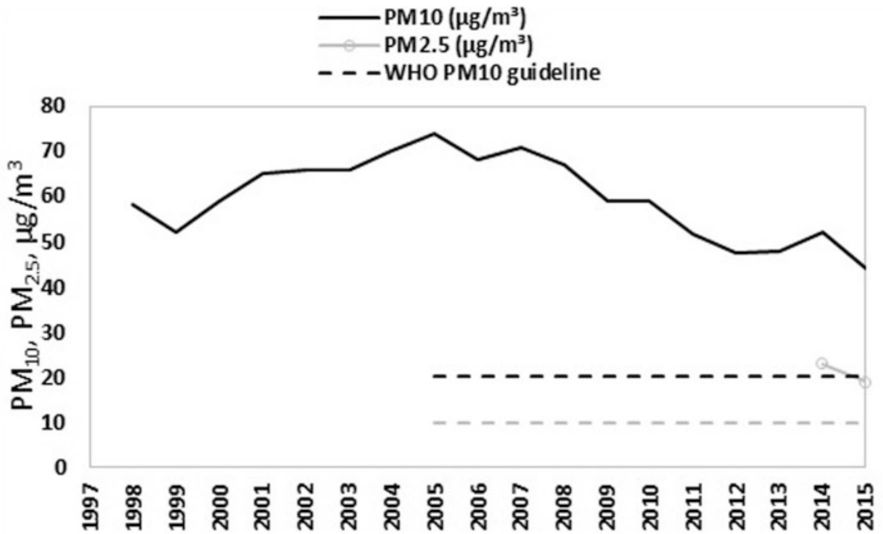

Fig. 7.5 Ambient PM_{10} and $PM_{2.5}$ annual averages at Bogota (IDEAM 2016)

with efficient emission controls. These include the country's largest food distribution center – Corabastos. There are highly congested roads with high flow rates of heavy-, medium- and light-duty diesel trucks associated with the previous facilities, in addition to high flow rates of diesel-powered transit buses and gasoline vehicles. Low-income, high-density housing is mixed with industrial facilities. The zone also has high rates of dust resuspension (Carmona-Aparicio et al. 2016; Perez-Peña et al. 2017). Figure 7.8 emphasizes the above by showing the spatial distribution of PM emissions rates from point and mobile sources on a 1-km × 1-km grid during 1 h at 12 m on a typical working day on 2012 (Rojas and Peñaloza 2012). Another factor is meteorology, with higher wind speeds on the eastern area that contribute to a better dispersion of pollutants, and lower on the western area, contributing to pollutant accumulation. In addition, records show lower precipitation rates and, hence, drier soil in the western than in the eastern area, reducing wet deposition and promoting more dust resuspension.

Still, emission inventories and source apportionment studies have not been conclusive about the contribution of different sources to PM in the city and the influence of aerosols transported from other regions of Colombia. Table 7.2 shows that there are significant differences among source apportionment studies conducted during different periods. These differences are likely the result of different sets of chemical components included in the PM speciation and different mathematical techniques used to find the contributing factors – see Sect. 7.3.1. From these, the most complete set of species was analyzed by Vargas et al. (2012), who found that mobile sources accounted for between 35% and 60% of PM_{10}; industrial sources, between 18% and 44%; dust resuspension, between 9% and 21%; and secondary

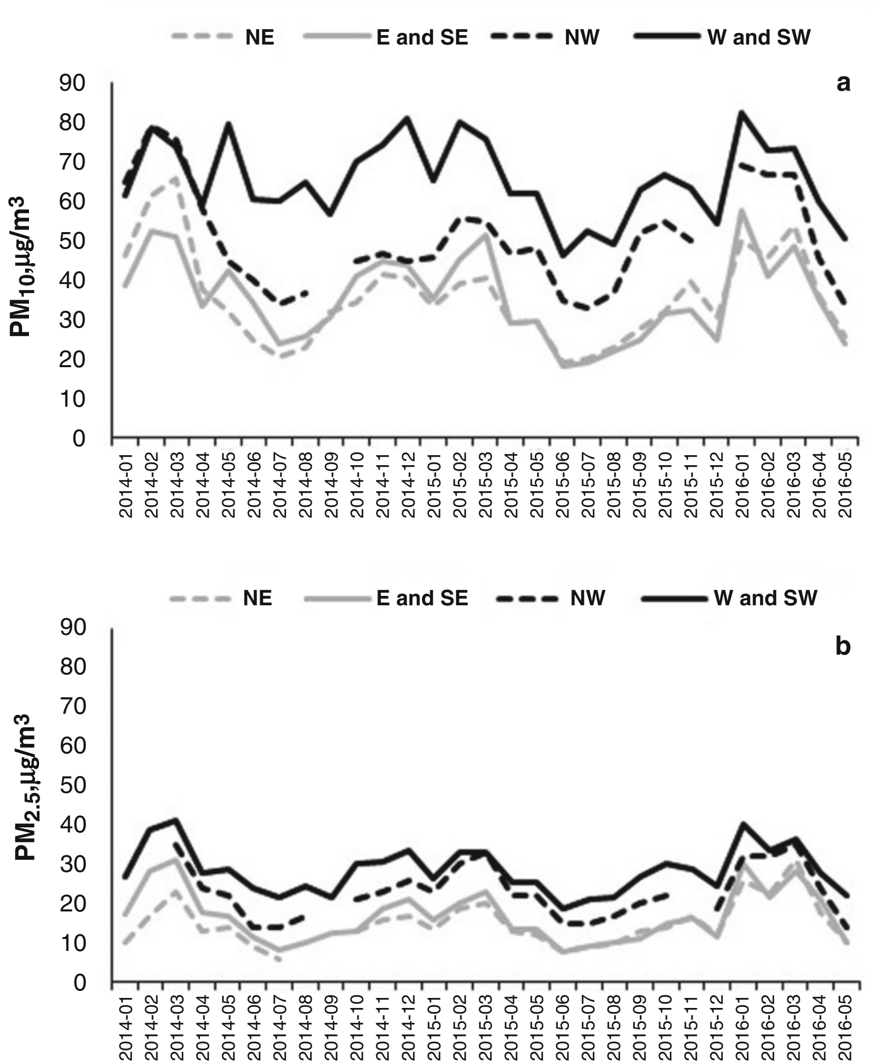

Fig. 7.6 PM_{10} (**a**) and $PM_{2.5}$ (**b**) monthly averages in four areas of Bogota since 2014. (IDEAM 2016)

aerosol, 13%. Clearly, the city government should prioritize emission controls for mobile sources throughout the city, particularly diesel buses and trucks, and strengthen industrial emission controls at the industrial south western area. Street sweeping with vacuum cleaning devices could also be implemented to reduce dust resuspension, especially in the south western area, during dry seasons.

A set of emission controls were established for the city's 2010–2020 Air Pollution Abatement Plan (Secretaria Distrital de Ambiente [SDA] et al. 2010), with the

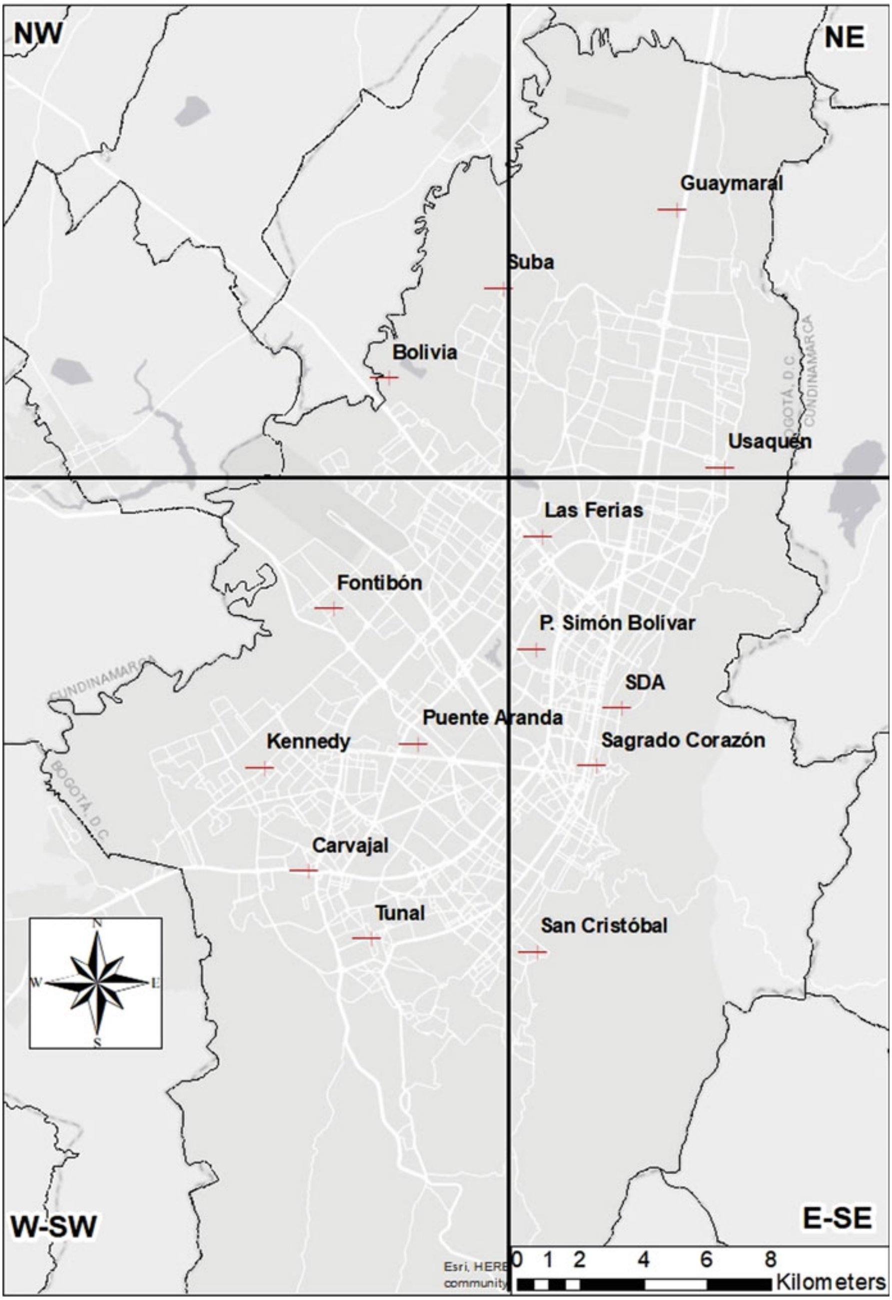

Fig. 7.7 Location of Bogota's air quality monitoring stations

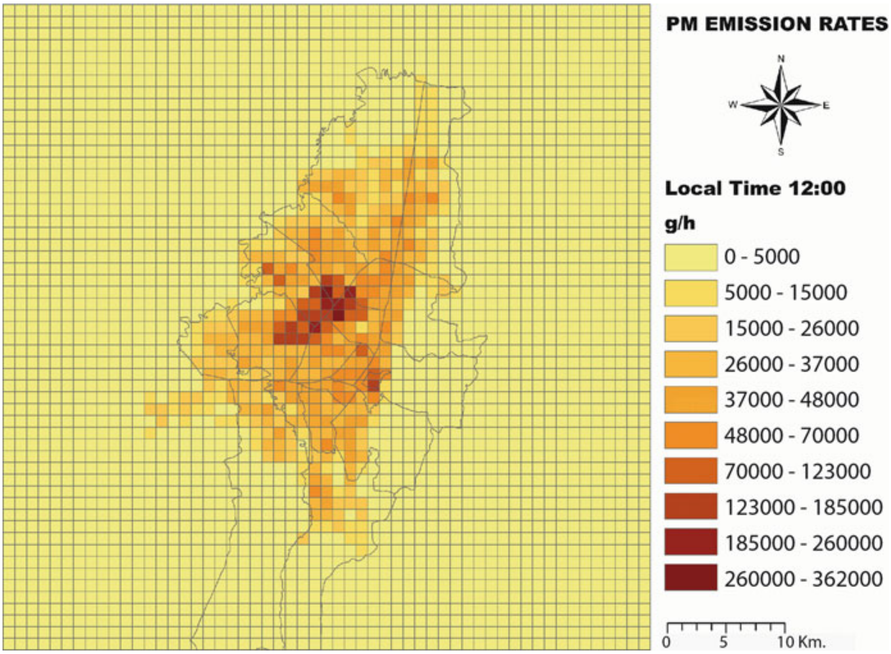

Fig. 7.8 Spatial disaggregation of PM emission rates in Bogota at 12:00 on a working day. (Rojas and Peñaloza 2012)

goal of meeting the ambient PM_{10} annual average national air quality standard in every monitoring station, and reduce significantly the number of exceedances of the 24-h standard by 2020. Health benefits associated with this plan were estimated to be around seven billion dollars over 10 years, from avoided premature deaths and avoided morbidity (Ortiz-Durán and Rojas-Roa 2013). The most important measures included reorganizing the public transit system and installing Diesel Particulate Filters (DPFs) in diesel buses and trucks, in addition to PM emission control devices for industrial facilities. Major changes upon the public transit system – performed between 2012 and 2015 – and diesel fuel with a sulfur content lower than 50 ppm – available since 2010 – can explain the observed reduction of PM_{10} throughout the city. Installing DPF systems has not yet been possible, despite significant efforts by the environmental agency; thus, black smoke puffs from diesel buses and trucks, even new ones, are frequent street sights. With a rapidly growing number of light vehicles and motorcycles, and the associated increasing congestion, further reductions in PM_{10} and $PM_{2.5}$ concentration levels are not foreseeable during the rest of the Plan's implementation period.

Table 7.2 Source contribution to PM_{10} estimated from receptor modeling studies in Bogota

	Residential site		Industry influenced site		Traffic influenced site
Source	Behrentz et al. (2009)	Vargas et al. (2012)	Behrentz et al. (2009)	Vargas et al. (2012)	Behrentz et al. (2009)
Resuspended dust	60%	9%	42%	21%	52%
Mobile sources	3%	60%	0.7%	35%	29%
Industrial sources	17%		23%		9%
Non-ferrous foundries				10%	
Nitrate-rich source				21%	
Sulfate-rich source				13%	
Ion-rich source		18%			
Secondary aerosol		13%			
Unidentified source	20%		34%		10%

Adapted from Vargas et al. (2012), Secretaria Distrital de Ambiente (SDA) et al. (2010)

7.5 Wood Burning Pollution in Southern Chile

Wood burning pollution is a severe problem in Southern Chile (beneath 35° S). Two million people living in Southern Chilean cities are exposed to annual $PM_{2.5}$ concentrations above 30 μg/m^3 (MMA 2014). This high air pollution comes from a widespread use of wood for space heating and cooking – it is the cheapest fuel available. Furthermore, most people burn wood using inefficient stoves in households with poor thermal insulation (Schueftan and Gonzalez 2015) and they often choke the air inlet so that combustion slows down and PM emissions rise (Jordan and Seen 2005; Tissari et al. 2008).

Figure 7.9 shows annual ambient $PM_{2.5}$ measured at several cities in Chile through the National System of Air Quality Information (MMA 2016); $PM_{2.5}$ urban ambient concentration (averages for 2013–2015) are plotted against the heating degree days (HDDs, a proxy for household heating demand). The almost linear relationship for the southern cities (HDD > 1100 °C-days) suggests that wood burning emissions dominate ambient $PM_{2.5}$ concentrations there. Figure 7.10 shows that ambient $PM_{2.5}$ concentrations rise in the evening and peak near midnight; thus, those emissions cannot come from mobile sources.

The problem originates from a combination of several factors. First, southern regions have the highest rates of poverty in Chile; this means a large fraction of the

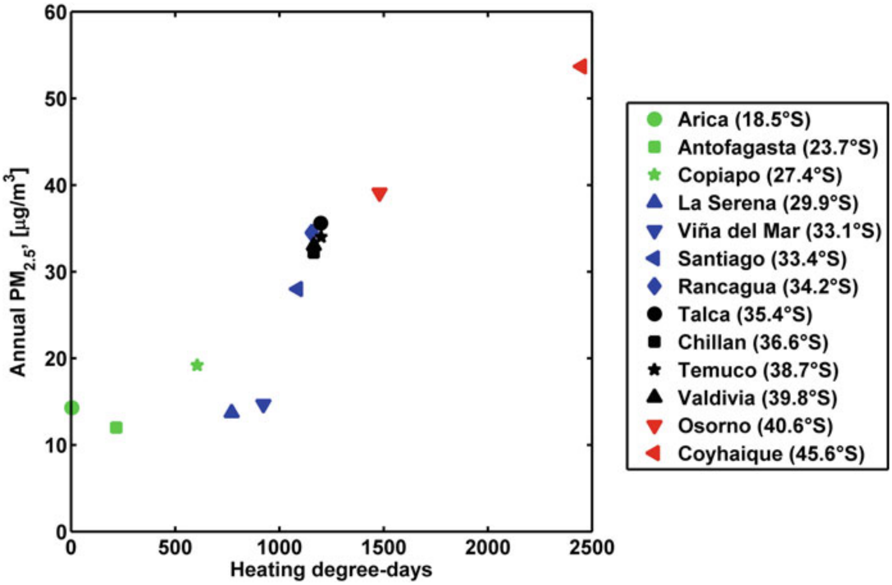

Fig. 7.9 Annual ambient $PM_{2.5}$ (average for 2013–2015) at selected Chilean cities plotted against heating degree days (HDDs) in °C/day. (HDDs retrieved from www.degreedays.net)

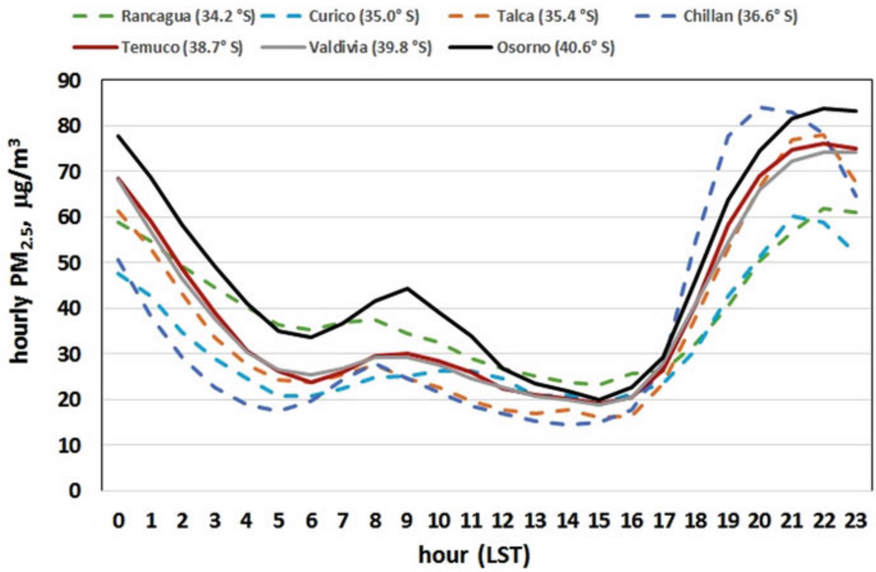

Fig. 7.10 Hourly profile of ambient $PM_{2.5}$ in several Chilean cities, during the austral cold season (May–August). (Source: MMA (2016))

population only has access to subsidized, low-quality housing. Second, a large fraction (85%) of households were built before 2007; thus, they lack adequate thermal insulation and are leaky (Schueftan and Gonzalez 2015), increasing household heating energy demand. Third, the cultural preference for burning wood (Reeve et al. 2013) and the fact that it is the cheapest fuel available make most households use it, even for cooking. Fourth, there is a large stock of old, inefficient wood stoves and cook stoves; most households operate stoves under air-choked burning conditions, when emissions are highest. Fifth, the wood market is largely informal and the wood sold has high moisture contents, which promote high emissions on any wood stove. A better option is to purchase dry wood in summer to stock up for the cold season, but people on low incomes cannot afford that. In summary, cultural, socioeconomic, and technological factors combine to produce a complex scenario of severe air pollution.

The authorities have implemented several initiatives to curb pollution from wood burning. The long-term measures include:

1. Wood stove replacement program
2. Subsidies for household thermal refurbishments

Both are aimed at improving household energy efficiency, and the government also promotes biomass as a renewable fuel coming from well-managed forest resources. However, the scale of the problem described above means that air quality improvements will take years to be accomplished.

The government has also implemented a pioneering, short-term air quality regulation. It uses an air quality forecasting system that predicts air pollution conditions 1–3 days ahead (Saide et al. 2016). With this technological tool, authorities can enforce bans on wood burning in selected districts within each southern Chilean city. This short-term strategy has been effective in reducing the magnitude of air pollution episodes in the last 3 years. Given the complexity of the problem, that short-term strategy would need to be operative in the coming years as well.

7.6 Indoor Air Quality in Latin America

Indoor air pollution has been consistently identified as a leading cause of morbidity and mortality for the past 25 years. In 2010, air pollution accounted for two of the top three biggest factors in disability-adjusted years in the world for both genders. Increasing scientific evidence is uncovering the complex and extensive level of health effects that air pollution has on the human body. Historically, the highest levels of indoor air pollution have been registered in developing communities (DCs), where there is limited access to clean energy. Although there have been many attempts to solve the air pollution crisis throughout the world, these efforts have resulted in limited success.

There is scant information about the state of indoor air quality (IAQ) in Latin America. The emphasis so far has been on ambient air quality and advancing

Table 7.3 Smoke-free national policies in Latin America

Country	Year	Comments
Uruguay	2006	100% smoke-free national policy
Panama & Colombia	2008	100% smoke-free national policy
Guatemala	2009	Exceptions allowed for smoking in hotels
Peru	2010	100% smoke-free national policy
Honduras	2010	Exceptions allowed for smoking cubicles in cigar factories
Brazil	2011	100% smoke-free national policy
Venezuela	2011	100% smoke-free national policy (Ministerial Regulation)
Ecuador	2011	Exceptions allowed for smoking in hotels
Argentina	2011	Exceptions allowed for smoking in private enclosed workplaces
Costa Rica	2012	100% smoke-free national policy

ambient air regulations in the region. However, there have been a few cases where poor communities have been the subject of multiple studies, such as in rural Guatemala (e.g., Boy et al. 2000, 2002), Chile (e.g., Cortés and Ridley 2013; Sanhueza et al. 2006), and Mexico (Ramírez-Venegas et al. 2014; Regalado et al. 2006). There have been also a few IAQ studies conducted in urban settings (Barraza et al. 2014, 2016; Burgos et al. 2013).

7.6.1 Indoor Air Quality Regulations in Latin America

Indoor air quality regulations in Latin America have revolved primarily around enacting smoke-free policies after the adoption of the World Health Organization (WHO) Framework Convention on Tobacco Control (FCTC) in 2005 (Sebrié et al. 2012). The FCTC provided the mechanisms needed to enable national and subnational legislations to effectively protect people from second-hand smoke. Since then, several Latin American countries have enacted smoke-free policies in public places. Table 7.3 shows the list of countries that have adopted such policies. Some of these are 100% smoke-free policies at the national level, whereas others have included notable exceptions.

Some local smoke-free policies have been enacted in places like Mexico City (Thrasher et al. 2010). All these initiatives have been encountered by strong opposition from the tobacco industry, which has often turned to litigation to stop them.

7.6.2 Gender and Environmental Justice Issues

In general, the preponderance of the burden of indoor air pollution is faced by the poorest sectors in Latin American countries, often the rural and urban poor. The incidence of rural poverty has been consistently above 50% in many Latin American countries (de Janvry and Sadoulet 2000), particularly when it is defined as multidimensional poverty (Battiston et al. 2009). Consequently, the burden of poor IAQ is shouldered by very large segments of these populations, due mostly to their limited access to clean energy and sustainable housing.

In poor communities, the use of solid fuels indoors is extensive. Depending on the country and region, the fuels can range from animal waste, as in the Andean region of Peru (Gomez et al. 2011) to wood in southern Chile (Cortés and Ridley 2013) and coal in rural Guatemala (Boy et al. 2002). The associated health effects due to indoor air pollution exposure in these communities have received some attention (Smith-Sivertsen et al. 2009), although much of what we know is deduced from studies conducted in developed countries at much lower pollution levels.

In these communities, exposure to indoor air pollution from solid fuel use disproportionally affects women. Because of strong gender role segregation, women are usually in direct contact with indoor combustion emissions during cooking and heating activities. Small children also become exposed as they are in the care of their mothers and often, for the poorest sectors, are attached to them.

In addition to the exposure to indoor air pollution from solid fuel use, cigarette smoke and secondhand smoke pose additional risks to poor communities and to poor women, in particular. The extent of this exposure and the corresponding health effects have not been properly evaluated in Latin America; however, Pichon-Riviere et al. (2016) determined that cigarette smoking is responsible for about 33.6 billion US dollars in direct costs to health systems in Latin America. A study on the prevalence of smoking in Brazil (Godoy 2010) also found that smoking decreased at much higher rates for men and women with higher purchasing power than for those with lower purchasing power (i.e., poorer population).

A study conducted in the USA (Klein et al. 2014) found that comprehensive smoke-free policies may improve preconception health among a population at risk for smoking and can be associated with a reduction in smoking among low-income women. Similar studies should be conducted in Latin America.

7.6.3 Case Studies in Indoor Air Quality

7.6.3.1 Argentina

In the case of Argentina, it is appropriate to focus on research related to secondhand tobacco smoke (SHS). Argentina was the first country in the region to adopt 100% smoke-free policies at the sub-national level starting in 2006, allowing comparisons among cities with differing policies. These smoke-free policies have been opposed by the tobacco and by the tourism industry.

As part of the Global SHS Research Study (Hyland et al. 2008), the levels of indoor air pollution in hospitality venues (bars, discos, pubs and restaurants) in 15 cities in Argentina were evaluated by Schoj et al. (2010). Among the 15 selected cities, there were 5 smoke-free cities, 3 with partial smoking restrictions, 3 with no legislation, and 4 in transition to 100% smoke-free legislation.

The results of this study showed that the levels of $PM_{2.5}$ in cities with no legislation were five times higher than those in smoke-free cities. For cities in transition to smoke-free legislation, the levels of $PM_{2.5}$ decreased significantly after enacting the policies. Similarly, for cities with designated smoking areas (partial smoking restrictions), $PM_{2.5}$ levels were not statistically different between the smoking and nonsmoking areas. Overall, this study demonstrated that $PM_{2.5}$ levels decreased significantly after the implementation of 100% smoke-free legislation in Argentina and provided the evidence needed to support such policies.

7.6.3.2 Chile

The use of wood is very common in the southern part of Chile, and Temuco is the most wood-smoke-polluted city in the region. The impact of ambient PM_{10} levels on daily mortality in Temuco was evaluated by Sanhueza et al. (2006). This study determined that there was a significant and positive association between the levels of ambient PM_{10} and daily mortality in Temuco owing to cardiovascular and respiratory diseases in people 65 years and older. PM_{10} in the region were highest in the fall–winter season.

The study by Sanhueza et al. (2006), however, did not determine the likely contribution from indoor air pollution to these outcomes, even though the researchers recognized that indoor wood combustion is significant in this city. It is important to emphasize this limitation because using only outdoor measurements as proxies of population exposure to PM means that indoor exposure is neglected. In communities where indoor air pollution from solid fuels is significant, this limitation should not be overlooked. Taking into account indoor exposure to PM would improve epidemiological modeling.

The effects of wood combustion inside homes in Temuco was later studied by Cortés and Ridley (2013) using computer simulations. In this study, the researchers simulated a Temuco residence using indoor wood burning. They evaluated the indoor PM_{10} and $PM_{2.5}$ levels assuming different permeability levels of the building envelope. Researchers acknowledged that using wood indoors has strong cultural roots, which do not correspond to typical economic market factors (e.g., price, cost). Ultimately, this study determined that it is very important to consider indoor air pollution sources to determine the health effects of PM.

Another study, conducted in Santiago, determined that relocating families from slums to public housing improved indoor air quality directly and also indirectly through the reduction of air pollution sources (Burgos et al. 2013). This study found that both indoor and outdoor $PM_{2.5}$ were significantly higher in slum houses than in public housing. This is one intervention approach that could be considered in other communities. Similarly, Barraza et al. (2014) conducted the first source apportionment of indoor $PM_{2.5}$ in Santiago. They found that indoor and outdoor sources each contribute about half the $PM_{2.5}$ indoors and the main contributors were indoor cooking and traffic. Indoor $PM_{2.5}$ levels were also affected by socioeconomic status.

7.6.3.3 Guatemala

Indoor air quality and its health effects on rural Guatemalan communities has received considerable attention, compared with other communities (Boy et al. 2000, 2002; Bruce et al. 2007; Diaz et al. 2007; McCracken et al. 2007, 2009; Smith et al. 2006). Boy et al. (2000) compared the fuel efficiency of the traditional open three-stone fire with that of an improved *plancha*, a popular wood-burning stove used in western Guatemala. Although the improved stove showed efficiencies on a par with open fire, it also showed a reduction in fuel use. Overall, this study concluded that close attention must be paid to the long-term sustainability of improved stoves.

The Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) is an intervention trial focused on Mayan women in Guatemala that evaluated the health effects linked to reductions in indoor air pollution from biomass use (Smith-Sivertsen et al. 2009). Before RESPIRE, other studies in the area had measured PM_{10} levels about 15 to 20 times those of the WHO guidelines (Naeher et al. 2000). The RESPIRE trial showed that using a *plancha* significantly reduced carbon monoxide levels, and reduced the risks for all respiratory symptoms reported in the study. However, no significant effects on lung function were found 12–-18 months after the intervention.

In a related RESPIRE study, Thompson et al. (2011) determined that using a chimney stove reduced wood smoke exposure in these Guatemalan communities and was associated with reduced, but not statistically significant, low-birth-weight occurrence. Before RESPIRE, Boy et al. (2002) first reported an association between biofuel use (wood smoke) and reduced birth weight in a human population. Further studies continue to provide evidence for health effects related to these exposures.

7.6.3.4 Mexico

Biomass is the primary cooking fuel in over two thirds of the households in rural areas of Mexico. Regalado et al. (2006) studied the effect of biomass burning on respiratory symptoms and lung function in rural Mexican women. They found that women cooking with biomass had increased respiratory symptoms and a slightly higher reduction in lung function (FEV1/FVC) compared with those cooking with gas.

Ramírez-Venegas et al. (2006) set out to determine the clinical profile, survival, and prognostic factors of chronic obstructive pulmonary disease (COPD) associated with biomass exposure and tobacco smoking. This study determined that women exposed to biomass at home developed COPD with clinical characteristics, quality of life, and increased mortality similar to those of tobacco smokers. In a subsequent study, Ramírez-Venegas et al. (2014) assessed FEV1 in a Mexican cohort of patients with COPD associated with biomass or tobacco during a 15-year follow-up period. However, the results showed that the mean rate of decline in FEV1 was significantly lower for the COPD group exposed to biomass than for the group exposed to tobacco smoke.

7.6.3.5 Need for New Frameworks

The use of solid fuels for heating and cooking is a recognized challenge in the reduction of exposures to PM, both in developed and in developing countries. In the developed world, except for the poorest communities (e.g., Native Nations in the United States), wood is often a conscious choice, one among other alternatives (Champion et al. 2017). For developing communities, however, those alternatives may be limited and, in some cases, there is no choice at all. Proponents of cleaner alternatives for all these communities, especially developing communities, should consider the context and realities of each community before offering any solution or intervention. Reeve et al. (2013), for example, identified affective attachment to wood heating and socio-cultural norms as obstacles to the implementation of cleaner alternatives in Armidale, Australia.

Reducing indoor air pollution in developing communities has been the focus of many efforts. Many cooking stove interventions have taken place around the globe with marginal success (Clark et al. 2013), but fundamental scientific and technical knowledge must be coupled with contextual understanding of the local community.

A recent study proposed and applied a new framework for identifying heating alternatives for the Navajo Nation in the United States (Champion et al. 2017), a community that uses wood and coal for residential heating. This new framework incorporated three essential assessments: perception, cultural, and scientific, to provide a holistic solution for this community. Figure 7.11 shows the generalized

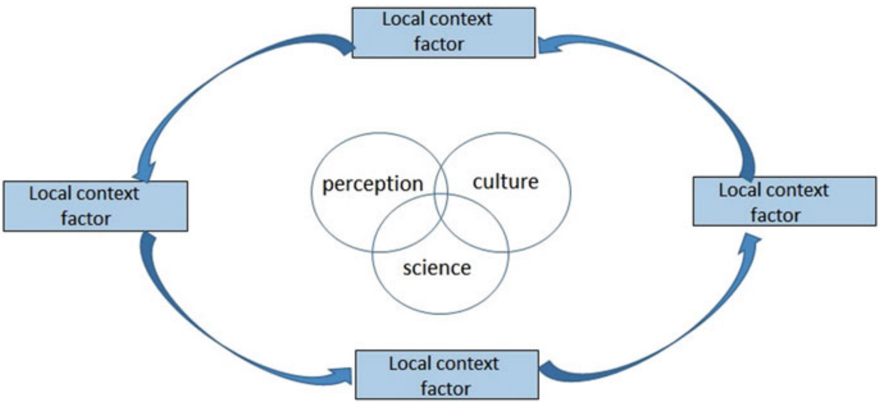

Fig. 7.11 Generalized framework for addressing indoor air quality issues

framework developed. The overall approach is to embed this three-prong assessment within a framework already in place in the community. This contextual framework is denoted by the outer circle in Fig. 7.11. Within that circle, the most important factors pertinent to that context (community) must be identified and integrated into the solution.

For the Navajo, the outer circle in Fig. 7.11 is represented by the Fundamental Navajo Law, with its corresponding factors. Details of that framework can be found in Champion et al. (2017). Developing communities with strong cultural identities are expected to have their own version of such laws, whether they are explicit or implicit. Outsiders must recognize that these factors belong to the community and cannot be substituted by opinions or recommendations from people not members of those communities. The best way forward is to earn the trust of these communities and to work closely with them to identify and address any solution.

This new framework could be applied to communities in Latin America, especially rural communities with strong cultural identities and long-standing traditions and behaviors that have a direct impact on their surrounding environments, including indoor air quality in their homes. These factors are often imported into cities when these rural populations migrate to urban centers, a trend expected to increase in the future.

7.7 Conclusions and Recommendations

This is a short exposition of the state of knowledge of outdoor and indoor air quality in Latin America. A more comprehensive review of the literature is required, but more importantly, more research is needed.

Latin American cities have ambient PM concentrations strongly influenced by local climate and socioeconomic conditions: good air quality in some coastal cities, poor air quality in some cities spread within narrow valleys. Large cities with long-standing air quality management plans (Mexico City, Sao Paulo, and Santiago) have shown significant improvements since the 1990s. This means that the urban transport systems of those cities have achieved more sustainable pathways. Some mid-sized cities with weaker local regulations have ambient concentrations higher than in the same country's largest city. Hence, in addition to climate and socioeconomic variability, a sustainable local governance does make a difference (e.g., Curitiba, Brazil, and Medellin, Colombia).

In Colombia, Bogota, and Medellin have areas with the highest annual average concentrations of airborne PM. High pollution events occur during dry seasons as a result of adverse meteorological conditions. Other cities and industrial areas are known to have poor air quality, but monitoring is absent, insufficient, or low-quality. Air pollution abatement plans have been implemented, but their results are limited because of insufficient enforcement capacity or lack of continuity of local government plans.

In southern Chile, most mid-sized cities are subject to the highest ambient $PM_{2.5}$ concentrations recorded in Latin America. Several factors explain this situation:

widespread urban poverty, poor building standards (especially subsidized housing for migrating dwellers), availability of cheap wood for heating and cooking, and climate conditions. Current government policies are the correct ones: subsidies for woodstove replacement and thermal refurbishment programs. However, given the scale of the problem, it will take several years to achieve compliance with ambient $PM_{2.5}$ air quality standards.

Several overall conclusions can be drawn from this summary of indoor air pollution. The most significant contributors to indoor air pollution and its related health effects in Latin America are tobacco smoke and biomass burning. Both sources affect the poor in addition to women, children, and the elderly in disproportionate ways. Both tobacco smoke and biomass smoke appear to have similar health effects. Proposed solutions or interventions should directly involve the affected populations to become sustainable in the long term. This exposition is designed to start a much-needed conversation on how to best address the need for healthy indoor environments and sustainable communities, especially for the poorest populations in Latin America. This conversation should involve researchers, governments, nongovernmental entities, industry, and community members in general, each with distinctive and critical roles to play.

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Chapter 8
Urban Trees and Their Relationship with Air Pollution by Particulate Matter and Ozone in Santiago, Chile

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Abstract Most Latin American cities have air quality problems owing to high levels of particulate matter and ozone. By 2050, it is expected that more than 80% of Latin Americans will live in urban areas, leading to an increment in pollution problems. Santiago, Chile shows a high level of pollution from PM_{10} and $PM_{2.5}$, especially during the autumn–winter period and from ozone (O_3) during the spring–summer period owing to natural and anthropogenic causes. Information for this chapter was obtained from the official monitoring system of pollutants, but also from scientific papers and experimental work developed in our laboratory. The chapter contains a general description of the particulate matter, some analytical methods of studying it, and their officially reported sources; also, some new findings are included. For tropospheric ozone, a similar procedure was followed. The result is essentially focused on considering the ability of urban trees in capturing PM, while at the same time emitting minimal amounts of biogenic volatile organic compounds (BVOCs) that can potentially generate ozone. Available information shows that native species and a few exotic species were the most frequently appropriated to accomplish both requirements. As the vegetation of Santiago is mainly composed of exotic tree species that lose their leaves during the winter and produce high quantities of BVOCs during spring–summer, it does not contribute to the improvement of air quality; on the contrary. This situation should be remedied as soon as possible through the correct choice of trees and urban planning measures. The chapter also includes some similar variables reported in the literature from other countries of Latin America.

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8.1 Introduction

Most Chilean cities have air quality problems due to high levels of particulate matter (PM) and ozone. In particular, Santiago (the capital city of Chile), shows a high level of pollution from PM_{10} and $PM_{2.5}$, especially during the autumn–winter period and from ozone (O_3) during the spring–summer period. These pollutants produce several health effects such as asthma attacks and heart attacks. Even several studies performed by different disciplines from universities and government agencies showing the effects, consequences, and establishing tactics and strategies for addressing air pollution, the problem re-appears every year. The economic impact associating $PM_{2.5}$ with medical expenses and lost work productivity is US$ 670 million annually, and can rise to US$ 1,900 million when considering the loss in social welfare and risk of death, due to air quality (World Bank 1994). These values (the last available) underestimate the real impact and do not consider all environmental pollutants. According to data from the national monitoring stations, 44% of cities or regions exceeded the annual limit of PM_{10} and 15% exceeded the daily PM_{10} level, whereas 67% did so with the annual $PM_{2.5}$ threshold and 77% with the daily limit of $PM_{2.5}$ (CEPAL/OCDE 2016).

On the other hand, the problems of greatest concern worldwide due to ozone pollution are increased hospital admissions, exacerbation of asthma, and lung inflammation. The World Bank (1994) made an estimated savings in public health to Santiago of US$ 1,315 per ton of O_3 reduction; the average value varies depending on the conditions of pollution and vegetation cover of the communes of the city of Santiago.

The reduction of air pollution by urban trees has been recognized as a cost-effective component of pollution reduction strategies in several cities, such as Chicago (Yang et al. 2008), New York (Morani et al. 2011), Beijing (Yang et al. 2005), Santiago (Escobedo et al. 2006), London (Tiwary et al. 2009), and Toronto (Millward and Sabir 2011). The urban forest provides many direct and indirect ecosystem services. Direct contribution occurs when PM deposits on the leaves of trees or intercepts PM by leaves, branches, and twigs, or absorbs ozone and other gases through the stomata or dissolution of contaminants in the moist surfaces of the leaves; the capture or interception of PM depends on many characteristics of each species, e.g., leaf structure, pubescence, the presence of wax on the leaf surface, the size of the petioles, and the structure of the canopy that need to be assessed in the local conditions. Among the air pollutants removed by vegetation, PM, carbon dioxide (CO_2), and tropospheric ozone (O_3) are dominant (Altimir et al. 2004). However, vegetation also emits biogenic volatile organic compounds (BVOCs), principally isoprene and monoterpenes (scents), and thus potentially contributes to ozone production in the atmosphere, especially in an urban environment. Every tree emits a particular mix of chemical compounds, which reacts in a different way depending on site-specific conditions in the atmosphere generating secondary pollutants, ozone between them. The speed of BVOC emission (emission factors [EFs]) is characteristic of each tree and needs to be studied in relation to the real places where they are going to live (climatic, geographic, hydric, and other conditions) (Préndez et al. 2013a).

Also, some trees produce bio-aerosols such as *allergenic pollen* and *alternaria mold spores*. Trees are also affected by pollution in both structure and performance. There is information at an international level, but in Chile information is scarce.

In this context, the atmospheric pollution of Santiago has two principal implications: economical loss and human health problems. In this chapter, we show some of the efforts of our laboratory (*Química de la Atmósfera y Radioquímica*) interested in looking for solutions to improve the air quality of the city. The studies consider the use of the ability of special urban trees to capture PM, which, at the same time, does not emit too many BVOCs, potentially generating ozone. Our first results show that native species and a few exotic species are those most frequently appropriated to accomplish the two requirements. However, the urban forest of Santiago is principally formed by exotic species, which lose the leaves during the winter period and produce high quantities of BVOCs during the spring–summer period; this means that most do not contribute to the improvement of air quality. Therefore, our proposition is the gradual replacement of the actual urban forest by selected species according to the scientific bases exposed in this chapter.

This chapter is structured in five sections:

(1) Atmospheric pollution of Santiago
(2) Atmospheric pollution by PM
(3) Atmospheric pollution by tropospheric ozone
(4) Effects of the atmospheric pollution
(5) Discussion, and a conclusion. Additionally, Sects. 8.1, 8.2, 8.3 and 8.4 explore similar variables analyzed for Santiago with the information obtained from other countries of Latin America.

8.2 Atmospheric Pollution of Santiago

At present, 54% of the world's population lives in urban centers. In Chile, it is 89.5% of the population of the country, which in 2025 will rise by over 90% (UN 2016). The effects of urban air pollution on health will worsen, and air pollution could become the leading environmental cause of premature mortality in 2050, despite national and international interventions and reductions in major pollutant emissions (Sigman et al. 2012). Air pollution in urban centers is related to various health problems, from minor eye irritations to short-term respiratory symptoms, and chronic respiratory disorders such as asthma, cardiovascular disease, and lung cancer

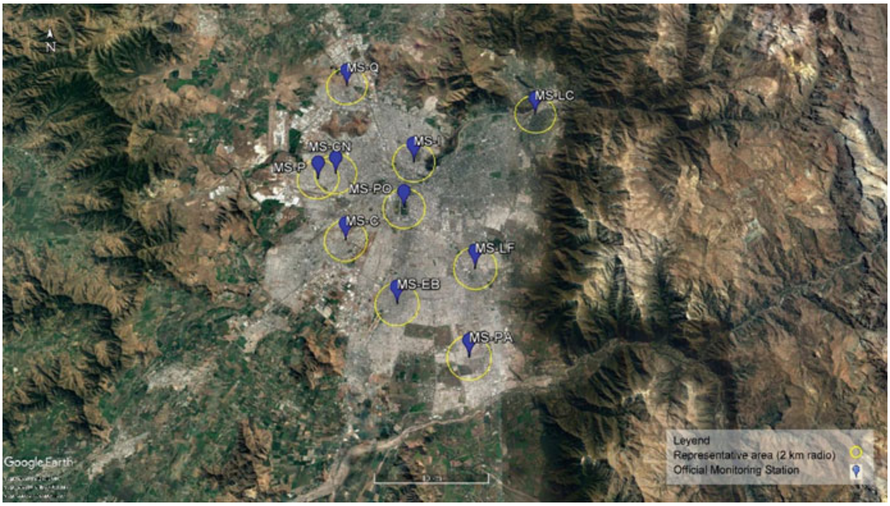

Fig. 8.1 Location of the official monitoring stations of the contaminants: West: MSQ = *Quilicura*, MSCN = *Cerro Navia* MSP = *Pudahuel*, and MSC = *Cerrillos*; Downtown: MSI = *Independencia,* MSPO = *Parque O'Higgins* and MSEB = *El Bosque*; East: MSLC = *Las Condes*, MSLF = *La Florida* and MSPA = *Puente Alto*. The yellow circles show the representative area assigned to each station (2 km)

in the long term. Children and the elderly are particularly vulnerable (Cakmak et al. 2007). Pollution also affects the natural and the built environment.

Santiago is a complex city of studying and modeling of natural and anthropogenic causes. It hosts 40% of the country's population, generates 48% of the PGB and presents the problems of PM and ozone distributed in a spatially and temporally nonhomogeneous manner. Figure 8.1 shows the location of the official monitoring stations of contaminants belonging to the Sistema de Información Nacional de la Calidad de Aire (SINCA). The yellow circles show the representative area assigned to each station. There is no homogeneous distribution of the stations and it is possible to group three rough sectors, west, downtown, and east.

8.2.1 The Contaminants

Figure 8.2 shows a temporal representation, corresponding to the monthly average of 24 h for the last 7 years (2009–2015) of the concentrations of PM_{10}, $PM_{2.5}$, and ozone, reported by SINCA (2016). Values correspond to the mean concentrations reported for 10/11 urban monitoring stations. Only *Talagante* station is not included. The maximum concentrations for PM occur during the autumn–winter period (March to September) and for ozone during the spring–summer period (September to March). The $PM_{2.5}$ varies approximately from the 30% of the PM_{10} during the spring–summer period to 50% during the autumn–winter period. The period March

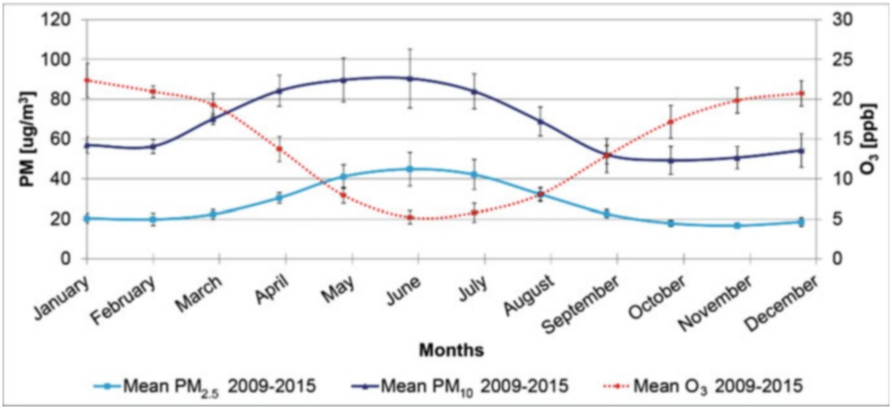

Fig. 8.2 Temporal representation of the monthly average from 24 h values for the last 7 years (2009–2015) of the concentrations of PM_{10}, $PM_{2.5}$, and ozone. (Source: Data from (SINCA 2016))

to September is always above the annual national standard (20 μg/m^3) with a larger standard deviation. Note that during this period the critical episodes occur (Préndez et al. 2011) and that only during October and November the $PM_{2.5}$ is below the national standard. The spatial differences throughout the city are shown in Fig. 8.3.

Figure 8.3 shows the monthly average from 24 h values for the last 7 years (2009–2015) of the concentrations of PM_{10}, $PM_{2.5}$, and ozone grouped in three regions of the city: East Santiago, including the monitoring stations MSLC, MSLF, and MSPA; Downtown Santiago, including the monitoring stations MSI, MSPO, and MSEB; West Santiago including the monitoring stations MSQ, MSCN, MSP, and MSC. Statistical calculations for the period 2009–2015 show that the concentrations of $PM_{2.5}$ corresponding to West Santiago are similar to those of Downtown Santiago, but both regions have higher concentrations than East Santiago (around 7% and 8% respectively); the concentrations of PM_{10} corresponding to West Santiago are around 1% higher than those of Downtown Santiago, but around 12.5% higher than those of East Santiago. In turn, concentrations of ozone corresponding to East Santiago are around 12.5% higher than those of Downtown Santiago and around 8% greater than those of West Santiago.

It is important to note that autumn–winter of 2014 and 2015 showed especially high concentrations of PM_{10} and $PM_{2.5}$ in West Santiago. Spring–summer of the same years show especially high concentrations of ozone, but in East Santiago.

8.2.2 *The Sources*

Contaminants reach the atmosphere from well-defined and diffuse or indefinite sources. To evaluate their contributions, the so-called emission inventories are used to assign responsibilities to the different sources. According to the last official

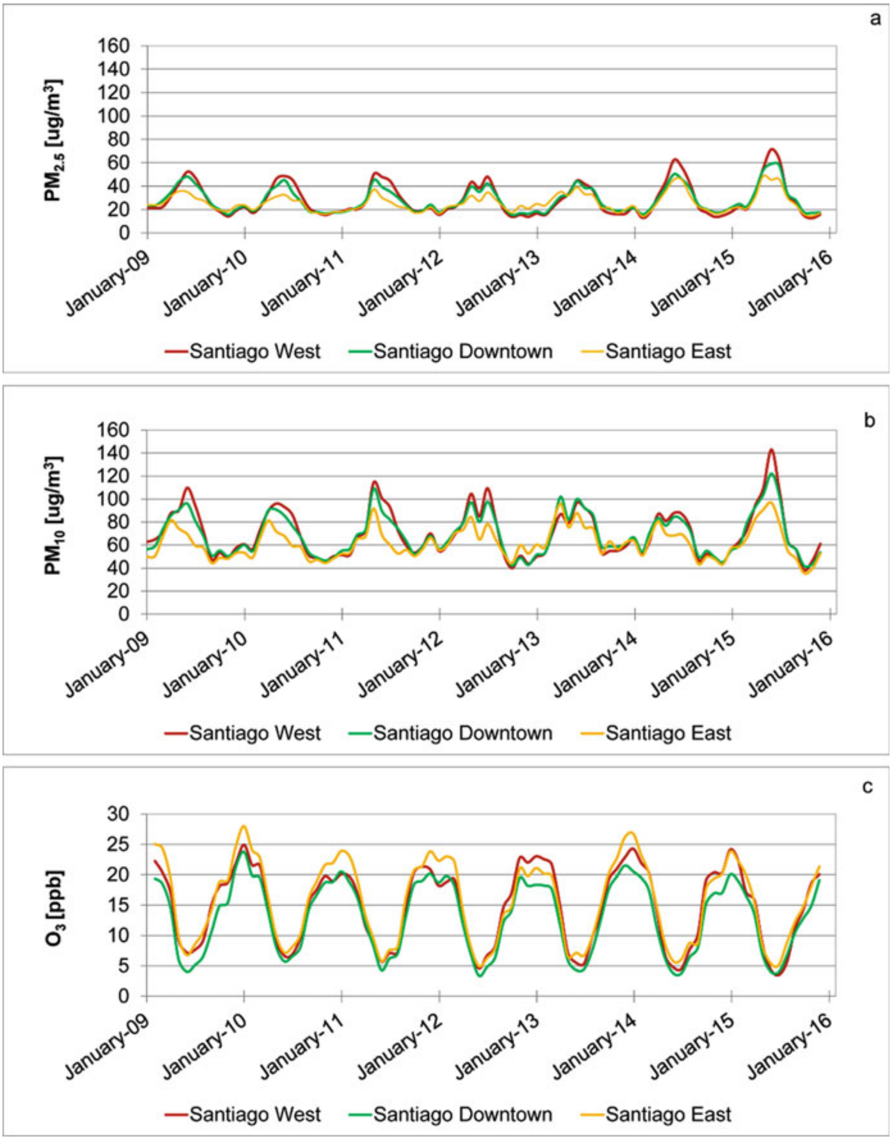

Fig. 8.3 Monthly average from 24 h values for the last 7 years (2009–2015) of the concentrations of PM_{10}, $PM_{2.5}$, and ozone grouped in three regions of the city: East Santiago, Downtown Santiago, and West Santiago. (Source: SINCA 2016)

inventory, Fig. 8.4 shows that the principal source of PM_{10} is transport (44%), the second largest source being the consumption of firewood in homes (33%). Much less significant are the industrial contributions (11%). However, considering only the sources of $PM_{2.5}$, the most significant sources are domestic emissions (95%),

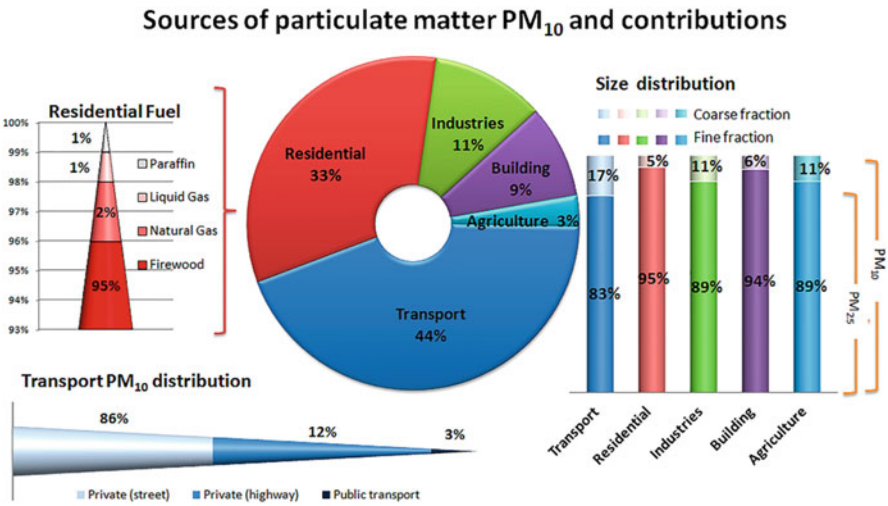

Fig. 8.4 Contribution of the various sources of particulate matter (PM_{10} and $PM_{2.5}$) to the air quality of the Metropolitan Region. (Source: USACH 2014))

followed by building, agriculture, industries, and transport, $PM_{2.5}$ always forming more than 80% of the total PM_{10}.

The fine fraction of the PM_{10}, the $PM_{2.5}$, is the most dangerous for human health and Préndez et al. (2007) reported that around 80–90% of particles coming from light and medium diesel vehicles in Santiago are smaller than 0.5 μm in diameter. In 2014, of a total of 1,828,033 vehicles circulating in Santiago, 333,355 were fueled by diesel; in 2015, there were circulating 358,296 diesel vehicles; these numbers correspond to around 18–19% of vehicular parking (INE 2016). It is also important to note that sales of light/medium vehicles (around 75% of the market) fell sharply during 2014 only to start rising later and reaching record levels by the end of 2016 of 187,110 vehicles (ANAC 2016). Norms to circulate in Chile is given in mass, g/km or mg/km. For instance, in Chile, there are vehicles circulating that are norm Euro 5 approved, which establishes 60 mg/km for gasoline vehicles and 180 mg/km for diesel vehicles.

8.3 Atmospheric Pollution by Particulate Matter

Data from OECD (2016) published for Chile stated that the $PM_{2.5}$ level of atmospheric particles is 18.5 μg/m^3, which is higher than the average of 14.05 μg/m^3 in the OECD countries. MMA (2016) reports 731 critical episodes (alerts, pre-emergencies, and emergencies) in central and southern Chile in the last 2 years, 2015 and 2016, of which only 92 correspond to emergencies, distributed in the following cities: Rancagua = 45, Curico = 62, Linares = 94, Temuco = 86, Valdivia = 120, Osorno = 92 and Coyhaique = 232. Declaration of an emergency occurs for concentrations of $PM_{2.5}$ greater than 170 μg/m^3. To date, in the Metropolitan Region 48, 51, and 42 critical episodes of $PM_{2.5}$ have been decreed during 2014, 2015, and 2016 respectively (MMA 2016). This worrying situation could be partially because in 2014, the declaration of a saturated zone according to $PM_{2.5}$ and not to PM_{10} began to operate, as it had been until then. Another cause could be the unprecedented urban growth. A rapid and unorganized urbanization of the country could lead to an increase in the release of PM into the atmosphere ($PM_{2.5}$, PM_{10}, and PM_1), owing to a marked increase in motorized traffic, the burning of fossil fuels and firewood, and energy consumption (see Fig. 8.4). The cost has already been observed in the greater effects on the health of the urban population of the country exposing 10 million Chileans (60% of the population) to $PM_{2.5}$ concentrations above the Chilean standards, and certainly also from other countries (USA and Europe) and the World Health Organization (WHO 2005). Between 2009 and 2015, the annual average of $PM_{2.5}$ surpassed the Chilean annual norm by 138.1% and the recommendations of the WHO by 276.1%. In the same period, the annual average PM_{10} exceeded the Chilean annual norm by 143.5% and the WHO recommendations by 358.7%. The standards and recommendations for different institutions and countries are shown in Table 8.1.

The PM, technically called atmospheric aerosol, is a complex contaminant with very different physical and chemical characteristics, the main ones being mass, size (μm), morphology, concentration (μg/m^3), and chemical composition. The size

Table 8.1 Standard values accepted in different countries and recommended by the WHO for a 24-h average and annual average for $PM_{2.5}$ and PM_{10}

	Average concentrations (μg/m^3)				
	PM_{10}		$PM_{2.5}$		
Country or city	24 h	Annual	24 h	Annual	Reference
Argentina, Buenos Aires	150	50	65	15	D N° 198 (2006)
Bolivia/La Paz	150/50	50/20	–/25	–/10	MMAYA (2015)
Brazil, Sao Paulo	120	40	60	20	D N° 59113 (2013)
Chile	150	50	50	20	DS N°59 (1998) and DS N°12 (2011)
Colombia	100	50	50	25	IDEAM (2016)
Costa Rica	150	50	–	–	UNA (2016)
Ecuador	150	50	65	15	NCAA (2011)
Mexico	75	40	45	12	NOM-025-SSA1 (2014)
Peru	150	50	25	–	DS 74-2001-PCM (2001)
Dominican Republic	150	50	65	15	NA-AI-001 (2003)
WHO	50	20	25	10	WHO (2005)
USEPA	150	–	35	15	USEPA (2009)
EU	50	40	–	25	EU (2008)

frequently used is the so-called aerodynamic diameter (AD) defined as the diameter of a sphere of density 1 gcm^{-3}, which has the same settling velocity. Thus, PM_{10} describes particles equal to or smaller than 10 μm of AD; $PM_{2.5}$ describes particles smaller than or equal to 2.5 of AD (usually named fine particles) and $PM_{10-2.5}$ to particles with a size between 2.5 and 10 μm AD (usually named coarse particles).

The meteorological and geographical conditions of each locality and the particle size determine the permanence and transport of PM; the PM_{10} can remain in the atmosphere from minutes to hours and travel 1–10 km from the source, whereas $PM_{2.5}$ can remain in the atmosphere from days to weeks and travel 100–1,000 km (Srimuruganandam and Nagendra 2012; Cheung et al. 2011). In Santiago, meteorological and geographical conditions are very important, many times determining the concentrations of PM (Ortiz et al. 1993; Préndez et al. 1995, 2011; Gramsch et al. 2014). The Chap. 9 of this book consider different aspects of the climatology of Santiago.

The shape of the particles is usually linked to their source (regular and irregular); for example, spherical particles are related to combustion processes. The chemical composition of the PM is also very diverse, including nitrates, sulfates, organic or elemental carbon, organic compounds (e.g., polycyclic aromatic hydrocarbons), biological components (e.g., pollen, cell fragments, among others), metals (Fe, Cu, Ni, Zn, V, among others) (Préndez et al. 1984, 1991; Préndez 1993; Sienra et al. 2005; Richter et al. 2007; Villalobos et al. 2015).

Historically, the PM collection has been made using filters or other substrates, which are subsequently analyzed in the laboratory. In this method, the selection of the filter type is crucial at the time of the physical and/or chemical analysis of the PM collected (Hitzenberger et al. 2004; Raynor et al. 2011). In the last few decades, so-called "continuous or semi-continuous" methods have emerged, combining collection (with or without filters) and reporting the results in almost real time (Solomon and Sioutas 2008). Within the latter, we can mention the Tapered Element Oscillating Microbalance (TEOM) and the Beta Attenuation Monitors, with different properties, but widely used in air quality monitoring stations in Chile, which allow the mass concentration to be determined in almost real time (SINCA 2016).

The chemical composition of PM varies greatly depending on the geography, meteorological factors, and emission sources (Zereini and Wiseman 2010). In the cities of Chile, the relationship between the formation of aerosol episodes and meteorological–geographical conditions, in addition to its relationship with the sources pattern, are not completely understood. Several analytical techniques (destructive and nondestructive), consolidated for the analysis of various chemical species, have been used in atmospheric aerosols to discover, for example, the sources of the PM, the long-range transport identification, and the health assessment studies. Among the destructive ones, the most frequently used are atomic absorption spectroscopy and inductively coupled plasma mass spectroscopy (ICP-MS); among the non-destructives X-ray fluorescence (XRF), instrumental neutron activation (INAA), and proton-induced X-ray emission are frequently used (Maenhaut et al. 2011; Calzolai et al. 2015; Almeida et al. 2013). Recently, the portable XRF (pXRF) has been proven to be a reliable elemental technique for environmental research, especially for quantifying some elements: Ti, Cr, Mn, Fe, Cu, Zn, Sr, Cd, and Pb (Rouillon and Taylor 2016). All these analytical techniques have been used in Chile. For decades, several studies have focused on determining or re-determining the physical and chemical properties of PM (Préndez et al. 1984; Ortiz et al. 1993; Artaxo et al. 1999; Sienra et al. 2005; Toro et al. 2014; Villalobos et al. 2015; Fuentealba 2017).

The first studies of PM in Santiago began in the 1970s. In 1998, the first plan for the prevention and decontamination of the Metropolitan Region was established (MMA 2014). Many strategies have been adopted throughout the years; however, at present, Santiago continues to be one of the world capitals with the higher levels of air pollution by PM (WMO/IGAC 2012; WHO 2014). Many researchers agree that the air pollution persisting in the region is in large part due to meteorological–geographical characteristics, but also to the anthropogenic activities developed in it (Rubio et al. 2006; Préndez et al. 2011; Seguel et al. 2012). The PM events occur in the winter months owing to meteorological factors that generate a low PM dispersion of the contaminants (Préndez et al. 2011), whereas in the spring–summer months better meteorological conditions generate the false perception that the air quality has improved (Fuentealba 2015).

Study by Seguel et al. (2009) has quantified primary and secondary organic aerosols (SOAs), determining that around 20% of the total organic aerosols correspond to the secondary airborne $PM_{2.5}$ during winter time. Other studies of a chemical fractionation analysis in PM_{10} samples show that the elements with high toxicity, such as Pb, Cd, and As, are highly concentrated in the bioavailable fraction (Richter et al. 2007).

To contribute to the decontamination of the city, research in our laboratory is using different physical and chemical analytical techniques (old and new) to analyze the PM deposit on the leaves of trees and on streets (urban dust, UD), to better assign the sources of that PM. The introduction of magnetic techniques (magnetic susceptibility and Saturation Isothermic Remanent Magnetization [SIRM]) has permitted us to identify magnetite (Fe_3O_4), which is a chemical compound closely related to mobile sources and vehicular flows. The work by Muñoz et al. (2017) is pioneering in Chile. These are promising techniques for experimentally evaluating the anthropogenic fraction of UD coming precisely from vehicular flow, and allows us to compile a comparative record of which arboreal species are the most efficient at capturing PM. Also, the spatial resolution describes differences in the estimated concentration of PM deposited on leaves at distances of a few meters. In a recent work, Fuentealba (2017) re-treated the urban dust of the communes of Vitacura and Recoleta reported by Muñoz et al. (2017), using pXRF, which is a faster and more easily accessible technique than the INAA (Maenhaut et al. 2011; USEPA 1998, 2008; Weindorf et al. 2014). Figure 8.5a and b show correlations greater than 99% and greater than 95% for 14 samples containing Fe and Cr respectively; around 35 elements can be quantified in theory, but the application limits of the technique are the amount of UD collected, which must be greater than 5 g (Rouillon and Taylor 2016; Gazley and Fisher 2014). In this study, that quantity was not possible to collect in every sampling place.

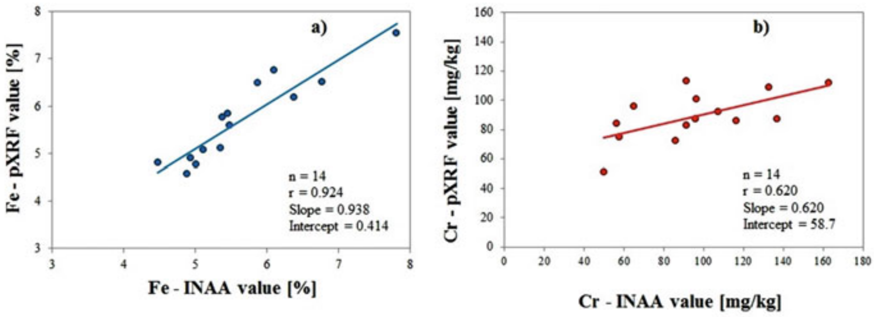

Fig. 8.5 Correlations between elemental concentrations measured by pXRF and by INAA measurements in urban dust collected in the northeastern sector of Santiago, Chile: (**a**) Fe (expressed in wt %) and (**b**) Cr (expressed in mg/kg). (Source: Fuentealba 2017)

Similar magnetic techniques have also been applied in other Latin American countries to study PM deposited on streets or leaves of plants used as biomonitors, as shown in Table 8.2.

8.4 Atmospheric Pollution by Tropospheric Ozone

Tropospheric ozone formation results in the urban atmosphere from reactions between nitrogen oxides (NOx = NO + NO_2) and volatile organic compounds (VOCs) emitted from different natural (BVOCs) and anthropogenic sources (AVOCs). BVOCs belong to a large group of compounds including alkanes, alkenes, carbonyls, alcohols, esters, ethers, and acids (Kesselmeier and Staudt 1999). Tropospheric ozone interacts with both solar short-wave (SW) and terrestrial long-wave (LW) radiation and consequently changes in its distribution can generate radiative forcing and lead to changes in climate. At an urban level, the increase in temperature could reinforce local heat islands due to the urban structure; the relationships of this parameter with temperature, wind, and air quality have been assessed using numerical models and field measurements (Stewart and Oke 2012). On a global level, changes in tropospheric ozone between 1750 and 2010 had generated mean radiative forcing of +0.40 W m^{-2} (90% confidence interval: 0.20–0.60 W m^{-2}) (Myhre et al. 2013).

Figure 8.6 shows the sources of VOCs and the percentage of the different contributions in the Metropolitan Region. The major source corresponds to residential emissions. BVOCs represent 15%. However, in this inventory, as in preceding official inventories of the Chilean government, the calculations were made using emission factors obtained in other environments. In this case, the emission factors come from Guenther et al. (2012) and the model used was the Model of Emissions of Gases and Aerosols from Nature (MEGAN). MEGAN is a model system calculating the temporal and spatial rates of emission of chemical compounds from terrestrial

Table 8.2 Environmental studies relating to vegetation, urban dust, and air pollution using magnetic techniques in some Latin American cities

Country	Objective	Method	Plant	Sample	Reference
Colombia, Bogota	Magnetic survey on environmental samples. Evaluation for pollution markers: soils, urban dust, and leaves	Susceptibility, SIRM	*Sambucus nigra*	Soils, urban dust, leaves	Aguilar-Reyes et al. (2013)
Mexico, Santiago de Queretaro	Magnetic monitoring air pollution in an urban area with different exposures to pollution	Susceptibility, SIRM, SEM, ICP-MS	*Tillandsia recurvata* L.	Leaves	Castañeda-Miranda et al. (2016)
Mexico, Mexicali	Assessments of magnetic enhancement on urban dust samples to evaluate the environmental contamination in Mexicali	Susceptibility, SIRM		Paved and unpaved roads	Sánchez-Duque et al. (2015)
Mexico, Morelia	Magnetic parameters and concentration of heavy metals to find a proxy for the atmospheric pollution monitoring in Mexico City	Susceptibility, SIRM	*Ficus benjamina*	Leaves	Aguilar-Reyes et al. (2012)
Argentina, Tandil	Magnetic techniques to monitor the air pollution in Tandil	Susceptibility, SIRM, SEM	*Parmotrema pilosum*	Lichen	Marié et al. (2016)
Chile, Santiago	Magnetic monitoring air pollution in two urban communes with different vehicular exposition to pollution	Susceptibility, SIRM, INAA	*Platanus orientalis*, *Robinia pseudoacacia*, *Acer negundo*	Urban dust, leaves	Muñoz et al. (2017)

SIRM saturation isothermic remanent magnetization, *SEM* scanning electron microscopy, *ICP-MS* inductively coupled plasma mass spectroscopy, *INAA*: instrumental neutron activation

ecosystems to the atmosphere under varying environmental conditions. Thus, it is possible that the results are biased because of the use of emission factors that are different from those corresponding to local vegetation behavior.

Table 8.3 shows that the 8-h average standard values for ozone accepted in different countries of Latin America are frequently above the recommendation of the WHO, implying different degrees of damage to the population. The only exception is Colombia, with a restricted standard.

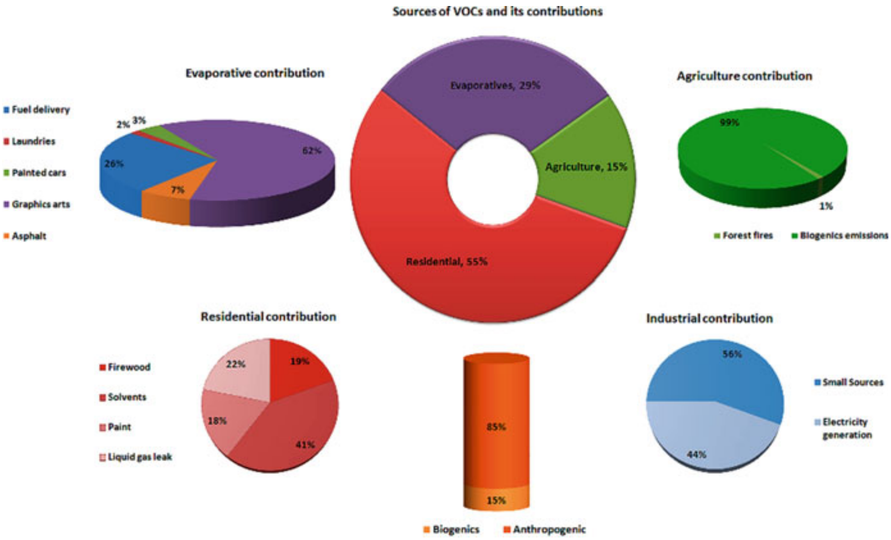

Fig. 8.6 Sources of volatile organic compounds (VOCs) and the percentage of the different contributions in the Metropolitan Region. (Source: USACH 2014)

Table 8.3 Eight-hour average standard values for ozone in different countries of Latin America and the recommendation of the United States Environmental Protection Agency (USEPA), the European Union (EU), and the World Health Organization (WHO)

Country/ institution	Mean ozone concentration, 8 h (ppbv)	Mean ozone concentration, 8 h ($\mu g/m^3$)	References
WHO	50	100	WHO (2005)
USEPA	70	140	USEPA (2015)
EU	60	120	EU (2008)
	55	110	EC Ozone Directive (2016)
Bolivia	50	100	MMAYA (2015)
Chile	61	120	DS 112/02 (2002)
Colombia	40	80	IDEAM (2016)
Ecuador	50	100	NCAA (2011)
Mexico	70	140	NOM-020-SSA1 (2014)
Peru	60	120	DS 74-2001-PCM (2001)

8.4.1 *Reaction of COVs with ·OH radicals*

The hydroxyl radical (·OH) is a fundamental chemical species in the atmosphere. Basically, its formation results from the photo dissociation of ozone (O_3) in the presence of water vapor, with the initial formation of highly energetic atomic oxygen or singlet oxygen (O^{1D}), which is deactivated to triplet oxygen (O^{3P}), which finally reacts with molecular oxygen catalyzed by particles also present in the atmosphere.

The existence of the double bond carbon–carbon gives the terpenes a high reactivity in the atmosphere, being able to react with an extensive series of chemical species normally present in it, such as hydroxyl radicals (·OH), ozone (O_3), and nitrate radicals ($\cdot NO_3$) giving rise to several oxidation products. In the troposphere, OH radicals are rapidly formed because of the photolysis of O_3 in the presence of water vapor. The production of ozone in atmospheric systems containing VOCs and NOx is generally initiated by the radical ·OH; this radical reacts with hydrocarbon molecules, RH (AVOCs and BVOCs) to produce hydroxyalkyl radicals, $\dot{}RO_2$, which interfere with the photolytic cycle NO–NO_2–NO. The final result of the series of reactions is an additional net contribution to the production of tropospheric ozone (Chameides et al. 1992; Bowman and Seinfeld 1994).

$$RH + {}^{\cdot}OH + O_2 \rightarrow {}^{\cdot}RO_2 + H_2O \qquad (R1)$$

$$\text{Follow by } O_2 + NO + O_2 \rightarrow R'CHO + {}^{\cdot}HO_2 + NO_2 \qquad (R2)$$

$${}^{\cdot}HO_2 + NO \rightarrow {}^{\cdot}OH + NO_2 \qquad (R3)$$

There are many possible reaction pathways for peroxyalkyl radicals RO_2, formed by the reaction from RH where NO is oxidized to NO_2 generating a potential variety of reaction pathways. One possible reaction pathway is the photolysis of NO_2 to form oxygen atoms in their basal state (O^{3P}), which subsequently form ozone, in addition to a reaction that in the presence of radicals OH leads to the formation of nitric acid. When there is a sufficient concentration of NO_2 and O_3, nitrate·NO_3 radical and N_2O_5 nitrogen pentoxide are formed. The chemistry of the NO_3 radical acquires importance only during the night because during the day it is rapidly photolyzed. On the other hand, formation and subsequent hydrolysis of N_2O_5 on wet surfaces, including aerosol particles, makes an important contribution to the formation of nitric acid, both locally and globally (Finlayson-Pitts and Pitts 1997).

8.4.2 Volatile Organic Compounds

There is no internationally accepted definition for this type of organic compound; most of them are based on strictly chemical descriptions. VOCs include alkenes, aldehydes, ketones, esters, ethers, alcohols, and acids (Atkinson 1990; Bowman and Seinfeld 1994). The European Economic Commission (1991) defined "volatile organic compounds other than methane of an anthropogenic nature capable of producing photochemical oxidants in the presence of sunlight by reaction with nitrogen oxides." Swiss legislation in its regulations for the control of VOCs defines them as those organic compounds of at least 0.1 millibars at 20 °C or with a boiling point of a maximum 240 °C at 1,013.25 millibars. In Chile, SINCA (2017) defines

VOCs as chemical compounds mainly produced by the evaporation of liquid fuels, solvents, and some organic chemicals such as enamels, paints or cleaners, in addition to the incomplete combustion of gasoline and other organic fuels, and the biological activity of certain plants and animals. In the atmosphere, the VOCs react with other compounds, in the presence of sunlight, generating ozone.

Anthropogenic sources of VOCs, AVOCs, include, but are not limited, to petrochemical plants, vehicles, industrial and commercial paints, diluents and solvents (Guéguen et al. 2011). Among the natural sources are the oceans, soils and sediments, and the microbiological decomposition of organic matter; but, the most important is emission from vegetation, especially the forests (Guenther et al. 1995). All plant species emit BVOCs, particularly terpenes, the basic molecule of which is isoprene (2-methyl-1,3-butadiene, C_5H_8), which represents a source of atmospheric hydrocarbons that make up almost twice the emissions, as anthropogenic sources (Calfapietra et al. 2009). Arneth et al. (2008) estimated that on average 15 or more monoterpenes ($C_{10}H_{16}$), are emitted per plant species. Although, the role of isoprene is still not fully understood, there is evidence for its protective role in oxidative stress caused by heat shock and/or ozone exposure of the trees (Calfapietra et al. 2008). BVOCs are emitted by plants to attract herbivorous pollinators and predators, to communicate with other plants and organisms, or as protection of plant membranes against high temperatures (Peñuelas and Lluisá 2002); they originate in the different plant tissues through various physiological processes, accumulating in leaves and stems and emitting or storing according to the species (Pichersky and Gershenzon 2002). The rate of BVOC emissions is determined by the rate of synthesis, physiological and physicochemical characteristics, mainly its solubility, volatility, and diffusivity (Peñuelas and Staudt 2010). Concentration and reactivity of BVOCs in the atmosphere are very diverse, affecting the C cycle, and forming SOAs (Chen and Jang 2012; Liu et al. 2014), which are part of $PM_{2.5}$, including compounds that are very toxic to humans (peroxyacetyl nitrate, and others) and possibly contributing to scatter sun radiation depending on the refractive index and chemical composition (Kim et al. 2012, 2014), therefore affecting the thermal balance and weather on Earth.

Other particles also affect solar radiation and temperature measured at superficial levels. In turn, weather changes can affect BVOC emissions, producing a positive feedback on the weather system, and irreversible changes have been predicted due to thermal stress related to climate change, depending on species. In general, the atmospheric chemistry perturbation will be higher for higher concentrations of NOx.

Thus, at least in part, the formation of ozone in cities is due to the presence of urban vegetation. To undertake good management of urban afforestation it is necessary to determine the differences between the tree species and to choose those that emit fewer BVOCs or BVOCs that lead to lower concentrations of tropospheric ozone, without losing other positive qualities.

8.4.3 Emission Factors of Biogenic Volatile Organic Compounds

Each type of vegetation responds to characteristic emissions; the variability of the emission depends on the interactions between the organism and its environment; thus, there are many factors that influence the emission of a specific plant species and the uncertainty in their quantification. The main factors and the most frequently studied are light and temperature (Guenther et al. 1993), but in addition and no less important are the phenological processes of the species, and the stress caused to the plant, such as leaf damage or air pollution. If the projections for the twenty-first century are an increase in temperature between 1.8 and 4.0 °C (Peñuelas and Staudt 2010), emissions of BVOCs should also increase; at a global level, Bon et al. (2011) have estimated emissions of BVOCs of between 1200 and 1600 TgC/year.

It is important to repeat that BVOCs emitted by trees correspond to a large quantity of terpenes, especially isoprene and monoterpenes, each of them with very different reactivity in the atmosphere. In Chile, CONAMA (1997) emissions inventory, estimated 9,379 TgC/year emissions of BVOCs from a total of 80,682 TgC/year of VOCs, which corresponds to 11.6%. In this case, the EFs were assigned using the values determined in other environments and by taxonomic proximity with the native trees. The last inventory developed by USACH (2014) attributes to the VOCs 0.74% (97,028 TgC/year) of total emissions; only 15% of the total corresponds to BVOCs, calculated with the EFs given by Guenther et al. (2012) using the MEGAN model, as was mentioned and represented by Fig. 8.6.

In the Metropolitan Region, Préndez et al. (2013a, b, 2014) have reported the experimental EFs corresponding to exotic and native tree species. From the point of view of atmospheric chemistry, it is important to distinguish the reactivity of different groups of monoterpenes. This is the idea of developing the potential ozone creation index (POCI), which evaluates, as a first approximation, the potential of each tree to generate ozone, based on the Photochemical Ozone Creation Potentials (POCPs), proposed by Derwent et al. (2007) for conditions in the UK.

The formula to calculate POCP is:

$$\mathrm{POCPi} = \frac{\mathrm{Final}\ O_{3i} - \mathrm{Final}\ O_{3\mathrm{zero}}}{\mathrm{Final}\ O_{3\mathrm{ethylene}} - \mathrm{Final}\ O_{3\mathrm{zero}}} \times 100$$

where

$O_{3i\ zero}$ refers to the mixing ratio found at the end of each run of the model.

O_{3i} is the mixing ratio of species i.

Ethylene is used as a reference, given its low molecular weight and because it is one of the most significant in the formation of O_3 in northeastern Europe.

The formula for calculating POCI is (Préndez et al. 2013a):

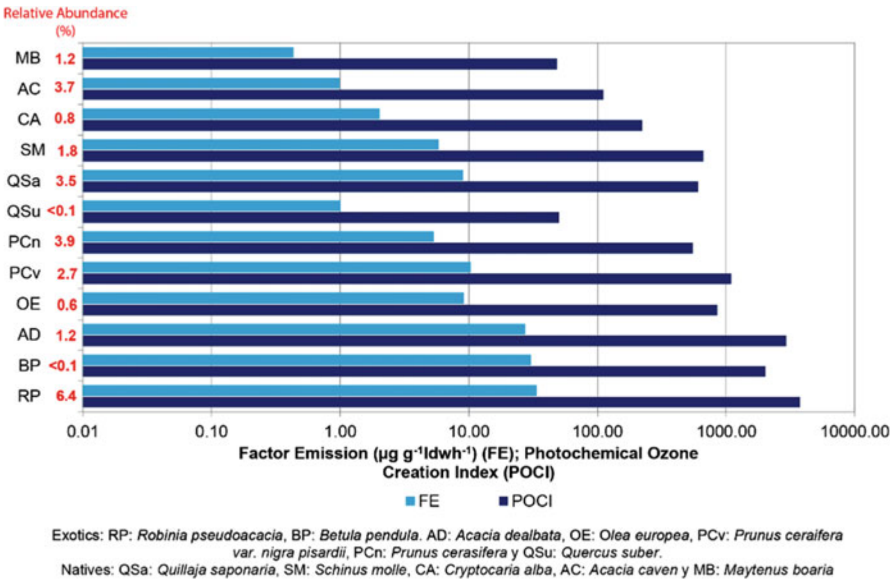

Fig. 8.7 Experimental emission factors (isoprene and total monoterpenes) and the corresponding Potential Ozone Creation Index (POCI) for a set of exotic and native species present in the urban forest of Santiago

$$POCP = \sum (EF_i * POCP_i)$$

where:

EF_i = emission factors obtained experimentally for each BVOC chemical species.

$POCP_i$ = Photochemical Ozone Creation Potential calculated for each BVOC chemical species based on Derwent (2011) (personal communication).

Figure 8.7 shows the EFs (isoprene and total monoterpenes) and the corresponding POCI determined for a set of exotic and native species studied in situ in the city of Santiago, corresponding to around 26% of the urban forest of Santiago (Hernández 2016). The experimental EFs were obtained using gas chromatography coupled with automatic temperature desorber equipment (GC-FID-ATD) to quantify the different terpenes (BVOCs) emitted by trees (Préndez et al. 2013a, b, 2014). Results clearly show that most of the native species studied emit lower concentrations of potentially ozone-producing chemical compounds, have much lower EFs, and also have much lower POCI. When EFs of exotic species in Santiago are compared with the EFs of isoprene and monoterpenes for tree species in other environmental conditions, differences are also found, as shown in Table 8.4. It has also been shown that the use, in the models, of EFs by default or the values obtained in other realities produces incorrect calculation of emissions (Préndez et al. 2014).

Table 8.4 Emission factors of isoprene and monoterpenes for tree species in different environments, expressed in μg (g dry leaf weight)$^{-1}$ h^{-I}

Scientific name	Common name	Isoprene	Monoterpenes	Reference
		μg (g dry leaf weight)$^{-1}$ h^{-I}		
Schinus molle	California Pepper	NED[a]	3.7	Corchnoy et al. (1992)
Schinus molle	California Pepper	NED	NED	Winer et al. (1983)
Schinus molle	Cotinus	3.86 ± 2.7	0.144 ± 0.14	Préndez et al. (2014)
Liquidambar styraciflua	Liquidambar	35.3	3.0	Corchnoy et al. (1992)
Liquidambar styraciflua	Liquidambar	17.8	2.9	Evans et al. (1982)
Liquidambar styraciflua	Liquidambar	3.5	51.5	Zimmerman (1979)
Liquidambar styraciflua	Liquidambar	0.607 ± 0.247	0.11 ± 0.015	Préndez et al. (2014)
Quercus suber	Cork Oak	0.97	0.17	Préndez et al. (2013b) Young trees
Quercus suber	Cork Oak	0.44	0.14	Préndez et al. (2013b) Adult trees

All emissions expressed in μg (g dry leaf weight)-1 h-I normalized at 30 °C using the algorithms of Guenther et al. (1993)
[a]*NED* No emission detected

Works is in progress to analyze chemical compounds other than VOCs present or formed in the atmosphere and/or emitted/absorbed by trees or emitted by anthropogenic sources using a GC-MSD chromatograph with an Injection System of Solid Phase Microextraction (SPME).

Information from Latin America regarding BVOCs in urban environments is scarce. Table 8.5 shows some results.

8.5 Effects of the Pollutants at the City Level

The Chilean government (MMA 2013) reports that all monitoring stations exceed the annual primary standard of 20 μg/m^3 for $PM_{2.5}$; the daily primary standard of 50 μg/m^3 is only fulfilled in two monitoring stations. The corresponding economic impact associated with medical expenses and loss of work productivity is US$ 670 million per year, which may amount to US$ 1.9 billion, considering the social welfare loss that represents an increase in the risk of death, due to the deterioration of the air quality. These values are determined only in relation to $PM_{2.5}$ pollution, underestimating the real environmental impact produced by the pool of

Table 8.5 Emission information on biogenic volatile organic compounds (BVOCs) in different urban environments from Latin America

Country (Place/city)	Objective	Method	Tree species	Reference
Brazil (Tapajos)	Emissions of BVOCs from Amazonian rainforest	Solid adsorbent cartridges/GC-MS and FIS	Amazonian rainforest	Rinne et al. (2002)
Brazil (Sao Paulo)	Chromatographic profiles from volatile fractions of plant clones to determine specimens susceptible to rust disease	HS-SPME/ GC × GC-qMS	*Eucalyptus grandis*	Wang et al. (2013b)
			Eucalyptus urophylla	
Brazil (Rio Grande do Sul)	Chromatographic profiles of volatiles to determine disease markers in plants	HS-SPME/ GC × GC-qMS	*Eucalyptus globulus*	Wang et al. (2013a)
Brazil (Cruz das Almas and Conceição do Almeida, Bahia)	Volatile organic compounds from leaves	HS-SPME/GC-MS	*Eugenia uniflora*	Mesquita et al. (2017)
Chile (Santiago)	Emissions factors of BVOCs from urban forest	The static enclosure method and Tenax adsorption/GC-FID	*Prunus cerasifera*	Préndez et al. (2013a)
			Prunus cerasifera var. nigra Pissadii	
			Robinia pseudoacacia	
			Acacia dealbata	
			Betula pendula	
			Olea europaea	
			Acacia caven	
			Cryptocarya alba	
			Schinus molle	
			Maytenus boaria	
Chile (Santiago)	Emissions factors of BVOCs from urban forests	The static enclosure method and Tenax adsorption/GC-FID	*Liquidambar styraciflua*	Préndez et al. (2014)
			Brachychiton populneus	
			Quercus suber	
			Quillaja saponaria	
			Caesalpinia spinosa	
Costa Rica (Canton Sarapiqui, Heredia)	Emissions of BVOCs from rainforest	Portable GC-PID	*Euterpe precatoria*	Geron et al. (2002)
			Prestoea decurrens	
			Socratea exorrhiza	
			Welfia regia	
			Cordia alliodora	

(continued)

Table 8.5 (continued)

Country (Place/city)	Objective	Method	Tree species	Reference
			Protium pittieri	
			Pourouma bicolor	
			Alchornea costaricensis	
			Miconia impetiolaris	
			Cissampelos spp.	
			Pentaclethra macroloba	
			Stryphnodendron microstachyum	
			Zygia longifolia	
			Musa acuminata	
			Virola sebifera	
			Dipteryx panamensis	
			Pterocarpus officinalis	
			Bambusa vulgaris	
			Warszewiczia coccinea	
			Nephelium ramboutan-ake	
Mexico (Monterrey)	Estimation of emissions for isoprene and monoterpenes compounds in the different plant communities	Remote sensing estimation	*Acacia rigidula*	Gastelum et al. (2016)
			Acacia berlandieri	
			Acacia farnesiana	
			Acacia malacophylla	
			Acacia sp.	
			Salvia sp.	
			Bumelia lanuginosa	
			Prosopis glandulosa	
			Celtis pallida	
			Cercidium macrum	
			Fraxinus greggii	
			Sophora secundiflora	
			Dalea sp.	

(continued)

Table 8.5 (continued)

Country (Place/city)	Objective	Method	Tree species	Reference
			Diospyros texana	
			Celtis laevigata	
			Hibiscus sp.	
			Quercus polymorpha	
			Quercus rysophylla	
			Quercus canbyi	
			Quercus tuberculata	
			Quercus virginiana	
			Platanus occidentalis	
			Juglans mollis	
			Sapindus saponaria	
			Juglans sp.	
			Ulmus crassifolia	

GC gas chromatography, *MS* mass spectrometry, *FIS* fast isoprene sensor, *HS-SPME* headspace solid phase microextraction, *qMS* quadruple mass spectrometry, *FID* flame ionization detector, *PID* photo-ionization detector

contaminants. On the other hand, applying a value of US$ 9.55 to earnings in an average work-day in Chile, the World Bank (1994) estimated to generate for Santiago an annual health benefit of US$ 18,192 per ton captured of PM_{10}, and US$ 1,315 per ton of O_3 reduction, calculated assuming that NOx and VOC contribute equally to ozone generation, with 12,336 tons of reduction. Average values vary depending on the pollution conditions and vegetation coverage of the different communes of the city of Santiago. The vegetation coverage is quite different throughout the province of Santiago and the entire Metropolitan Region, but it is always dominated by exotic species (Criollo et al. 2016; Hernández 2016).

8.5.1 Effects of Particulate Matter $PM_{2.5}$ on Human Health

The mass concentration (expressed in μg/m^3) as a function of particle size and time parameters has been the main criterion for characterizing PM exposure levels in Chile. The breathable PM has both short-term and long-term effects. Among the former are increased respiratory morbidity and mortality, decreased lung function, interference with lung defense mechanisms, obstructive bronchial syndrome

(Astudillo et al. 2012; Liu et al. 2014; Ostro et al. 1996; Román et al. 2009; Romieu et al. 2012; Samet et al. 2015). In the long term, the damage is more complex, owing to the lower development of the structure and function of the respiratory system (Oyarzún 2010).

$PM_{2.5}$ produced mainly from combustion processes and gas–particle reactions in the atmosphere, associated with a complex mixture of inorganic and organic compounds, has a direct impact on human health because of its 100% respirability, depositing in the nonciliated epithelium of the respiratory tract and generating various acute and chronic diseases of the respiratory and cerebrovascular systems, among others (Kampa and Castanas 2008; Pope et al. 2008; Mauderly and Samet 2009; Diaz-Robles et al. 2014; Kim et al. 2015). In Chile, a potentially significant effect of $PM_{2.5}$ concentrations on respiratory disease mortality has been found, increasing by 1.75% for each 10μg m^{-3} increase in $PM_{2.5}$ on an average day (Leiva et al. 2013; Valdés et al. 2012).

The recent publication by Criollo et al. (2016) shows an interesting correlation between urban woodland and asthma and pneumonia with air pollution by $PM_{2.5}$ and ozone, with differences in six communes of the province of Santiago, in relation to vegetation.

8.5.2 *Effects of Tropospheric Ozone on Human Health*

Tropospheric ozone is also recognized to be a threat to human health (WHO 2003, 2005). The problems of major concern due to ozone pollution are: increased hospital admissions, exacerbation of asthma and lung inflammation. Several investigations have shown the relationship between high concentrations of ozone and asthma in children performing physical activity (McConnell et al. 2002), as well as the increase in the short-term mortality rate due to increases in ozone concentrations in the atmosphere (Bell et al. 2004). Burnett et al. (2001) reported an increase in hospital admissions for respiratory conditions in children younger than 2 years, associated with ozone pollution. Sigman et al. (2012) states in the 2050 that increased ozone pollution could increase premature deaths from respiratory failure and premature children deaths.

In Chile, Matus and Lucero (2002) showed an increase in infant urgency consultations of up to 23% with ozone levels of 106 μg/m^3, presenting a statistically significant relationship between daily mortality and ozone for the period 1988–1996 in the warm months. In turn, Cakmak et al. (2007) showed a direct positive relationship between ozone and daily mortality for maximum concentrations of ozone close to 200 μg/m^3 associated with a 4.9% mortality compared with 2.1% for the cold months. Epidemiological studies of time series demonstrated small positive associations between daily mortality and an ozone level of 120 μg/m^3, a mobile average of 8 h (Chilean standard), and independent of the effects of the PM; therefore, the current value recommended by the WHO is 100 μg/m^3, an average of 8 h.

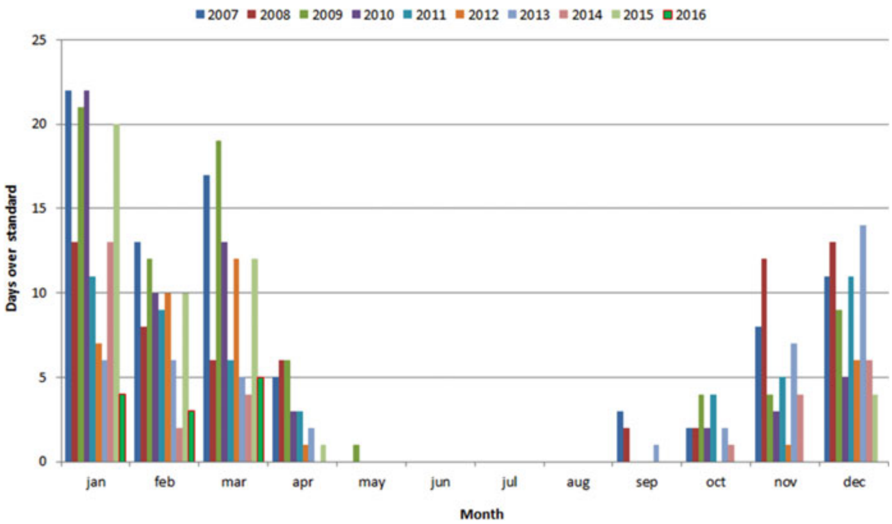

Fig. 8.8 Number of days above the national regulation during the austral spring–summer period from 2007 to March 2016 from Las Condes commune. (Source: SINCA 2016)

Other recent researches have focused on the health effect of PM on the general population (Román et al. 2009; Barrios et al. 2004; Oyarzún 2010; Leiva et al. 2013). Regarding the multi-effects of contamination, Franck et al. (2015) published a study on the negative effects of CO, NO_2, PM_{10}, and $PM_{2.5}$ in relation to hospital admissions, but found no relationship with tropospheric ozone.

Figure 8.8 shows the number of days above the regulation during the austral spring–summer period from 2007 to March 2016 for Las Condes (north-east of the city), one of the richest and highly vegetated communes. In general, the number of days has diminished between January and April over the years; this result is much more difficult to establish and is probably contrary between October to December, especially during December.

Criollo et al. (2016) reported results that correlate asthma and pneumonia, inflammatory diseases, and infectious characteristics of the respiratory system with environmental ozone, $PM_{2.5}$, and vegetation contribution in six communes in the province of Santiago, The results showed that $PM_{2.5}$ has no statistically significant correlation with hospital discharge for asthma, but it does with ozone, except in the commune of Las Condes, which has more vegetation, but the smallest $PM_{2.5}$ concentrations and the highest ozone concentrations of Santiago. In the case of pneumonia, $PM_{2.5}$ has a statistically significant positive correlation in all communes except Las Condes and has a statistically significant negative correlation with ozone in all the communes studied. It is important to note that in all communes, vegetation consists principally of exotic trees, which in turn have higher emissions of BVOCs, POCI index, and lost the leaves during the autumn–winter period.

8.5.3 Effect of Pollutants on Plant Health

Trees are also affected by pollution in both structure and performance, i.e., it interferes with the uptake of carbon into the biosphere (Sitch et al. 2007). There is information at an international level, but in Chile this is a new line of research. Some pollutants adhere to the surface of leaves or enter through the cuticle and stomata, causing an anatomical, structural, and physiological response in leaves and stems (Gostin 2009; Lukjanova and Mandre 2010), modifying the resistance to contamination (Saadabi 2011). CO_2 affects plant growth, leaf anatomy, and pollen productions and their impacts on human health (Albertine et al. 2014). The growth of xylem causes a decrease in accumulated biomass rate (Speer 2010). Thus, when choosing urban trees the species with better structural and functional responses to specific pollution levels for each location and other attributes locally studied should be considered (Avolio et al. 2015; Das and Prasad 2010; Dineva 2006; Koeser et al. 2014), minimizing maintenance and replacement costs, and maximizing the lifetime of the trees.

Ozone produces effects on vegetation as it enters the plant through the stomata, generating several reactive oxygen species. If plant detoxification systems are insufficient, such species may react with membranes and other cellular components such as proteins, causing changes in membrane permeability and fluidity, enzyme damage, and a metabolic and ionic imbalance (Heath and Taylor 1997). The most obvious effect of O_3 on plants is visible leaf surface symptoms (chlorosis, specks, spots and necrosis), which usually appear first in older leaves and occupy the spaces between the ribs (Machler et al. 1995) or present physiological effects that manifest without visible damage in the short term, such as the reduction of photosynthesis (Soja and Soja 1995), or affect productivity in the long term (WHO 2000).

Figures 8.9 and 8.10 show scanning electronic micrographs of the adaxial/abaxial epidermis of leaves of different tree species in three different environments:

(1) A clean place in the *Facultad de Ciencias Forestales y Conservación de la Naturaleza, Universidad de Chile*, located in the suburban south of the city, called a clean site
(2) A site in the *Facultad de Ciencias Químicas y Farmacéuticas, Universidad de Chile*, located at the urban north of the city, called a semi-polluted site
(3) A typical urban site located north of the city, called a polluted site

Figure 8.9 shows the differences between the quantities of PM deposited on the adaxial epidermis of the leaves of four native tree species, exposed to the semi-polluted site. Results show that *Cryptocaria alba* shows a higher amount of PM of smaller particle size than the PM deposited on the other trees, meaning that this is the best native tree to capture fine PM, $PM_{2.5}$.

In a similar way, Fig. 8.10 shows the differences between the quantities of PM deposited on the adaxial epidermis of the leaves of five exotic tree species, exposed to the polluted site. Micrographies show that every tree captures a different quantity and size of particles. Clearly, *Robinia pseudoacacia* capture only a few and small

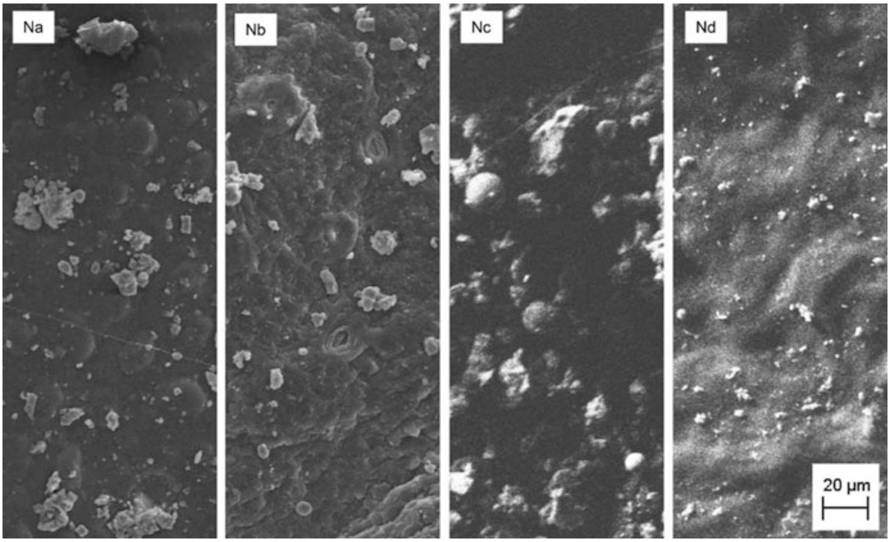

Fig. 8.9 Electronic scanning electron microscopy of the adaxial epidermis of the native species *Quillaja saponaria* (Na), *Schinus molle* (Nb), *Maytenus boaria* (Nc), and *Cryptocaria alba* (Nd) exposed to the semi-polluted site. (Source: The authors of the chapter)

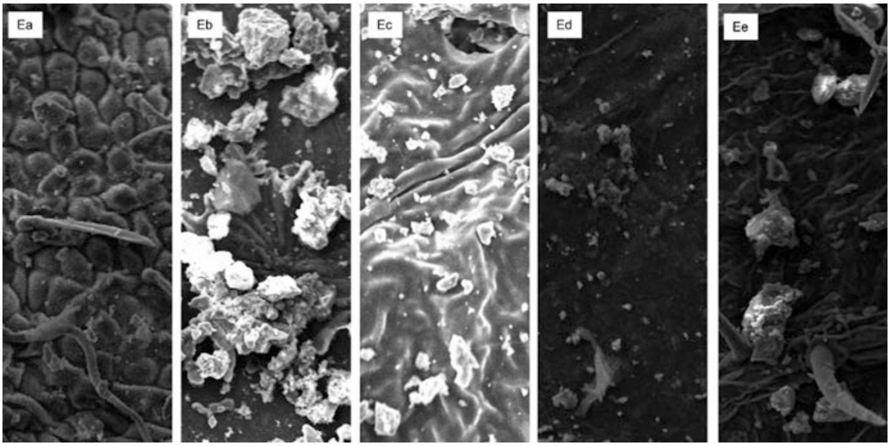

Fig. 8.10 Electronic scanning electron microscopy of the adaxial epidermis of the exotic species *Robinia pseudoacacia* (Ea), *Olea europaea* (Eb), *Melia azedarach* (Ec), *Brachychiton populneus* (Ed), and *Acer negundo* (Ee) exposed to the polluted site. (Source: The authors of the chapter)

particles, more or less the same as *Brachychiton populneus*; in contrast, *Olea europaea* captures many and large particles; *Melia azedarach* and *Acer negundo* capture rather large particles, but not many. If it is necessary to capture large particles, the choice should be *Olea europaea;* however, as $PM_{2.5}$ is more dangerous than PM_{10}, the choice could be *Brachychiton populneus* or *Robinia pseudoacacia*,

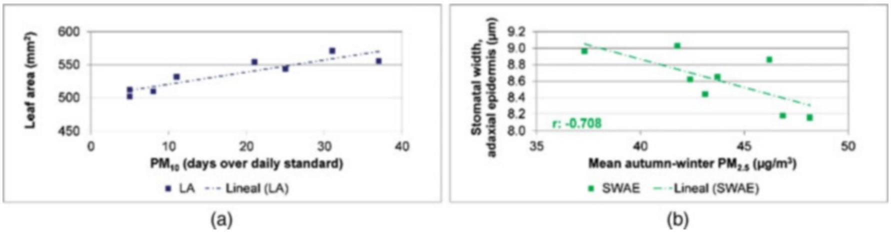

Fig. 8.11 Correlations between particulate matter concentration and the morphological and anatomical effect on the leaves of *Quillaja saponaria* during the autumn–winter period. (**a**) Positive correlation (>99%) between the leaf area and the number of days above the PM_{10} standard. (**b**) Negative correlation (>95%) between the stomata width from the adaxial epidermis and the mean concentration of $PM_{2.5}$. (Source: Egas 2017)

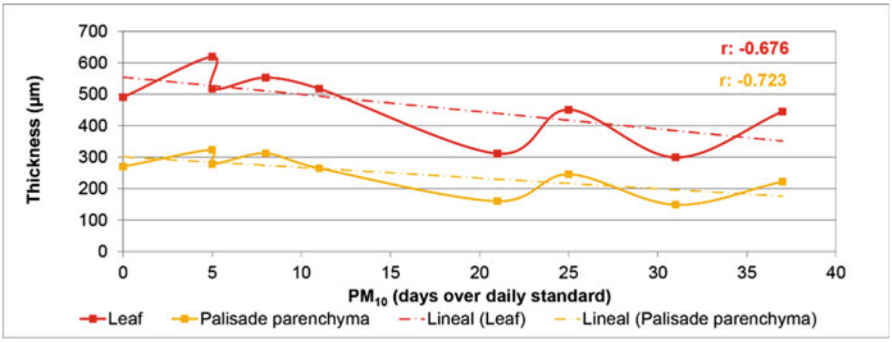

Fig. 8.12 Negative correlation (>95%) between the thickness of the leaf and the thickness of the parenchyma palisade of *Quillaja saponaria* and the number of days of PM_{10} above the 24-h standard. (Source: Egas 2017)

but only *Brachychiton populneus* is evergreen and could really contribute to improving air quality.

The effect of the air quality over *Quillaja saponaria* was studied by Egas (2017) analyzing some of the morphological and anatomical variables of ten individuals growing around 100 m from each of the official monitoring stations of Santiago (nine stations, Las Condes and Talagante were not included). Figure 8.11a shows a significant positive correlation (>99%) between leaf area and the number of days above the PM_{10} standard. Figure 8.11b shows the negative correlation (>95%) between the stomata width from the adaxial epidermis and the mean concentration of $PM_{2.5}$ during the autumn–winter period. These results indicate that the leaves of *Quillaja saponaria* tend to react to the pollution of the air, increasing the area and decreasing the stomatal width of the leaves.

Figure 8.12 shows the negative correlation (>95%) between the thickness of the leaf and the thickness of the parenchyma palisade of *Quillaja saponaria* and the number of days of PM_{10} above the standard. The results demonstrate another negative effect of pollution on the leaves.

The other results of the study by Egas (2017) related to other characteristics of the stomata and the spongy parenchyma of the individuals of *Quillaja saponaria* are in progress. All results agree in the sense that long-term exposure to high concentrations of $MP_{2.5}$ and MP_{10} would affect the integrity of the epidermis and the mesophyll of leaves, reducing the number of photosynthetic cells and then the performance of the trees, and, as Sitch reports, it could impede the uptake of carbon from the biosphere (Sitch et al. 2007).

8.6 Discussion

The role of the urban forests in providing ecosystem services has been reported by many researchers in many papers and used in different cities, considering both basic ecosystem functions, such as primary productivity (Costanza et al. 2007), and services, such as the improvement of urban air quality (Escobedo et al. 2006) generating, for example, local and regional ventilation during calm conditions; fresh-air transportation circuits to built-up areas, and air purification and fresh-air production (Hebbert and Webb 2012). Also, the economic benefit of the capture/interception of air pollutants by leaf-like PM and ozone has been modeled, all depending on the many characteristics of each species, e.g., leaf structure, pubescence, presence of wax on the leaf surface, petiole size, and canopy structure (Prajapati and Tripathi 2008), that need to be assessed under the local conditions. Paoletti (2009) discusses the advantage/disadvantage of BVOC emissions and ozone capture for the selection of trees.

In Chile, some information exists on Santiago about the environmental benefits of vegetation. For instance, Escobedo et al. (2006, 2008) have reported a modeled removal of PM_{10}, O_3, CO, NO_2, and SO_2. Préndez et al. (2013a, b, 2014) showed the necessity of determining the experimental EFs of BVOC (in only approximately 26% of the urban forest has this been undertaken), in addition to quantifying the real amount of PM captured by trees. Escobedo et al. (2011) said that all the C emissions and the strategies for reducing CO_2 by urban forests are comparable with other policies to reduce CO_2 emissions, meaning that urban forests are in the edge cost/benefit ratio with other technologies to reduce the PM, if trees and places are well chosen. Paoletti (2009) maintained that the benefit of ozone capture is greater than the BVOC emissions if the trees are correctly selected.

Green space, or more properly green open space (IFPRA 2010), has been defined in different ways in different countries/institutions, but, in general, its benefits have been categorized into environmental, social, economic, and health benefits. Green capital cities are increasingly promoting the concept of "clean and green" through the idea of having a defined percentage of the total geographical area of the city under green cover, or having a number of m^2 per capita that could range from a few m^2 up to 60 m^2 per capita or even more, in an effort to retain the environmental sustainability of the cities. However, accessibility and distance to the green areas are also important (Thaiutsa et al. 2008; IFPRA 2010; Morar et al. 2014; Kabisch et al. 2015; Khalil 2014; Badiu et al. 2016; Pafi et al. 2016).

In 2003, CONAMA (at present MMA) reported an average of 3.2 m^2/inhabitant, with values between 2.9 and 0.4 m^2/inhabitant for the poorest communes and between 6.7 and 18.8 m^2/inhabitant for the communes of higher incomes (Nilo 2003). In 2009, Reyes-Päcke and Figueroa (2010) reported an average of 3.9 m^2/inhabitant, with extreme values of 1.1 m^2/inhabitant in Quinta Normal (west part of the city) and 12.6 m^2/inhabitant in Santiago (downtown).

Considering the information reported in this chapter, Santiago undoubtedly needs urgent forestation; the positive physical and chemical benefits would be enormous. In addition, it could generate social interaction in the green areas, strengthening the attachment of the community and the positive effects on human health. But it is necessary not to ignore the interactions of the vegetation with atmospheric chemistry. It is necessary to complete, or at least strongly advance, in the experimental determination of EFs and other characteristics of tree species before their use in urban tree-planting.

From the point of view of air pollution, tactics and strategies are strongly based on emission inventories. An emission inventory is an effective management tool if providing reliable information on which to base effective control actions; in the case of ozone, a secondary pollutant, actions should be focused on emission inventories of nitrogen compounds ($NO + NO_2$) and VOCs, including BVOCs, which are clearly poor in Santiago. The emission inventories in Santiago are using the EFs of tree species by taxonomic approximations, which do not agree with the experimental ones; thus, the bias in their results leads to actions not necessarily effective for the decontamination of the city, a situation that should be corrected as soon as possible. A new and real inventory is necessary.

Particulate matter capture is another crucial factor to be considered. The uses of magnetic measurements are rapid and effective techniques for evaluating the retention capacity of PM on leaves of different types of tree species. Muñoz et al. (2017) have shown that the abundant exotic species *Platanus orientalis* and *Acer negundo* have a better ability to capture PM than the species *Robinia pseudoacacia,* the most abundant tree in Santiago; however, all those species are deciduous and lose their leaves during the autumn–winter period, when the levels of PM pollution are highest and consequently contribute little or nothing to the process of decontamination and improvement of air quality in the city of Santiago. Guerrero-Leiva et al. (2016) studied the capture of three exotic ornamental species, *Nerium oleander, Pittosporum tobira, and Ligustrum lucidum*, reporting a better performance for *Nerium oleander. Ligustrum lucidum* is scarcely represented (3.7%) in the urban forest (Hernández 2016). Note that 85.1% of the vascular flora of Santiago is exotic (Figueroa et al. 2016).

Other important considerations when choosing trees to reforest, referring to their anatomical, structural, and physiological response and adaptation to the climate and pollution. Results presented in this chapter show the response of the native species *Quillaja saponaria* to air pollution. More species must be studied.

The necessity of obtaining an ordered list of species according to their ability to have a positive impact on atmospheric chemistry is evident. The results can be easily applied to evaluating the potential of air pollution removal by the existing urban forests and for planning tree replacement or new plantings by local governments, the Housing Ministry, and the Environment Ministry. This will contribute to the improvement of public policies and planning aimed at reconciling urban growth, quality of life, and protection of the air, contributing to the sustainable development of the cities. Table 8.6 shows a selected group of characteristics to be considered in

Table 8.6 Different characteristics of 18 urban tree species, exotic and native, studied to facilitate the selection of the better tree species to forest Santiago

Exotic species												
	LS	BrP	QS	MA	AN	RP	BP	PCn	PCv	AD	PO	OE
PM capture autumn–winter	–	+	+	–	–	–	–	–	–	–	–	+
PM capture spring–summer	+	+	+	+	+	+	+	+	+	+	+	+
Low emissions BVOCs	–	+	+	nd	nd	–	–	–	–	–	nd	–
Low POCI	–	+	+	nd	nd	–	–	–	–	–	nd	–
Evergreen	–	+	+	–	–	–	–	–	–	+	–	+
High density foliage	+	+	+	+	+	+	+	+	+	+	+	+
Low water requirements	–	–/+	–	–	–	–	–	–	–	–/+	–	+
Large size	+	+	–	+	+	+	+	+	+	–	+	–
High growth rate	+	++	+	++	++	++	++	++	++	nd	++	–
Rough or resinous leaves	++	+	nd	+	++	++	nd	nd	nd	nd	++	+
Epidermal modifications (trichrome)	+	–	nd	+	+	+	nd	nd	nd	nd	++	++
Hypostomatic leaf	+	+	+	+	+	+	nd	nd	nd	nd	+	+
Amphistomatic leaf	–	–	–	–	–	–	nd	nd	nd	nd	–	–
Allergenicity	–	–	+	–	++	–/+	+	–	–	+	++	+
Resistance pruning	–/+	nd	–/+	–/+	–	+	–	–/+	–/+	nd	+	nd
Good sanitary conditions	+	–/+	+	–	–	–	–/+	–/+	–	nd	+	nd
Climate adaptation	–/+	–/+	+	+	+	–/+	–	+	+	nd	–/+	nd
Pollution adaptation	+	+	+	–/+	+	+	–/+	–/+	–/+	+	+	nd

LS *Liquidambar styraciflua*, BrP *Brachychiton populneus*, QS *Quercus suber*, MA *Melia azedarach*, AN *Acer negundo*, RP *Robinia pseudoacacia*, BP *Betula pendula*, PCn *Prunus cerasifera* var. nigra pisardii, PCv *Prunus cerasifera*, AD *Acacia dealbata*, PO *Platanus orientalis*, OE *Olea europaea*

+:positive characteristic, – negative characteristic, *nd* not determined

Table 8.6 (continued)

Native species						
	MB	AC	SM	QS	CA	CS
PM capture autumn–winter	+	–	+	+	+	+
PM capture spring–summer	+	+	+	+	+	+
Low emissions BVOCs	+	+	+	+	++	+
Low POCI	+	+	+	+	++	+
Evergreen	+	–	+	+	+	+
High density foliage	+	–	+	+	+	–
Low water requirements	–	+	+	–/+	–	+
Large size	+	–	+	+	+	–
High growth rate	++	++	++	+	++	–
Rough or resinous leaves	+	nd	++	+	+	+
Epidermal modifications (trichrome)	nd	nd	–/+	–/+	nd	nd
Hypostomatic leaf	nd	nd	–	–	nd	nd
Amphistomatic leaf	nd	nd	+	+	nd	nd
Allergenicity	–	+	–	–	–	–
Resistance pruning	–/+	+	+	+	+	+
Good sanitary conditions	–/+	–/+	–/+	–/+	–/+	+
Climate adaptation	–/+	+	+	+	+	+
Pollution adaptation	–	–	+	+	+	nd

Sources: Alvarado et al. (2013), Donoso (2005), Gutiérrez (2005), Hoffmann (1998a, b), Riedemann and Aldunate (2004)

MB *Maytenus boaria*, AC *Acacia caven*, SM *Schinus molle*, QS:*Quillaja saponaria*, CA *Cryptocaria alba*, CS:*Caesalpinia spinosa*

+: positive characteristic, –: negative characteristic, *nd* not determined

this direction. Also, it is interesting to repeat that native trees, in general with the smallest EFs and the generation of ozone, and mostly evergreens, have better qualities for the retention of PM, such as roughness, villi or a resinous surface. In addition, they have complex structures, a high density of foliage, and they are adapted to the natural environment, all factors that aid in the capture of PM.

8.7 Conclusion

Well-planned urban forests are essential for cities offering a high quality of life. In Chile, the urban forest is considered within air quality improvement policies and urban afforestation programs, both mainly focused on the increase in the green area cover, and somehow the maintenance and landscaping. Nevertheless, the international and the local scientific knowledge has shown that trees simultaneously capture PM and gases and emit BVOCs; therefore, not only the increment in the area becomes important, but also the selection of appropriate species that can maximize PM removal while minimizing the VOC emissions that can eventually contribute to generating urban ozone. Not only that aspect is relevant, but also other factors such as its age, resistance to pollution, weather, and soil. Therefore, a strategic selection needs to be made by carefully analyzing the benefits and potential negative aspects of the tree species planted in the city. To fulfill this purpose, many gaps remaining in Chile must be filled. It is necessary to collect much more solid scientific data related to:

(1) The local conditions affecting/controlling vegetation (e.g., local and micro-scale local climate, geography, physiological and genetic characteristics, adaptability to the environment)
(2) The survival and growth of trees
(3) The quantification captures of PM and gases by tree species in addition to its emissions (BVOC-O_3, SOA)
(4) The use of new, rapid, and efficient techniques of analyses approved internationally
(5) The study of health problems related to primary and secondary pollutants and pollen characteristics
(6) The social acceptability of the people affecting the resulting proposals

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Chapter 9
Urban Climates and the Challenge of Sustainable Development of Chilean Cities

Hugo Romero

Abstract Rapid urbanization and countryside depopulation in Chile, as in the whole of Latin America, has not been accompanied by the available resources, urban planning and management necessary to supply urban societies and spaces with the required services and environmental quality. Although Chile currently has one of the highest indicators of per capita income and human development index in Latin America, and it has achieved some of the lowest poverty figures, Chilean cities still have neighborhoods where poverty is linked to a lack of opportunities and equipment, and higher insecurity levels that result from combining natural and socio-economic threats. The poor people live in places with urban heat islands, where a lack of vegetation dries the air and generally occupy areas with less ventilation, which, consequently, lead to a higher concentration of air pollutants. In contrast, richer inhabitants are used to living in areas of urban cooler islands, where temperatures are not as high because of the presence of gardens, urban forests, and parks. First, this chapter addresses the spatial relationships between land uses/cover changes and surface temperatures in Santiago de Chile. Second, such urban internal differences are represented by local climate zone (LCZ) analyses for some of the Chilean cities located throughout the country: Calama, Antofagasta, Valparaíso, Santiago, Concepción, and Chillán. Three cases of land use changes in Santiago neighborhoods (LCZs) are described and related to socioeconomic conditions. Urban heat islands and heat waves in Santiago are examined. Finally, the relationship between the spatial distribution of particulate matter, temperatures, urban geography, and socioeconomic groups are shown.

Keywords Chilean cities · Climate justice · Local climate zones · Urban heat · Heat waves · Socioeconomic difference

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9.1 Introduction

The urban climatology of Latin American cities is strongly related to socioeconomic issues as climate and air quality have clearly become urban commodities under current models of socioeconomic development. As with any other goods and services, they are bought and sold like private resources in markets, most of the time as a relevant part of the price of a house. Therefore, access to a determined type of urban climate depends on the family's or individual's income. Richer inhabitants are used to living in areas of urban cooler islands, where temperatures are not as high because of the presence of gardens, urban forests, and parks. Humidity is higher because of the vegetation of parks and backyards, and ventilation is blowing because of lower densities and low-rise buildings. Topological location is always favorable in terms of clean air and distance from pollution sources, with the exception of roads and highways. In contrast, poor people live in places with urban heat islands, where a lack of vegetation dries the air, and generally in areas with less ventilation, which consequently have a higher concentration of air pollutants.

Therefore, Latin American city urban climates are outstanding components of the lack of social and environmental justice, as they are closely related to the uneven distribution of levels of economic affluence. However, given the fact that the urban atmosphere is also a common good for the entire population that inhabits the city, access to an adequate urban climate is also a permanent source of political conflict and societal concern.

Environmental reasons are not taken into consideration in most of the planning and design of cities, despite the fact that each new urban area is always creating important climatic transformations. Urban heat islands replace cooler landscapes such as woodlands and agricultural lands; the air humidity is reduced owing to the disappearance of evapotranspiration from vegetation cover, wetlands and wet soils; winds and breezes diminish because of increasing rugosity, thermal standardization of the ground, and elimination of parks and other cool air sources. Impervious surfaces increase surface run-off, which explains the loss of infiltration capacity, and therefore, reduces environmental resilience in terms of the negative effects of floods, droughts, and waterlogging.

Hundreds of thousands of new private cars become necessary to cover increasingly long distances between workplaces, service centers, and homes. This generates traffic jams and increases the rate of air pollution in practically all Latin American cities, whose complexity depends on size and shape. Adequate public transportation systems would be required to mobilize millions of daily commuters between increasingly dispersed or distant urban settlements and their available spaces for services and labor. People constantly suffer from a waste of time and money, lower quality of living, physical and mental diseases, and health and psychological consequences of limited public transportation systems.

The Latin American city shows an increasing gap between areas where some small groups enjoy accumulated environmental goods and services, and concentrated urban amenities and these neighborhoods where most of the population has to pay every day for the elevated economic, ecological, social and environmental costs of living in such cities.

Some of the Chilean political–economic reforms have had broad environmental effects after more than 40 years of application of the neoliberal model. At the end of the 1970s, urbanizable space was defined as an abundant resource and instruments of regulation were assessed like arbitrary public actions that, by preventing urban occupation in certain places, raised artificially the costs of land and housing. On the other hand, the rights to use surface and ground waters have been privatized since 1981. In successive years, other environmental components, such as public roads and highways, air, and biodiversity were also privatized and commodified. Private development companies largely replace the role played previously mainly by the State.

9.2 Regional Geography and Urban Climates

Achieving better climatic qualities in our cities depends on different factors such as meteorological, geomorphological, hydrological, and particularly on the social dimensions of urban spaces. For this reason, there are inhabitants of the same city who enjoy or suffer from good or poor climatic quality. Inequality in Latin America and the Caribbean mainly affects the urban areas and, although there has been an increase in GDP per capita, a reduction in poverty rates, and an improvement in other socioeconomic indicators, they have not expressed a significant decrease in socioenvironmental urban disparity. In this region, urban socioenvironmental–climatic inequalities emerge as a very particular issue for public policy.

One of the first ranges of geographic antecedents that are necessary to take into consideration for the understanding of Chilean urban climates includes the location, topology, and position of cities in such upper scale frameworks, such as climatic regions, topographical scenarios, and watersheds. Santiago, the capital city of Chile, with seven million inhabitants, is located in a closed river basin corresponding to the Maipo and Mapocho rivers and their mountain tributary streams system that descends at the eastern side of the city, from the nearest higher Andes chain with summits over 2,000 m (Fig. 9.1).

Between 1,000 and 2,000 m in height, relevant rainfall trigger belts are spatially associated with shrubs and woodland vegetation that ensure water infiltration and ground recharge. Conservation of such environmental service areas, controlling urbanization and imperviousness, are relevant goals for urban planning and management. At higher altitudes, glaciers and snowfields are still feeding air masses and surface and groundwater features, which, together with seasonal rainfalls and snowfall, provide the water needed for the largest concentration of Chilean population.

In the case of Santiago, rainfall occurs only on an average of 20 days per year, concentrated in the winter months of May–August, and consequently, the city life support system heavily depends on water accumulated in the Andean mountains,

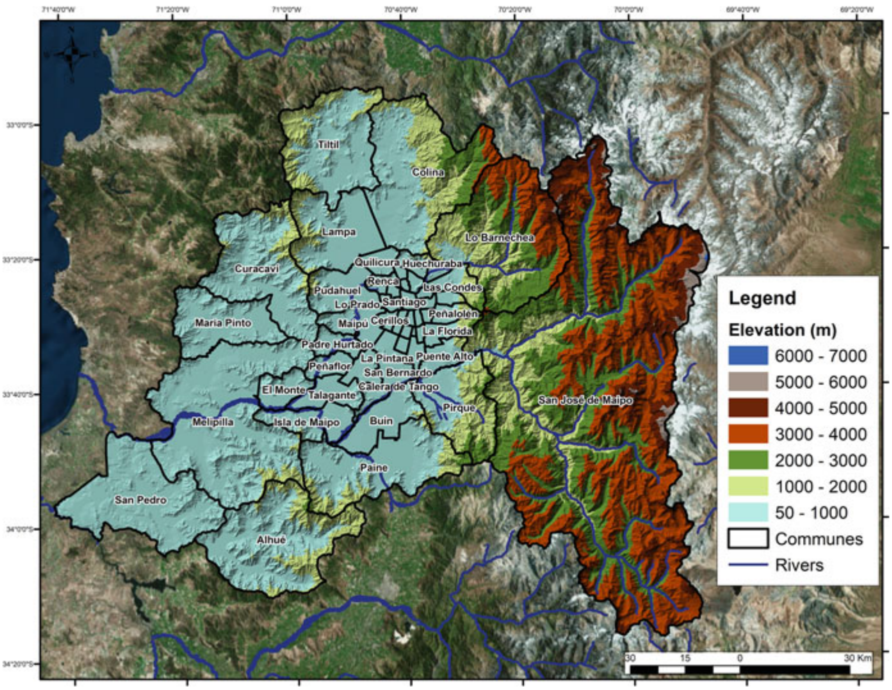

Fig. 9.1 The metropolitan region of Santiago, Chile

which is also the case for some of the other most relevant cities in South America, such as Lima, Quito, and Bogotá.

Projected scenarios of climate change generally reduce snow and rainfalls, predict the retreat of glaciers and the elevation of snowlines, reinforced by deforestation and increasing imperviousness caused by foothill urbanization and land uses, and cover changes on mountainous slopes. All of these are meaningful issues for environmental concern in most mountainous cities, such as Santiago.

The coastal mountain chain is close to the western side, the river basin where the city of Santiago is situated, separating it, in part, from the Pacific Ocean coastal influences. Between both the coastal and the Andes mountain chains, other northern and southern ranges also close the city completely for the arrival of external air masses. Therefore, Santiago is located in a topographically closed landscape that promotes some levels of continentality, reduces ventilation capacity, and increases air pollution potentiality.

On the other hand, Santiago city, located at 33° S, is under permanent influence of subtropical anticyclone cells due to general atmospheric circulation patterns, and records therefore, a series of air subsidence thermal inversion layers. In the autumn and winter seasons (i.e., between March and August) this stable atmosphere even becomes associated with surface radiation inversion layers that increase air pollution potentials, particularly in those urban areas located under 1,000 m height, where the population lives.

Unfortunately, because of knowledge and institutional limitations, the loss of climate and air quality and increasing levels of air pollution are now not only concentrated in larger metropolitan areas. In the case of Chile, and as an example of what is happening in most Latin American small and mid-sized cities (between 50,000 and 200,000 inhabitants, such as Talca, Chillán, Temuco, Osorno, and Coyhaique), they are now recording seasonally higher levels of air pollution and decreasing climate quality. Again, to their topographical and climatic restrictions, represented for example by the presence of thermal inversion layers, they must add the use of wood fire for cooking and heating, which explains why they are among the most polluted South American cities.

The urban sprawl process experienced between 1994 and 2014 in Santiago (Fig. 9.2) could be an example of a similar pattern exhibited for the spatial growth of most Latin American cities, transforming agricultural land uses and natural land cover in urban spaces. In 1994, Santiago had already consolidated a continuous urban landscape, increasing its density and conurbating the nearest cities, such as

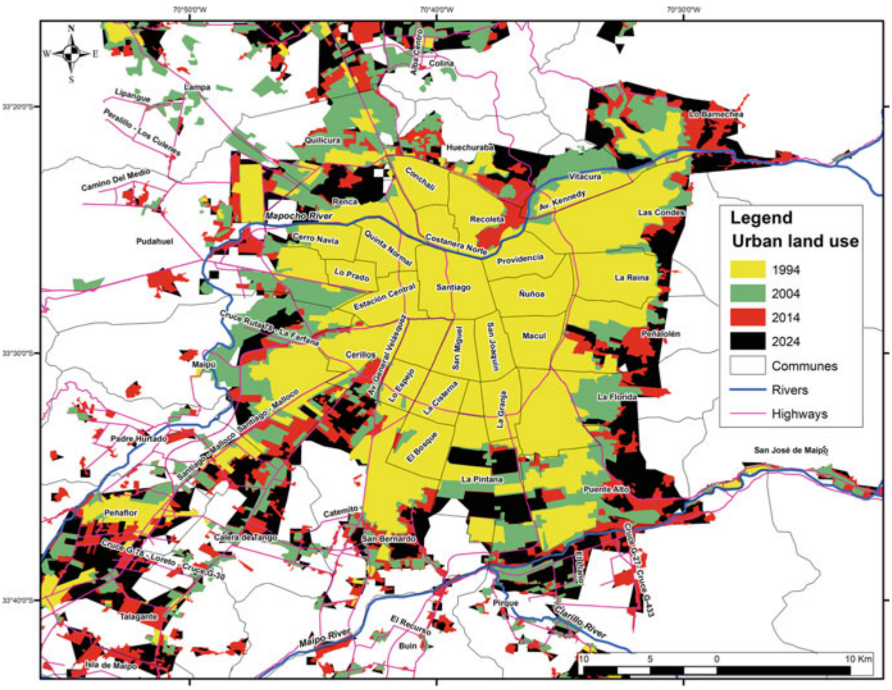

Fig. 9.2 Urban sprawl of the Santiago urban area observed between 1994 and 2014 and simulated growth for 2024. Note: The construction of the future land use map of the year 2024 was elaborated using the CA_ MARKOV module of the IDRISI software, which integrates the methods of Cellular Automata, Markov chains, and Multi-Criteria Evaluation. The validation was made using the Kappa index of agreement. (Source: Author's own elaboration based on Landsat imagery)

San Bernardo and Puente Alto (Romero et al. 2007). Small plots of urban space located in the middle of rural landscapes corresponded to the international airport, at the west, and some human settlements distributed along the valleys. In 2004, the urban space looked consolidated and the remaining rural areas were integrated into the city. In 2014, the urban space extended beyond the city boundaries with increasing distances along roads and highways, substituting agricultural and natural lands, especially at the northern and southern borders of the city. A leap-frog process also pushed suburban and ex-urban extensions that generated a dispersed city region instead of a compact one. Its growth to the east is still limited by slopes and the geomorphology of the Andean mountain chain and related regulations. According to spatial simulation applied for 2024, Santiago is refilling the nearest rural spaces, consolidating urban expansions of the north and south of the current city, and increasing the number of urban isolated plots in the middle of rural areas.

Each time, new urban spaces are added to the city and master plans are modified to incorporate new development areas. Large pieces of added land are continuously demanding higher priced goods and services for dwellings of differentiated social groups; poorer people are still asking for equipped urban spaces to survive generally under a precarious livelihood, and richer people are producing increasing amounts of wastes and pollution owing to overconsumption. Development companies, state agencies, and municipal governments pursue economic benefits that mean profits, taxes, financial speculation, and employment, ideas that are almost behind and supporting political priorities and decisions that cannot control urban growth. Contrary to environmental common sense, each Latin American city is permanently trying to expand their urban space, because of either economic profits or social pressures. A large proportion of new inhabitants can only afford housing in peripheral and distant zones. Such zones are mainly the areas affected by natural threats, social risks and pathological conditions, and additionally, characterized by the worst climatic and air quality conditions.

Given speculation, increasing transportation costs, and the scarcity of goods and services in distant places, housing becomes more expensive for poorer and middle-class people. Densification and verticalization through a series of tall buildings located near transport facilities or near city centers, are an ongoing process. In the case of Santiago, special subsidies favor the construction of such buildings in central and pericentral areas of renewal. In the Estación Central neighborhood, near the city center, 22 floors is the average height of some of these developments that have been called “vertical gentrification” or socially segregated tall towers that accentuate adverse climatic conditions. These buildings act like hot spots, interrupters of natural ventilation, generators of a drier atmosphere, and, consequently, places of higher air pollution and bad climatic quality concentrations.

The urban climatology of Latin American cities is strongly related to socioeconomic issues. Climate and air quality could be observed like urban commodities. Like any other good and service, they are bought and sold like private resources in markets, most of the time as a relevant part of the price of a house. Therefore, urban climates of Latin American cities are outstanding components of a social environmental lack of justice, as they are closely related to the uneven distribution of levels of economic affluence. However, given the fact that the urban atmosphere is also a common good for the whole population of the city, the access to adequate urban climates is also a permanent source of political conflict and societal concern. Environmental factors are not taken into consideration in most of the planning and design of cities, even though each new urban area is always creating an important climatic transformation.

Vegetation cover is one of the most important factors that controls urban climates. Urban vegetation absorbs direct solar radiation and heat, offers shade to temper excessive heat accumulation, produces humidity throughout evapotranspiration processes, generates park breezes, acts as a filter for particulate matter of air pollution, and recirculates some of the toxic substances. Vegetation environmental services are a fundamental part of urban ecosystems and quality of life and, as their installation and care are very expensive, they are practically non-existent in poor neighborhoods; green areas are concentrated in the richest part of the city and are a clear feature of socio-environmental spatial segregation in urban landscapes.

Santiago city previously occupied a small proportion of the total surface of the so-called metropolitan region, surrounded by agricultural land, woodlands, and shrub zones. In all directions, it was possible to observe extensive areas covered by woods, especially on the slopes of the Andes and coastal ranges and along the green natural corridors that connect them to the flood plains.

The 2004 land use/cover shows that vegetation cover has significantly diminished and that the segregation of green areas took place in most areas surrounding the city, resulting in an increasing loss of environmental services and climate regulations (Table 9.1). Consequently, increasing air heat and drying and ventilation reduction were produced at the same time that society was committed to apparent programs of environmental improvements supported by international agreements. Business behind the urban sprawl was continually substituting large areas, especially those located in the mountains, with smaller and scattered green patches. In 2014, vegetation land cover continued to reduce in size, spatial segregation, and diversity.

Figures on land cover degradation are presented in Table 9.1. Urban surfaces have increased by 124% between 1994 and 2014, passing from 61,000 to 123,000

Table 9.1 Land use and land cover variations in the Santiago metropolitan region in 1994, 2004, and 2014

Categories	Hectares			Variation (%)
Land use and land cover/year	1994	2004	2014	1994–2014
Urban area	61,257	94,504	123,515	101.63
Agricultural lands	291,512	238,060	212,379	−27.14
Silvicultural grounds	3,432	2,176	6,660	94.05
Wooded area	206,161	196,207	110,472	−46.41
Andean scrub	158,883	159,105	201,955	27.1
Scrub	438,021	423,183	523,860	19.59
Spaces with little or no vegetation	297,331	377,234	329,884	10.94

Source: Author’s own elaboration based on Landsat imagery built-up hectares. Agricultural lands and woodlands have substantially reduced their covers partially explaining growing surfaces occupied by shrubs and scrubs, which should mean a reduction of climate regulations.

Transformations in land cover and reduced vegetation observed have produced a meaningful increment of surface temperatures that, transferred to atmosphere, should increase regional warming. Figure 9.3 presents surface temperatures in Santiago Metropolitan region in 1994. Maximum values, over 35 °C were recorded mainly in such areas covered by scrub, beyond the north and east boundaries of the city. In 1994 (Fig. 9.3), warm areas slightly increased in comparison with the generalized and hard increment that could be observed in 2014 (Fig. 9.3), year in which an outstanding drought event took place in central Chile. Hot areas were distributed in the northern and eastern parts of the city, particularly in areas covered by little vegetation or bare lands. Table 9.2 illustrates classes of surface temperature variations between 1994 and 2014. Areas with temperatures less than 25 °C reduced their cover by more than 60%, whereas warmer zones, over 35 °C, increased their surfaces by impressive figures. Surface temperatures over 40 °C passed from 10,000 to more than 94,000 hectares between 1994 and 2014. It is not possible from this source of information to discriminate between permanent causes of surface heating such as land use and cover variations, and temporal events such as the drought that affected the Santiago metropolitan region and other Chilean zones between 2010 and 2015, and which has been classified as one of the most extreme events of the last hundred years. In any case, it is clear that Santiago's surrounding environment has substantially changed over the last 20 years and that these variations have corresponded to warmer and drier regional climates that constitute the geographical matrix where urban climate changes have taken place. To analyze some of these changes, observed variations in some built-up areas in the city are presented in the following sections.

Figure 9.4 presents spatial relationships between changes in an urban compacted area and surface temperatures. They correspond to an older and environmentally degraded part of the center of Santiago, the Estación Central commune. Although the urban surface has remained the same over the period 1994 and 2014, it has increased surface temperatures, owing to densification and verticalization.

On the other hand, in the commune of Vitacura, located in the eastern part of the city, woodland cover has decreased in an open neighborhood of a higher socio-economic level. As classified temperatures do not show relevant changes, it is possible to assume that the urbanization process in this type of urban zone is compensated for by the vegetated gardens, parks, streets, and squares that predominate in these affluent zones. In the same Vitacura commune, shrub lands decreased between 1994 and 2004, but this latter figure remains until 2014. However, again, surface temperatures present a stable value, possibly as a result of compensation caused by the increment of other green areas. Complementary, the results show the relevant urban land use and surface temperature increments recorded between 1994 and 2004 in Vitacura. Surface temperatures pass from the range 30–35 °C in 1994, to 35–40 °C in 2004, to 40–45 °C in 2014.

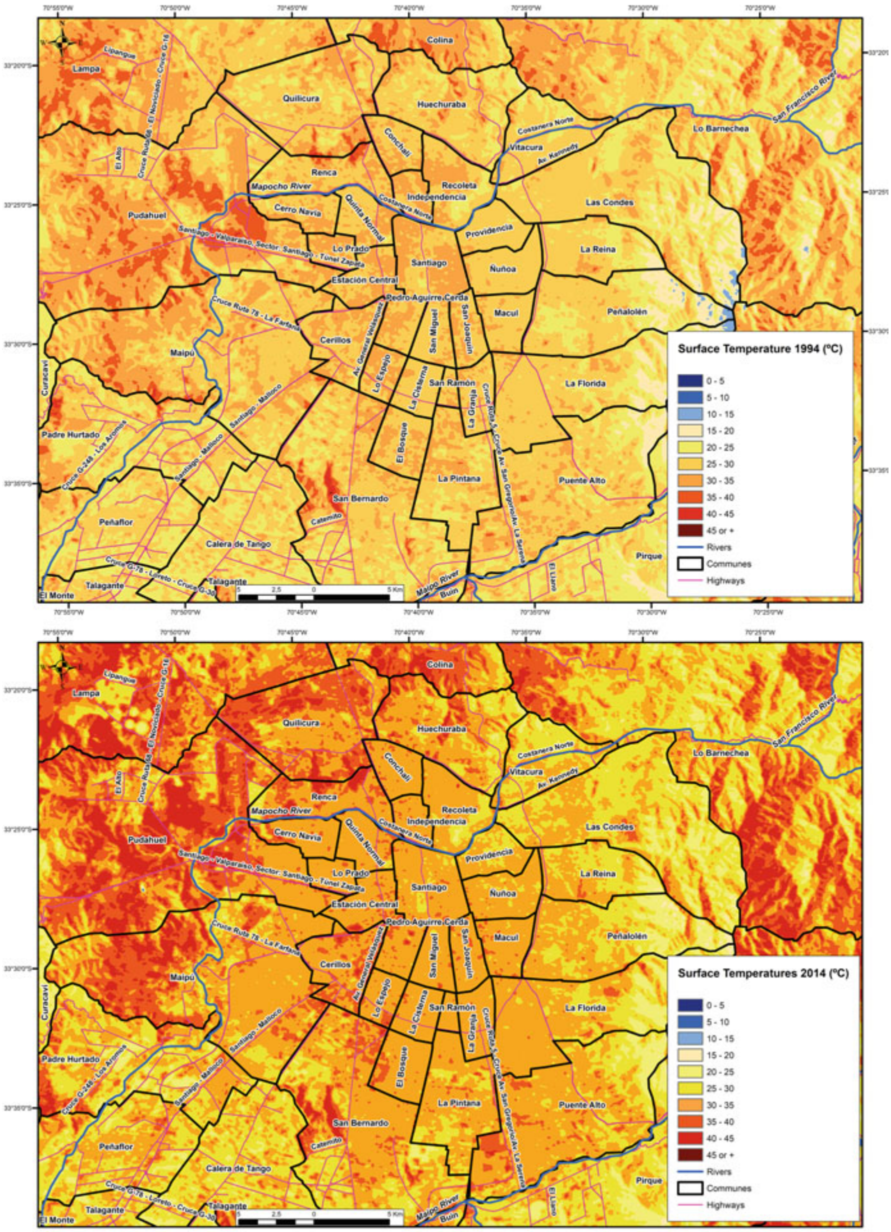

Fig. 9.3 Surface temperature of Santiago metropolitan region in 1994 and 2014. (Source: Author's own elaboration based on Landsat imagery)

Table 9.2 Surface temperature variations in 1994, 2004, and 2014

Surface temperature (°C)/year	Hectares			Variation (%)
	1994	2004	2014	1994–2014
0–5	48,639.2	47,791.3	16,515.5	−66.0
5–10	72,130.1	72,107.2	18,826.3	−73.8
10–15	117,417.9	107,325.1	31,676.3	−73.0
15–20	324,440.7	275.5	64,950.6	−79.9
20–25	509,469.0	542,596.4	192,221.1	−62.2
25–30	341,884.3	340,027.3	417,013.7	21.7
30–35	64,530.6	83,471.1	452,574.3	601.3
35–40	1,410.8	5,916.4	242,498.4	17,088.5
40+	10.4	50.6	94,834.1	904,805.5

Source: Author's own elaboration based on Landsat imagery

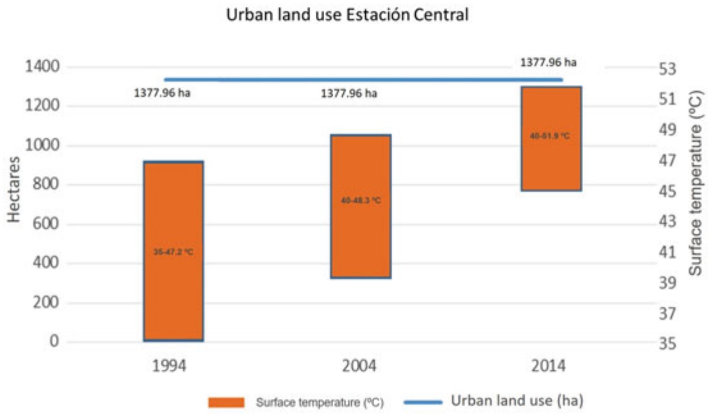

Fig. 9.4 Urban land use and surface temperature variations (hectares) in 1994 and 2014 in the Estación Central commune (consolidated compact use). (Source: Author's own elaboration)

La Pintana is another commune that corresponds to the peri-urban growth of Santiago toward rural areas located beyond the southern border. Agricultural lands have decreased from 2,136 to 1,378 hectares between 1994 and 2014, but surface temperatures have remained in the same class. However, urban land uses have passed from 1,300 to 2,100 hectares and surface temperatures have increased from 35–40 °C to 45–51 °C. Urban land uses in peripheral rur-urban areas seem to have a more conspicuous effect on surface temperatures of neighborhoods inhabited by poorer people and the product of recent urban sprawl.

Another example of a differentiated climate effect of land uses and cover changes in rur-urban peripheral areas is the Padre Hurtado commune, situated in the SW of the city of Santiago. In this case, woodland and shrub cover have been reduced, but their temperatures conserve the same range. However, the elimination of agricultural lands means an increment in surface temperatures from the 20–25° to the 25–30 °C range.

Spatial relationships between land use/cover changes and surface temperatures examined in previous paragraphs demonstrate that apart from regional environmental changes, type of variations and the nature of committed neighborhoods – either in physical or in socioeconomic terms – are important factors to take into consideration when urban climate is examined. The role of environmental changes is different in consolidated, older, and degraded areas of the city, where higher rates of densification and the lack of natural landscapes are evident. In contrast, those communes inhabited by richer people, with large green areas and low-rise constructions, are able to maintain their temperatures. Rur-urban areas, located at the southern and western sections of the city, are experiencing an outstandingly warmer process because of recent urbanization and the elimination of agricultural lands and natural landscapes.

9.3 Local Climate Zones in Chilean Cities

The concept of the local climate zone corresponds to an area of the city that, owing to its land uses, types of buildings, and vegetation cover, should be characterized by climatic conditions different from neighboring areas and consequently be subject to specific measures of adaptation and mitigation.

Chile is one of the longest countries in the world, extending for 4,329 km from 18° to 56° Southern latitudes: at the same time, it is a very narrow landscape, with an average width of only 180 km distributed between the several thousand altitude summits of the Andean chain and more than 6,000 km of coastal line along the south eastern Pacific Ocean. As a consequence, Chile presents a large variety of natural climates, controlled by latitude, oceanicity, and the aspect and height of mountain ranges. In the north, the Atacama Desert is one of the driest in the world; in the center of the country, Mediterranean-type climates are characterized by irregular rainfalls in winter, alternating rainy years with drought events. In the south, humid template climates culminate in permanent ice fields and rainforests located in western Patagonia. From a socioeconomic point of view, Chile is one of the most urbanized Latin American countries, as 89.2% of its total population (16.5 million inhabitants) lives in cities and towns. The number of people living under the poverty threshold is one of the smallest in Latin America (11%), following Uruguay (6.1%). The per capita economic income and human development figures were the highest in Latin America (US$24,170 and 0.822 respectively in 2015). These indicators are always presented as a direct result of the persistent application of a neoliberal market economy that, in the case of urban issues, has reduced the state participation on land and environmental planning. However, and in spite of a continuum and meaningful economic growth process, uneven development can be observed everywhere and particularly in terms of urban environmental landscapes. The Gini Coefficient – which represents the social distribution of income – is also the highest among the OECD countries, and as a consequence, socio-environmental segregation is still a representation of such unequal development features in all the Chilean cities. Urban climates are one of the important components of such levels of socio-environmental segregation and they have never been taken into consideration in the design and development of Chilean cities. Levels of socio-environmental segregation – and differences in urban climates – should be added to the natural climatic characteristics that can be found in cities located in the north, center or south of Chile, or along the coast, inland, or near the highlands.

Urban heat islands, cool islands, and their relationships with land use and cover were identified and classified according to local climate zones, obtained by crossing data and information provided by air photo-interpretation, rural and urban meteorological stations, and mobile measurements across morphological zones. Given the large unregulated urban sprawl process that is transforming most of the rural landscapes into urban areas in all the Chilean cities, an important desertification process of urban landscapes, increasing levels of climate discomfort, higher levels of air pollution, and the occurrence of extreme climatic events (floods, heat and cold waves) can be observed everywhere. Currently, it seems to be very necessary to incorporate urban climate research and knowledge in a renewed process of urban sustainable development, based on the integration of physical geography with social participation and involvement. However, for this purpose it is equally necessary to increase educational levels and institutional capacity, both features that are still canceled or postponed in most of Latin America.

Three pairs of cities, located at about the same latitude, and at the north, center and the southern center of Chile, have been selected to show summer season natural and urban climate variations. They are located at coastal or inland areas (Fig. 9.5, Table 9.3).

Urban spaces were classified in different local climate zones from land use and land cover maps, based on air photographs and satellite images. In most of them, temperature recorders were installed to differentiate urban climates, heat and cool islands, and their association with environmental variables such as percentages of vegetation cover, and some indicators of urban patterns such as the height and density of building areas. The adapted classification system of local climate zones is shown in Fig. 9.6.

Urban heat islands and urban cool islands were calculated by comparing the average hourly temperature recorded at one rural station with an urban station that has recorded the highest value for each city (see the location of stations in Figs. 9.7, 9.8, 9.10, 9.11, and 9.12). Additionally, temperatures were compared along selected transects that cross over different local climate zones, from the periphery to the center of each city.

There are differences in the number of local climate zones in each of the cities studied owing to the extension of urbanized areas, and the functional, environmental, and social complexity of each of them. The site, situation, and shape of cities are important differentiators of urban climates, as could be observed in the elongated coastal cities of Antofagasta and Valparaíso (Figs. 9.7 and 9.9), or in the inland square cities of Calama, Santiago, and Chillán (Figs. 9.8, 9.10, and 9.12). Concepción (Fig. 9.11) is between the two types.

Fig. 9.5 Location of the selected cities

In a long country such as Chile, regional climatology is a great determinant of urban climates. In the coastal and inland zones of Atacama Desert, at the North of Chile, vegetation is almost non-existent, and a hyper-arid environmental matrix controls the landscape. Sea-land breezes (caused by thermal contrast between cold sea surface temperatures and hot continents) become quite relevant for climatic comfort levels of coastal cities. This is the case for Antofagasta (Fig. 9.7), an elongated city of more than 15 km located on a marine terrace, bordered by the sea, and a coastal range of moderate slope and height. Annual average rainfall is around 1 mm and a series of up to 15 consecutive years without any rainfall can be

Table 9.3 Location, average temperatures, and number of measuring instruments installed in selected Chilean cities

City	Location	Latitude	Altitude (m.a.s.l)	Population	Temperature annual average (°C)		Total annual precipitation (mm)	Number of urban measuring instruments
					Rural station	Urban station		
Antofagasta	Coast	23°38′39″ S	40	309,832	17.4	19.5	1.7	9
Calama	Inland	22°27′24″ S	2,266	143,084	14.5	16.3	5.7	8
Valparaíso	Coast	33°02′21″ S	23	282,448	13.4	16.1	372.5	16
Santiago	Inland	33°27′24″ S	556	4,837,295	16.2	23.2	312.5	39
Concepción	Coast	36°49′37″ S	36	215,413	14.4	16.2	1,110	12
Chillán	Inland	36°36′23″ S	132	150,396	14.4	15.5	1,107	8

m.a.s.l. meters above sea level

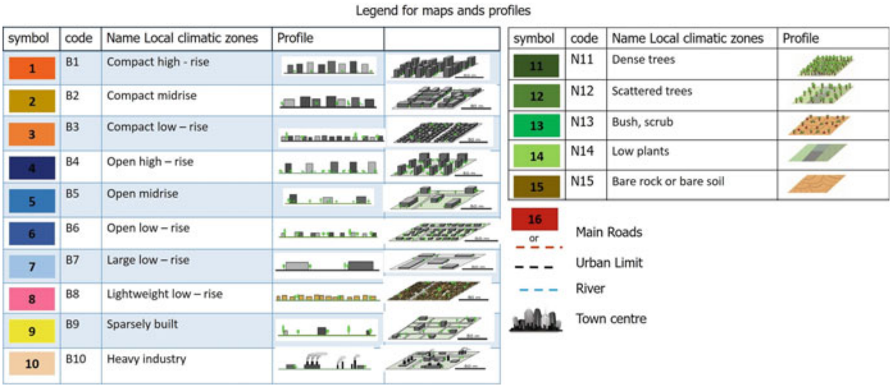

Fig. 9.6 Classification of local climate zones. (Source: Stewart and Oke 2012)

observed, as occurred between 1943 and 1958. The availability of drinking water has been a serious limitation for inhabitants, and today half the population is supplied by sources of seawater desalinization.

A set of creeks that usually do not have discharge – owing to the lack of precipitation – can activate in exceptionally rainy years. In 1910, only two events of rain account for 100 mm distributed over a few days in June (45 mm) and July (55 mm). In 1911, 64 mm fell, and 57 mm were recorded as an annual sum in 1940. In 1925, 1927, 1928, 1930, 1932, 1933, 1942, 1969, 1975, 1976, 1991, and 1992, annual amounts above 10 mm occurred. In 1991, 12 mm of rainfall caused a flood that killed several people and damaged hundreds of houses. In 2015, 20 mm were recorded in this city. The previous figures clearly indicate the occurrence of several rainy events that contradict the general belief that in Atacama Desert coastal cities it never rains. Flood occurrence should be permanently taken into consideration in the planning and development of Antofagasta and other cities located at the desert core.

Henríquez et al. (2018) has produced a series of maps about seasonal thermal amplitude and vegetation cover from a GIS based on satellite images, applied to the Chilean cities of Antofagasta and Chillán. In Antofagasta, there are three main zones from the distribution of annual thermal amplitude: The warmer north of the city, where temperature fluctuates between 15.9 and 23.2 °C; the temperate center (between 15.0 and 15.9 °C), and the cooler south, where it varies between 10 and 15.9 °C. Given the lack of vegetation, these spatial variations should be related to differential land use and cover and direct exposure to oceanic ventilation. In fact, only two small vegetation corridors are found along streets and gardens that are part of local climate zone located in the higher-income open low-rise dwellings.

In the neighboring city of Calama (Fig. 9.8), situated 200 km inland and at a height of 2,600 m, the oasis irrigated by the Loa river (the only Andean river that interrupts the arid landscapes and reaches the ocean at these latitudes), completely surrounds the urban area with bare or rocky soils. As in all the Chilean cities, a compact low-rise pattern is the predominant local climate zone. However, Calama

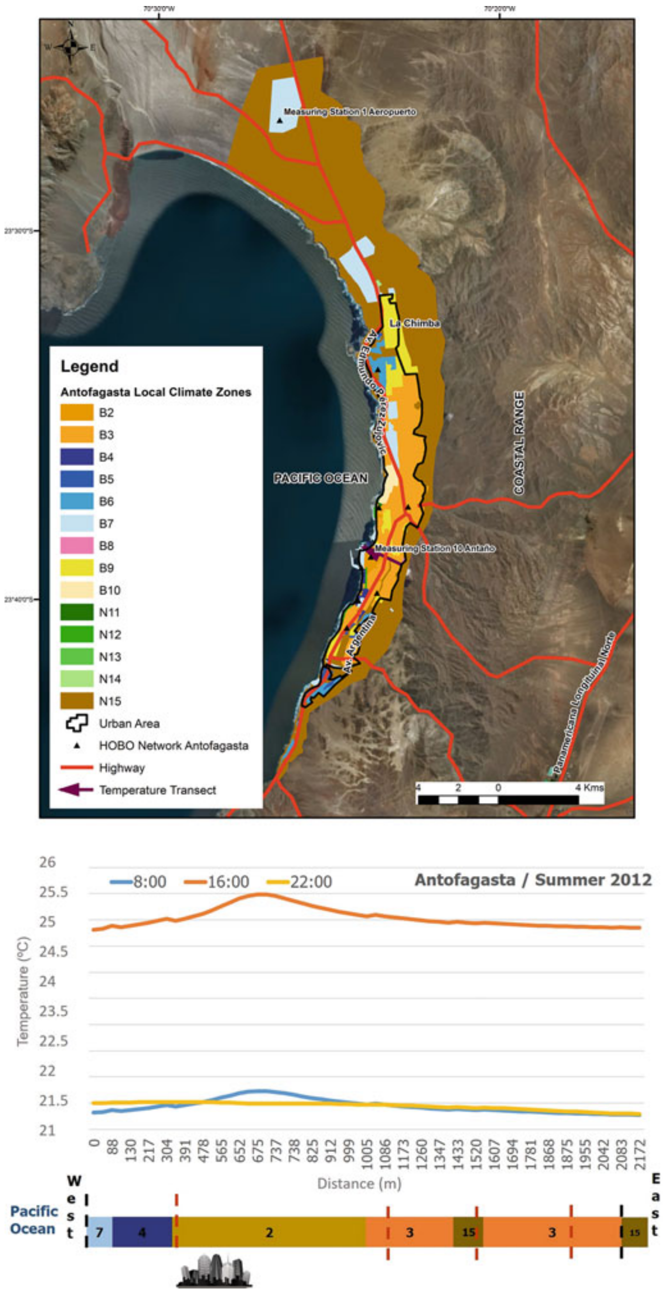

Fig. 9.7 Local climate zones and rural/urban thermal gradient in the arid city of Antofagasta. (Source: Author's own elaboration)

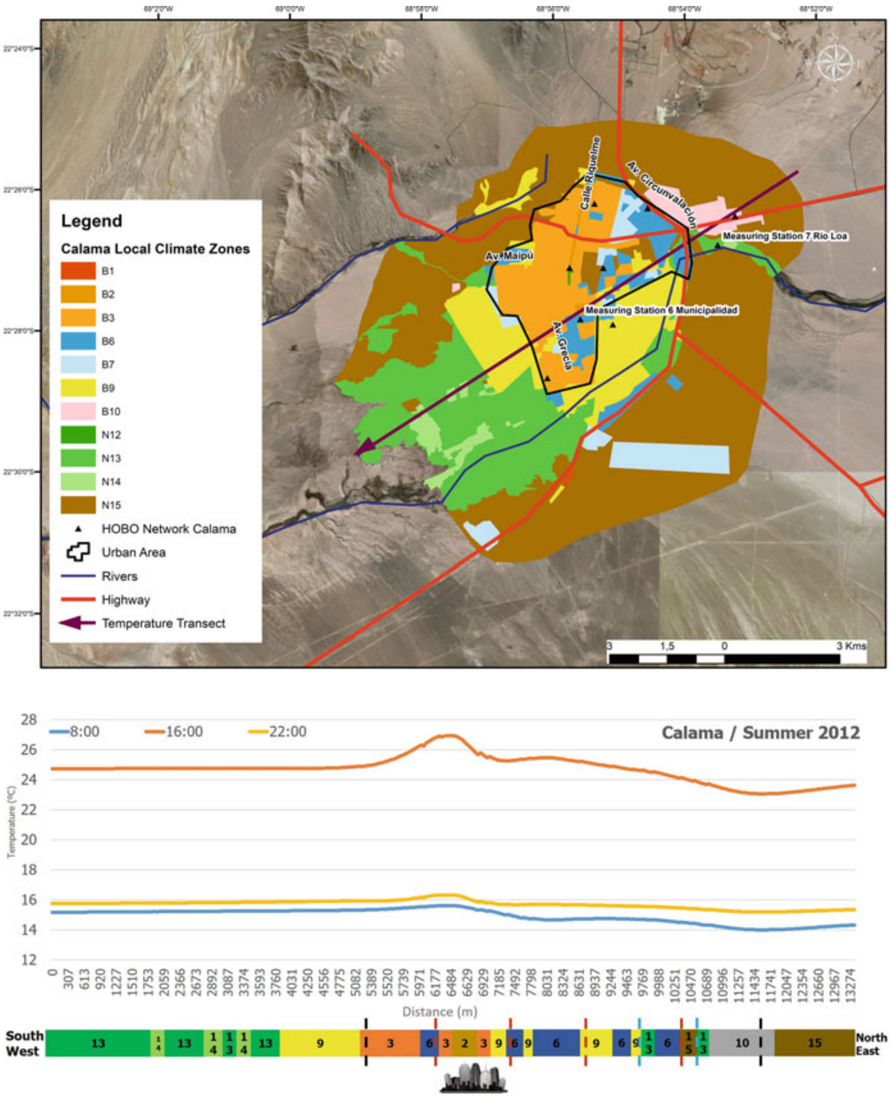

Fig. 9.8 Local climate zones and rural/urban thermal gradient in the oasis city of Calama, northern Chile. (Source: Author's own elaboration)

also includes remnants of natural and cultivated green and sparsely built areas, where farmers and higher-income families are now living. Some open low-rise homes are located along the riversides, particularly in the NE of the city, corresponding to dwellings of upper class residences.

In both arid cities, Antofagasta and Calama, only small urban heat islands are observed in summer, reaching 1 and 2 °C respectively. It is possible that these urban areas behave like cool islands throughout the day owing to the permanent presence

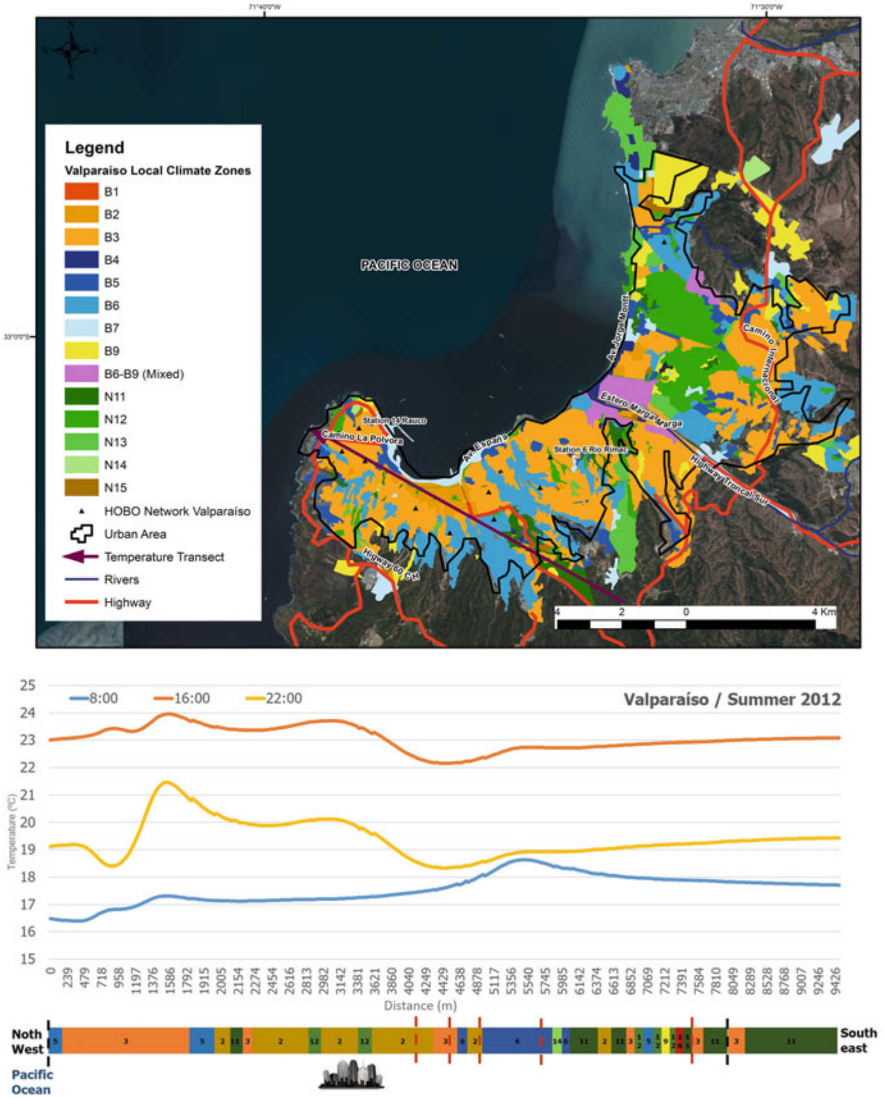

Fig. 9.9 Local climate zones and rural/urban thermal gradients in the Mediterranean-type climate coastal city of Valparaíso, central Chile. (Source: Author's own elaboration)

of warmer air masses arriving from the desert core, as is the case in numerous urban places located in arid lands.

Mediterranean regional climates, with their rainfalls concentrated mainly in the winter season, allow the development of streams, rivers, and vegetation that introduce important landscape and climatic differentiations in cities located in central

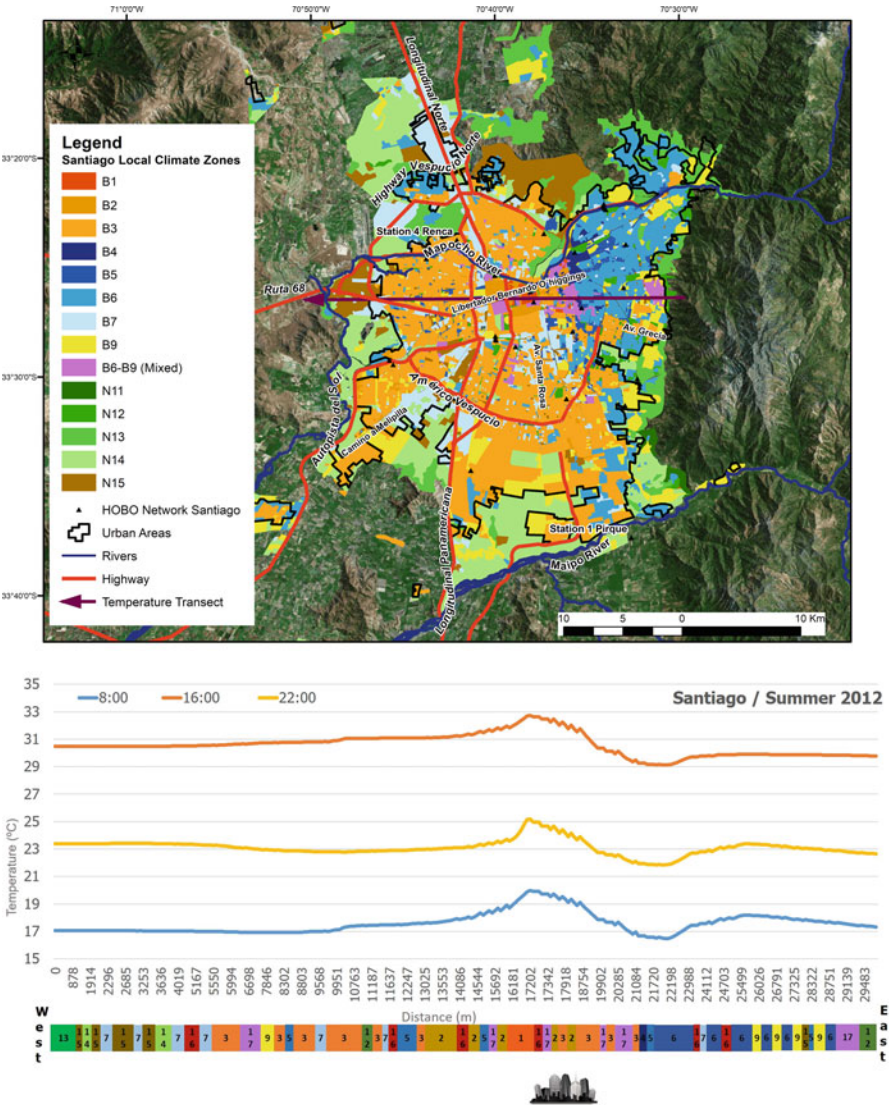

Fig. 9.10 Local climate zones and rural/urban thermal gradient in the Mediterranean-type climate inland city of Santiago, Central Chile. (Source: Author's own elaboration)

Chile and inside urban spaces of Valparaíso (Fig. 9.9), Santiago (Fig. 9.10), Concepción (Fig. 9.11), and Chillán (Fig. 9.12). Natural and agricultural lands that surround these cities generate climatic features that interfere in urban climates associated with predominantly compact low-rise built patterns.

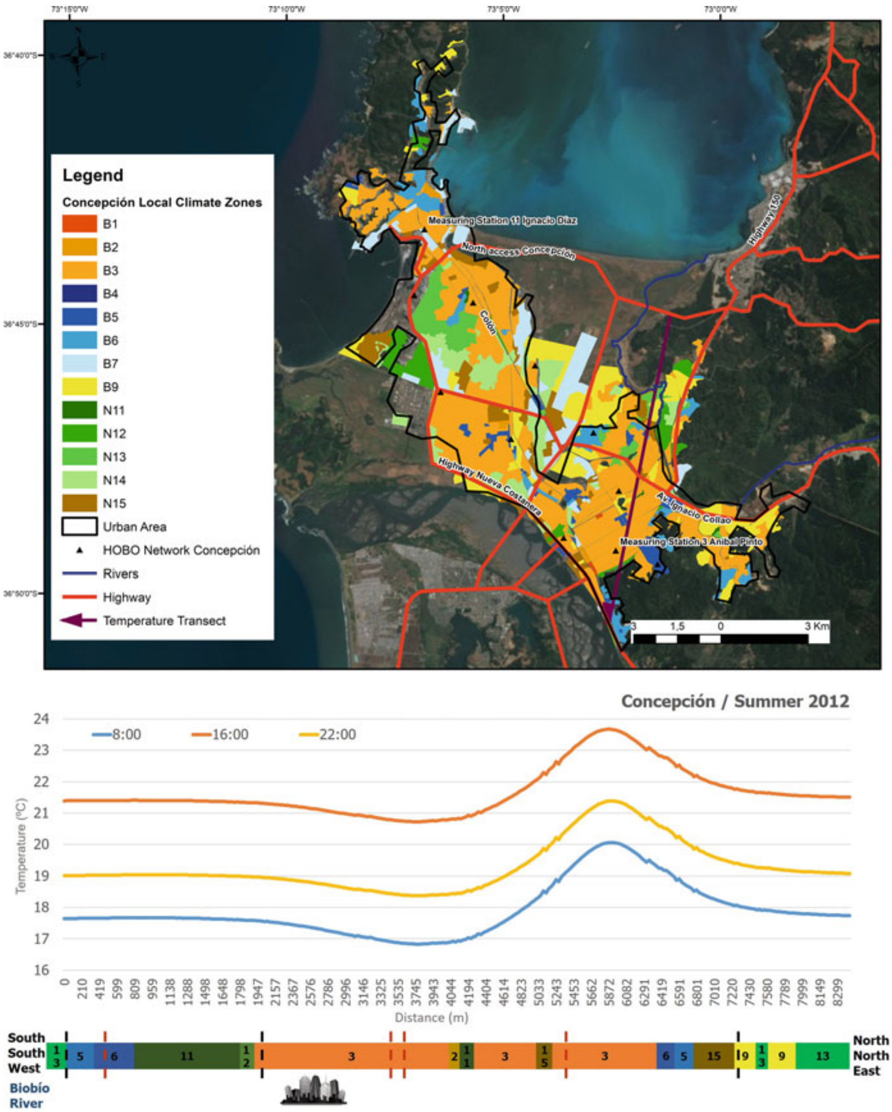

Fig. 9.11 Local climate zones and rural/urban thermal gradient on the southern border of Mediterranean-type climates, coastal city of Concepción. (Source: Author's own elaboration)

The conurbation Valparaíso–Viña del Mar is located in a series of abrasion marine terraces starting from the sea level and reaching several hundred meters in height. These geoforms are drained by numerous streams that act like water, air, and biological corridors, allowing the existence of green zones beyond and inside urban areas.

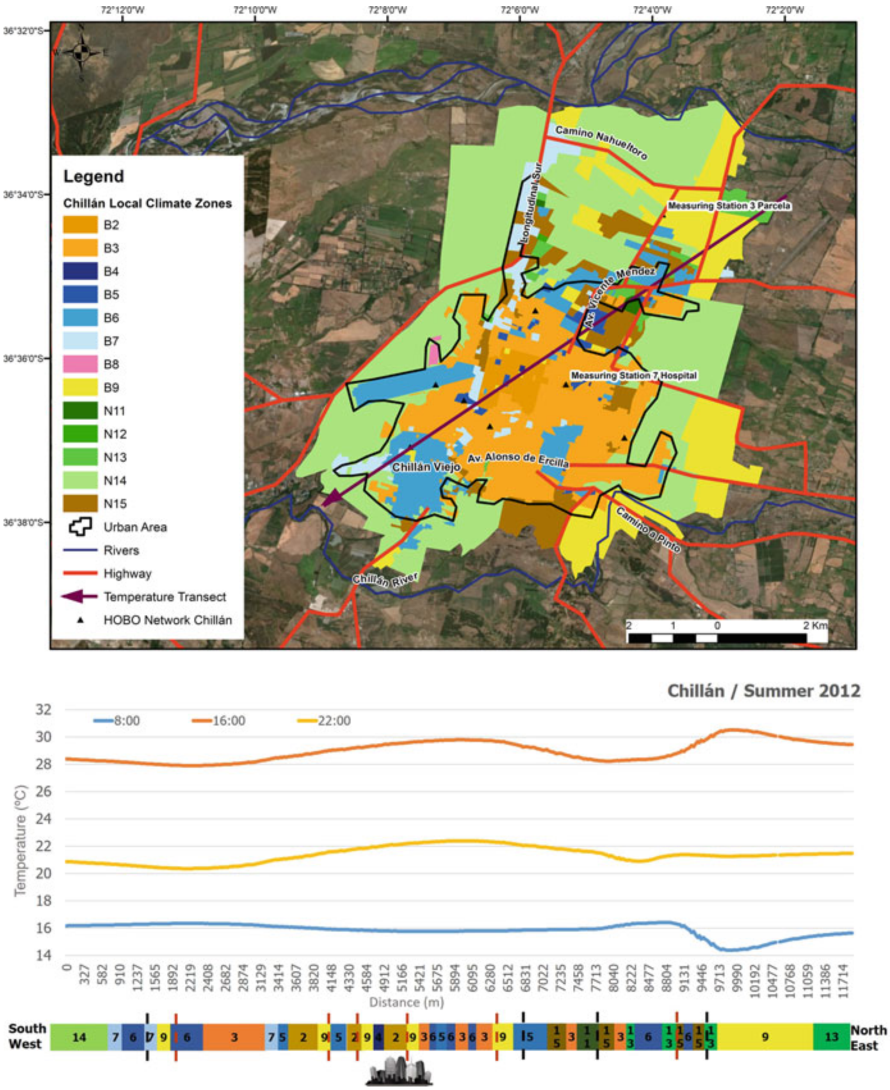

Fig. 9.12 Local climate zones and rural/urban gradient on the southern border of Mediterranean-types climates, inland city of Chillán. (Source: Author's own elaboration)

In these cities, streams and creeks and their associated riparian areas are not only usual boundaries for urban spaces, but they are also places occupied as lower-income dwellings, many in an illegal and informal way, as they are not part of urban planning and zoning. Rainy years associated with El Niño increase the amount and intensity of rainfall, causing floods and debris flows that then affect the most vulnerable people (Romero and Mendonça 2009). Between 1980 and 2000, a total of

45 storms caused 25 gradual floods and 20 flash floods, resulting in a large amount of damage. At that time, areas with a higher imperviousness ratio increased owing to the urbanization of the hills. In contrast, drought events mainly associated with La Niña years, produce landscape dryness and consequently, forest fires that equally affect the poorest people living in the hills. These fires are recorded each year, but the worst occurred in April 2014 when 1,145 ha of shrubs burned, 2,500 houses were destroyed, 11,000 inhabitants were affected and 15 persons were killed.

Figure 9.9 shows relevant differences between Valparaíso, located in the south of the area, and Viña del Mar, situated in the north of this conurbation. In Valparaíso, compact middle- and low-rise built areas predominate in lower and middle terraces, whereas in the upper hills open middle homes are located, even beyond the urban boundary. In Viña del Mar, there are still large patches of vegetated zones between the lower and upper terraces owing to steep slopes that prevent continuous urbanization. In the flat zones, where the richer people live, sparsely built areas used to predominate that during recent years are being heavily densified with middle and higher rise buildings. In the upper terrace, medium and lower class social homes correspond mainly to low- and middle-rise homes. In both cities, precarious settlements, the so-called "*campamentos*" (slums), are occupying the most hazardous places (Romero et al. 2008, 2009).

Valparaíso and Viña del Mar present a large variety of local climate zones because of their topography, represented by hills, slopes, terraces, and streams. Wind is a climatic feature that influences the degrees of climate comfort, particularly on settlements located near the sea cliffs and at the upper levels of the terraces. Owing to permanent ventilation, and interactions between the sea and the coast, only during some hours, some of the light features of urban heat islands are registered in the densest areas near the centers of the cities. However, this situation is changing faster because of a series of tall buildings that interrupt the sea-land breezes system along the coast. Small variations in urban temperatures are observed in Valparaíso mobile transects, particularly during the night and in compact low and middle urban areas, once they become distant from the coast.

In all the cities with a Mediterranean-type climate, green areas are represented by landscapes occupied by remnant crops, scattered trees and shrubs, sometimes planted forests, and even dense native woods in shaded slopes, which should constitute the basis for their environmentally sustainable development. In contrast, they are permanently degraded, burned (in Chile there are no spontaneous wood fires) and objects of economic land speculation.

In the case of Santiago, Chile's capital city, three main local climate zones are found. The first corresponds to cultivated and natural vegetation areas that still surround the city in all directions, but mainly toward the north west, south west, and south. The second feature is the absolute predominance of low- and medium-rise dwellings in the center and western parts of the city. The third zone consists of open spaces that characterize the urban pattern of most of the eastern section of the urban space. Although rural spaces are continuously disappearing in favor of urbanization (and remaining in a permanent unstable condition owing to constant social pressure and economic speculation), the city is losing permanently relevant environmental services, because every 10 years, large modifications in zoning and urban development plans continually expand urban spaces (Romero and Órdenes 2004).

In terms of differences between local climate zones distributed in the eastern and western sections of the city, they are the result of a combination of natural processes and social inequalities, demonstrated throughout the topological location of urban areas, contrasting urban designs, different densities and available spaces, and green areas. This combination clearly differentiates local climate zones between upper-class dwellings and middle- and lower-class homes and urban landscapes. In the former, residents have the option to live near the cooler and windy Andean foothills, and the latter are forced to live on the flood plains of the central and western sectors of the city, which are the climate areas where maximum thermal and humidity oscillations, lack of ventilation, and higher concentrations of air pollution are typical features.

Concepción is a coastal and riverine city with a relevant mixture of natural landscapes characterized by wetlands, current and paleo streams, a couple of large rivers that cross over the urban area (Biobío and Andalién), a series of lagoons, and a large surface of exotic forest plantations that surround the urban zones. Like all Chilean cities, compact low-rise homes and sparsely built areas are predominant urban designs. Large natural and artificial vegetation cover and the location of the city near the coast result in a temperate and comfortable regional climate and the development of small heat islands in the densest area.

Hernández (2013) has mapped the average values of Concepción's urban heat islands at 8:00 and 14:00 h for the winter and summer seasons respectively. On summer mornings, the heat island is concentrated in the historical center of the city and reaches a rur-urban difference of 4.91 °C. In winter, this difference is 3.56 °C. At 14 h, a secondary heat nucleus is observed in the historical center of the conurbated city of Talcahuano, which intensifies at 14 h. At this time, the maximum rur-urban difference is 9.14 °C in summer and 4.04 °C in winter. Local climate zones that record higher heat values are compact mid-rise and open mid-rise in both seasons.

The result of mobile transects also surveyed in the summer season shows almost the same pattern (Fig. 9.11) where a similar temperature is slighter modified by some heat island located at the densest area of the city center. However, several neighborhoods in Concepción are changing their urban designs, particularly because of the reconstruction process that followed the earthquake and tsunami that occurred in February 2010, and because of the modernization of the regional economy. Many forestry companies and industries exporting outward are building their corporate offices and dwellings in tall buildings, which are replacing traditional compact low-rise homes. Urban climate transformations in a city where sea–land and mountain–valley wind and breezes are frequently produced by recent verticalization are still unknown.

In spite of favorable climatic quality, Concepción has a polluted atmosphere during winter because of industrial emission, traffic pollution, and the use of domestic wood burners. On the other hand, the regularization and suppression of fluvial networks, wetlands, deforestation, and continuous imperviousness associated with the urban occupation of flood plains and slopes are the main causes of floods, which have caused serious damage and killed many people during heavy rainfall storms like that in 1986 (Vidal and Romero 2010; Romero and Vidal 2014, 2015; Smith and Romero 2016).

Chillán is approximately at the same latitude as Concepción, but its inland location at around 100 km from the coast introduces certain levels of continentality, which mean that this city records extreme summer and winter values of temperature. Local climate zones contain mainly natural vegetation and cultivated cover that surround the city and that allow the assumption of good quality urban climates. However, compact low-rise homes predominate in all the built-up areas of the city, with a low availability of green areas, favoring the generation of hot spots in summer. On the other hand, the installation of the city in a large flood plain under the prevalence of thermal inversion layers in the fall and winter seasons and the common use of wood heating, produce higher levels of air pollution (Romero and Vásquez 2009).

Some open low-rise neighborhoods are found in the SW, NW, and NE sections. In the case of the western pattern of urbanization, they are mainly garden houses, where old and large homes have indoor wooded yards as a demonstration of a typical countryside architecture, a remnant of colonial times, with deeply microclimatic consequences. Tree shade reduces heat, but also indoor impulse ventilation and cooling, as an example of urban adaptation to regional climates.

Unfortunately, recent denser neighborhoods of compact low-rise homes have replaced the old-style ones, losing climatic advantages and participating in the creation of extreme values. The other open low-rise zone, located on the NE border of the city represents a social appropriation by upper classes of previous rural lands and the construction of condominiums. However, this modern pattern of urbanization has a landscape dominated by grass and it does not play a meaningful climate role.

9.4 Recent Land Use Transformations in Local Climate Zones

In previous sections, land use and cover changes have been shown that form a regional framework of current urban climate transformations and their forecast, particularly in times of global changes. The present section includes an analysis of recent modifications in the composition of local climate zones that occurred between 2011 and 2017, comparing three socio-environmentally contrasting neighborhoods, located in the north west (Z1), south east (Z2), and west (Z3) zones of the border of Santiago (Fig. 9.13). Each of these zones represents a different pattern of peri-urbanization according to the social status of their dwellers: the emerging upper class in Colina; the emerging middle class and social mixture in Peñalolén, and the lower middle class in Cerro Navia (for the distribution of social classes in Santiago, see Fig. 9.14).

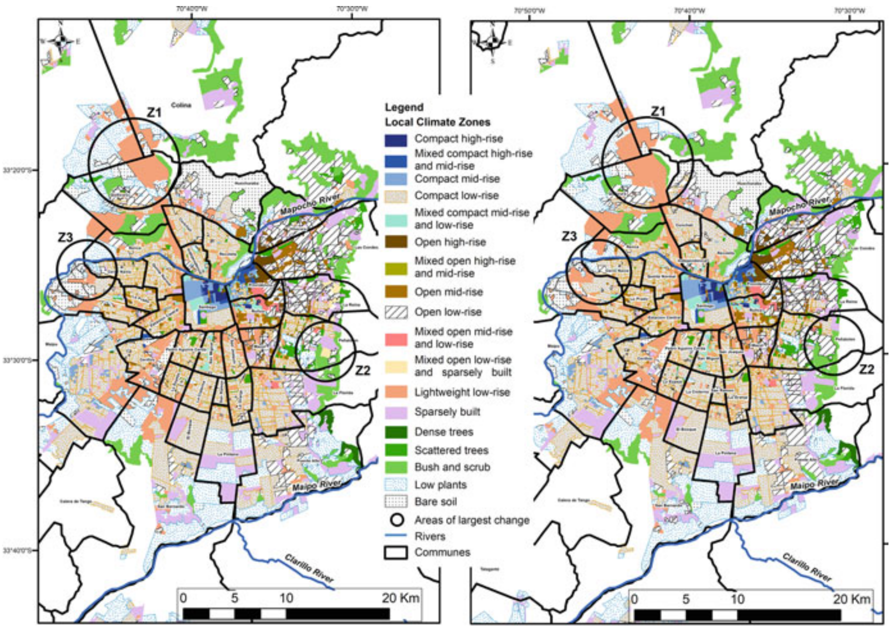

Fig. 9.13 Local climate zone changes in Santiago city between 2011 and 2017. (Source: Author's own elaboration)

The Quilicura and Colina neighborhoods, located in the north western part of the city, have been mainly older and traditional rural and countryside landscapes (crops, low plants, and bare soils) that during recent decades have begun a vigorous urbanization process (Fig. 9.15). Open low-rise dwellings, lightweight low-rise installations for new factories, storage, and the wholesale trade, are progressing because of the available land and good accessibility. Social differences are contrasting features between Quilicura, where the social compact of low-rise predominates, and Colina, where open low-rise condominiums are more common.

This part of the city could lose its amenities and environmental services if urbanization is not conducted carefully. Currently, Santiago's NW section is concentrating polluted air (particulate matter) and heat islands, climatic features that are analyzed in the next paragraphs. It is important to avoid adverse environmental effects in a zone that connects Santiago's basin with natural landscapes such as the coastal range, the Colina stream, and the Aconcagua watershed.

Peñalolén was also a peripheral urban zone located at the Andean foothills in the south eastern portion of the city (Fig. 9.16). Initially, this area was a series of large plots located in the middle of Mediterranean shrubs and native forests interrupted by streams and creeks descending from the Andes chain and supplying many environmental services such as clean air, superficial and ground water, biodiversity corridors and refuges, recreation sites, and a beautiful panorama of mountainous landscapes that surround Santiago. During recent years, a large socio and natural transformation

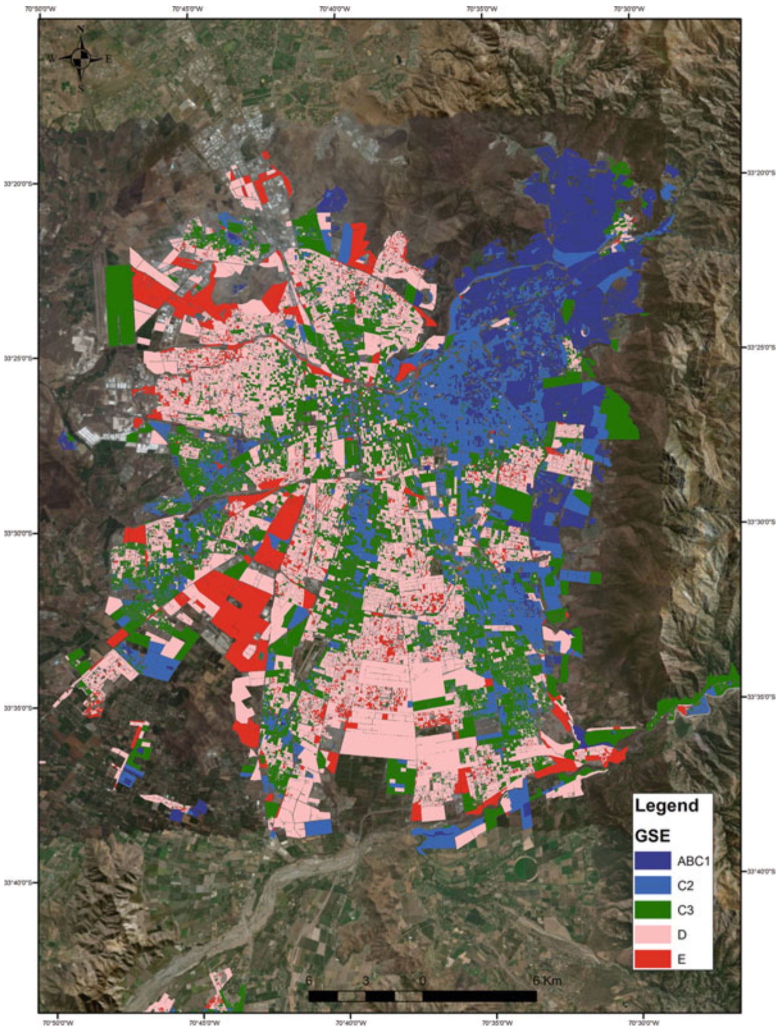

Fig. 9.14 Classification of socioeconomic groups of Santiago. (Source: IDE OCUC n.d.)

has taken place pushed by urban occupation for upper- and medium-class inhabitants. Open low-rise condominiums have been built over areas previously covered with shrubs, native forests, and some pasture lands. Unfortunately, environmental protection measurements are very slight and urban development is not properly assessed from an environmental point of view and climate terms. It is expected that this urban growth process oriented toward the upper part of the Andean foothills will continue in the near future if institutional regulations and social contestations are not introduced. There are pressures to elevate the urban boundary and to allow the construction of high buildings on steep slopes. The area is a place where many floods have occurred during the last few decades, and a large part of it is

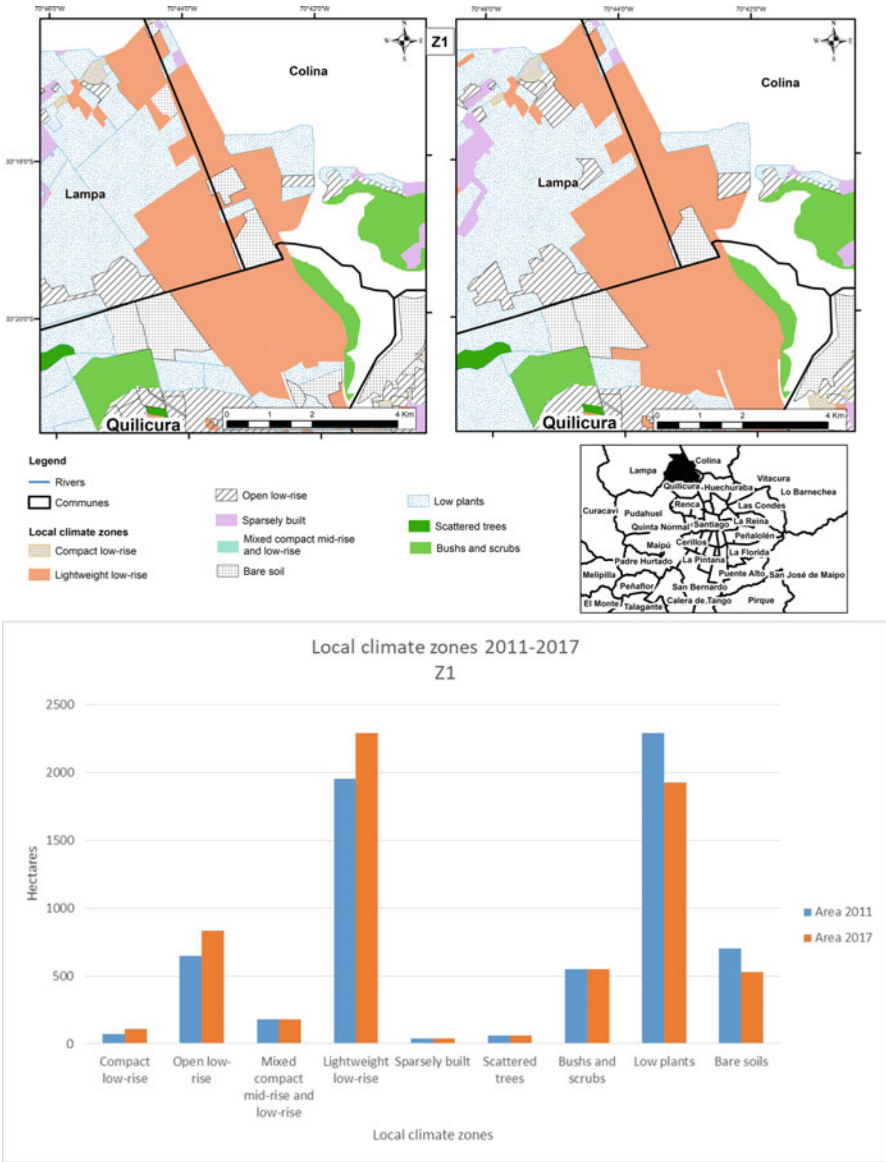

Fig. 9.15 Comparison of local climatic zones changes (ha) in peri-urban areas of Quilicura and Colina (north west of Santiago between 2011 and 2017). (Source: Author's own elaboration)

located over a dangerous geological fault and earthquake source. Climatically, numerous air corridors are set up along streams and creeks that connect the mountain summits with flood plains, transporting cooler and clean air, which is probably one

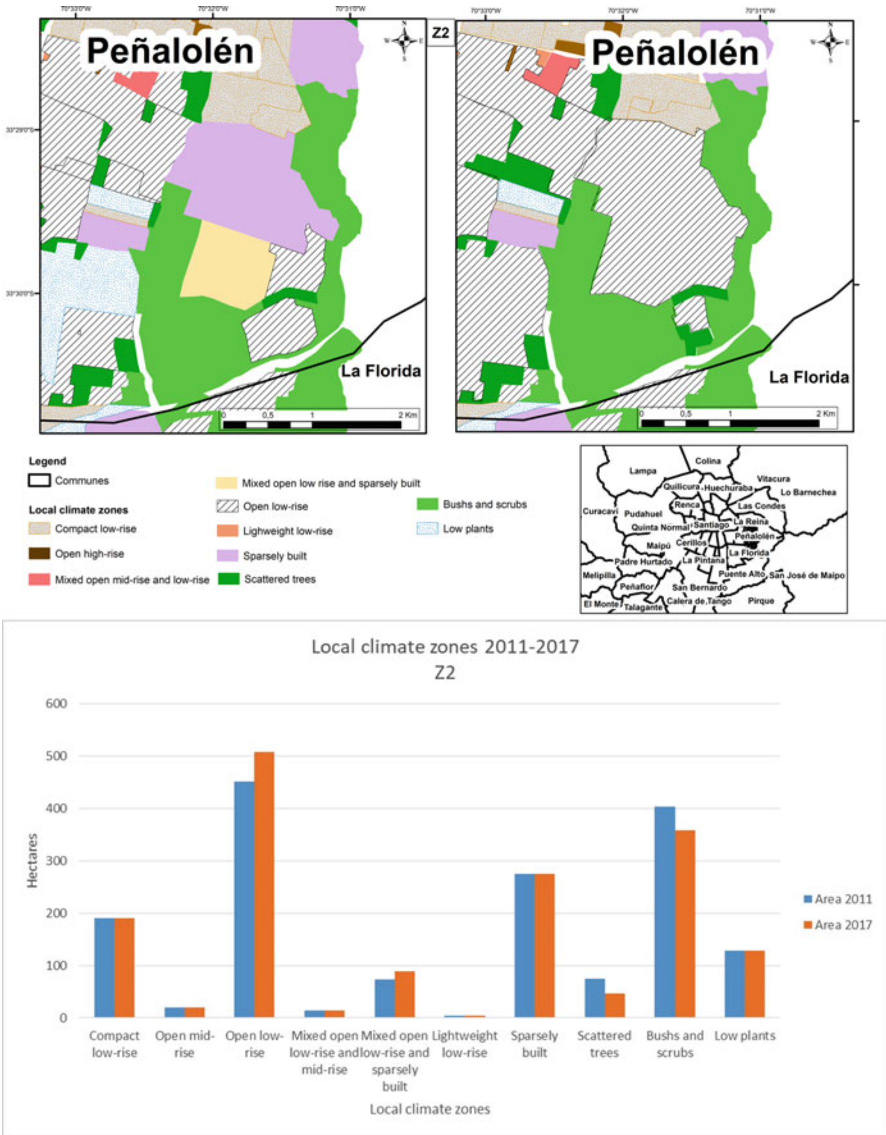

Fig. 9.16 Comparison of local climatic zone changes (ha) in peri-urban areas of Peñalolén (south east Santiago between 2011 and 2017). (Source: Author's own elaboration)

of the most valuable ecosystem services that millions of citizens living in the Chilean capital city receive from this natural landscape.

Cerro Navia is a much older and lower medium-class neighborhood located on the western border of the city. Local climate changes (Fig. 9.17) are mainly caused by the transformation of bare soils and land with scattered vegetation by compact low-rise dwellings, lightweight low-rise storage, and wholesale trade installations.

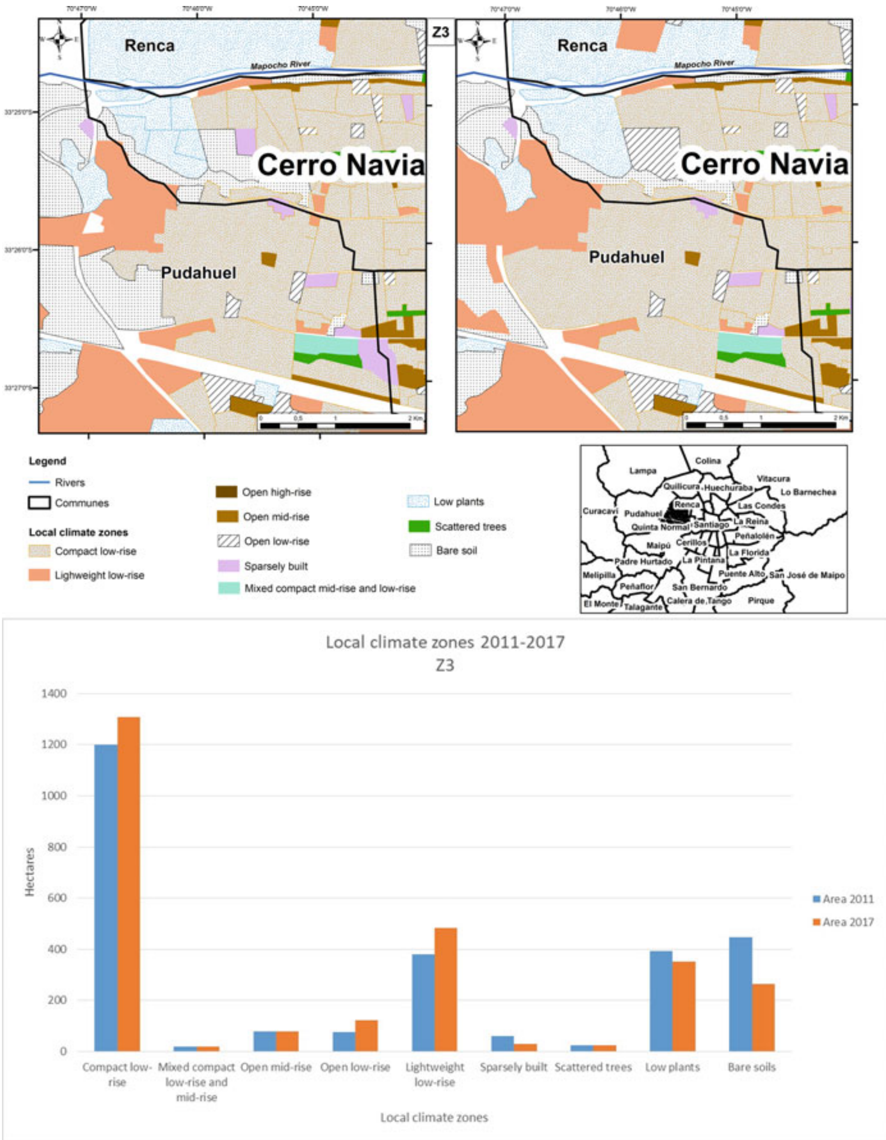

Fig. 9.17 Comparison of local climatic zones changes (ha) in peri-urban consolidated areas of Cerro Navia (western Santiago) between 2011 and 2017. (Source: Author's own elaboration)

Cerro Navia currently concentrates a series of environmental issues related to poverty, air pollution, and heat islands, representing a combination of geographical features that characterize most urban areas in Chile. This neighborhood should show a series of initiatives to improve its current environmental state. However, local climate zones show a worsening of previous conditions that will draw the attention about political and social commitments to reach authentic urban sustainable development in Chilean cities.

Concluding this section, most of the local climate zone changes do not represent progress toward climatic and environmental improvements. It seems that announcements in terms of the national contribution to controlling global climate change are concentrated on rhetorical declarations about decarbonization, but not necessarily on practical measures that improve the daily life of an increasing number of more concerned citizens.

9.5 Heat Islands in Santiago de Chile

During summer (January, for example), in the city of Santiago in earlier morning, the main urban heat island can exceed 21 °C. Specifically, in the south of the city with a prolongation to the north, following an elongated shape framed by rural areas by the West and Andean chain foothills by the eastern side (Smith and Romero 2016). At this time of the day, the southern section of the urban heat island is larger and compact, setting up a very different climate in respect to urban areas that extend from Vicuña Mackenna Avenue toward the east, where the development of a decreasing temperature gradient is found. Temperatures at the Andean foothills are around 3 °C lower at the border of the urban space. At this time, the core of the urban heat island is more than 6 °C.

In the earlier afternoon, the configuration of the urban heat island is quite different, migrating toward the north of the city reaching an average of over 30 °C and with maximum values over 33 °C. Temperatures in the southern rural areas and at the Andean foothills are lower, between 5 and 11 °C, advecting cooler air from rural areas, especially over the southern part of the city. In the center, the main three large public parks (O'Higgins, Quinta Normal, and Metropolitan of San Cristóbal Hill) are playing their role as cool islands (Smith and Romero 2016).

During the night, the urban heat island covers most of the city, with temperatures between 20 and 24.6 °C, transferring to the air the ground-accumulated heat during a complete sunny day, like most of them during this season in Santiago. Cooler rural areas of the south western corner are spatially reduced, and the zone of lower temperatures located at the Andean foothills disappeared (Smith and Romero 2016).

Smith and Romero (2016) have compiled urban climate data from several sources to analyze summer heat islands in Santiago. Using conventional meteorological stations, thermal points, and mobile transects of measurements, they have obtained temperature values from multiple regression models, using like explanatory variables emission surface temperatures, vegetation cover, and ground imperviousness rates. A 100% vegetation cover can reduce the air temperature to 1.5 °C after lunch in summer (Table 9.4). Conversely, a 100% imperviousness rate can increase air temperature over 0.6 °C in summer mornings and afternoons. Public parks like San Cristóbal Hill can generate a cool island of around 4 °C, demonstrating the capability of green areas to moderate urban heat islands in Mediterranean dry-type climates (Table 9.5).

Table 9.4 Effect of vegetation, waterproofing, and height on the air temperature in Santiago

	100% vegetation cover	100% impermeable surface	Temperature difference every 100 m in height
Morning	−0.5 °C	+0.6 °C	−0.1 °C
Afternoon	−1.5 °C	+0.4 °C	−0.1 °C
Night	−0.58 °C	+0.64 °C	N/A

Source: Smith and Romero (2016)

Table 9.5 Effects of vegetation cover and impermeable surfaces over an equal atmospheric temperature at 30 °C in the city of Santiago

Vegetation cover	Impermeable surface	Morning	Afternoon	Night
Percentage (%)		Temperature (°C)		
100	0	29.5	28.5	29.4
75	25	29.78	28.99	29.73
50	50	30.05	29.45	30.03
25	75	30.3	29.93	30.34
0	100	30.6	30.04	30.64

Source: Smith and Romero (2016)

Given the fact that heat islands are relevant climate features in Santiago, they should be related to land and housing prices. Irarrázaval (2012) has advanced the knowledge of the commodification of urban climates in Santiago. Working on an eastern–western transect that crosses over the totality of the city, he considered socioeconomic inequalities that characterize Latin American urban spaces in general. For this purpose, he examined the commercial price of homes and tall building apartments located in different local climate zones. The most expensive homes, belonging to the best climate quality, were open low-rise condominiums and scattered homes located mainly in the eastern section of Santiago; they can cost up to 12 times more than those situated in the western part of the city, under the worst climates. Of course, it is not possible to separate the portion of that price that could be attributed to the local climate zone from the size, accessibility, and social status of neighborhoods where the homes are situated. In the case of apartments, prices varied by around ten times.

Selecting a series of new urban development projects under construction or sold that year, Irarrázaval (2012) observed the environmental representations of each of the local climate zones in terms of beautiful landscapes (clean air, clear skies, and plenty of vegetation) that web pages and brochures distributed by development companies use to get buyers. Commodification of climate features can mean the falsification of reality and the private appropriation of common goods such as climate.

9.6 Heat Waves in Santiago, Chile

Used to dealing with average values regarding urban climates, extreme events such as heat waves and cold waves have scarcely been studied by Chilean climatologists. In terms of cold waves, a series of very low temperatures were recorded in most of South America in July 2010 (Romero and Mendonça 2011; Mendonça and Romero 2012). At least 5 days of Antarctic cold air masses covered the continent and caused the deaths of several persons, particularly in the human settlements of Bolivia and the Peruvian highlands. Argentina, Chile, and Paraguay also reported deaths and Brazil reported the devastation of tropical crops and livestock, even in Mato Grosso and Amazonia. In the south of Brazil, cold waves occurred in 1955, 1957, 1965, 1975, 1984, 1988, 1991, 1994, 1996, 1999, 2000, 2004, and 2010. In Chile, press releases indicate that around 100 homeless people died during winter 2010 as a consequence of the cold wave.

The same lack of information characterizes the opposite, i.e., the occurrence of exceptionally hot days that severely affect society mainly in tropical and subtropical cities. Sant'Anna Neto and Riboli (2016) indicate that the impact of heat waves on environmental and thermal comfort is one of the issues that most affect the quality of daily life in Brazilian cities.

Urban climate waves, either cold or warm, are another source of suffering for poorer people in Latin American cities. More affluent people can afford their dwellings to be heated or cooled in a healthy and safer way and their neighborhoods own enough urban equipment, such as tree shade or outdoor facilities. Conversely, people living in poorer areas, for example, in the cooler southern regions in Chile, heat their houses with wood fire in precarious burners, which explains the higher air pollution that records medium-sized and small cities such as Chillán, Temuco, Osorno, and Coyhaique. It is evident that Latin American cities, dwellings, and devices are not adapted to extreme climate events in the entire region.

During the month of January 2017, different cities and regions of the central southern section of Chile recorded intensive, spatially extensive, and unusually long-lasting heat waves. On Wednesday, 25 January of that year, the meteorological station located in Quinta Normal, near the historical center of Santiago, registered a maximum temperature of 37.4 °C at 16.31 h, which was the highest value historically observed in such a place. This temperature was part of two successive hot events, which correspond to what national meteorologists call a heat wave: the first lasted for 6 days – between 16 and 21 January – and the second for 4 days, between 24 and 27 January. During those successive days, the maximum daily temperatures were higher than 32.4 °C (Fig. 9.18), which is the threshold established by the Chilean National Weather Service (DMC) as an indicator of the occurrence of a heat wave in the city of Santiago, if such a maximum temperature is exceeded for at least 3 consecutive days. In this case, 3 days of lower temperatures that occurred between the two hot events, recorded maximum values also above 30 °C, influencing citizen perception and mass media assessment that climate change is affecting Santiago city.

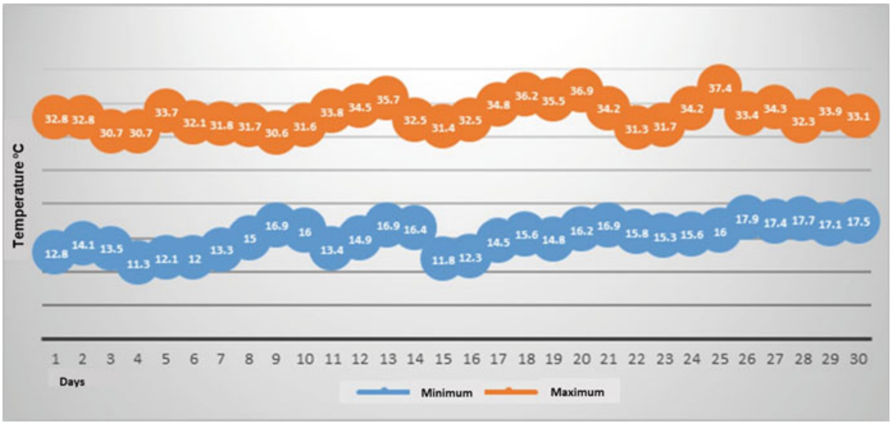

Fig. 9.18 Maximum and minimum daily temperatures recorded in January 2017 at Quinta Normal in Santiago's Heat Waves. (Source: Chilean meteorological service)

Heat wave occurrences seem to be rare climatic events in Santiago, but this generalized perception is contested, given the fragility of social memory in climatic terms. In fact, moderate climate is a characteristic of Chilean cities in general and of Santiago city in particular because the effects on the thermal conditions caused by the proximity of the Andes mountain chain (which provides cold air masses that regularly descend from its slopes during the nights and dawn through mountain–valley circulation). Additionally, the cold sub-Antarctic waters of the Humboldt Current, which reaches the Pacific Ocean coastline, located just 100 km away from the Chilean capital city, also have an influence. Both facts together constrain the occurrence of any prolonged hot event and generate cooler summer nights all year round.

However, what has predominated in Santiago's urban climates is the occurrence of two, three or, in the worst case in terms of discomfort, four consecutive days of higher temperatures, as happened on 8, 9, and 10 February 2012, and between 1 and 4 March of the same year. Hot days also occurred on 27, 28, and 29 December 2013 and on 8–11 and 24–27 January 2015. Exceptionally, five or six consecutive hot days have been recorded, such as between 24–28 December 2015 and 19–24 February 2016.

The most recent prolonged heat wave, in addition to the extensive geographic area that it covered, constituted a surprising environmental disturbance that has acted as a trigger for the occurrence and enhancement of disastrous forest fires in rural areas and the destruction of several human settlements in regions with Mediterranean-type climates located to the south of Santiago. Specific effects of this situation on the health and well-being of the inhabitants of the cities are unknown, but it is clear that it resulted in significant risks, uncertainty, and thermal discomfort for most of the Chilean population.

Conditions of thermal discomfort and associated forest fires were extreme in and around other central Chile cities that registered maximum temperatures above 35 °C.

Wood fires consumed more than 547,000 hectares of native forests and plantations – especially pine and eucalyptus – and affected agricultural crops, fruit trees, vineyards, and hundreds of homes unscrupulously located in these areas.

These facts promoted a generalized feeling of uncertainty and defenselessness in Chilean society, including the government authorities, who announced that they were overwhelmed by the magnitude and persistence of such events. Affected communities demanded more specific actions and various public and private actors questioned the quality and opportunity of the public institutions responsible for protecting forests and settlements. Consequently, a supposedly natural hazard with large social effects triggered a socioecological disturbance very similar to such issues experienced in the wake of the earthquake and tsunami that affected central Chile on 27 February 2010. At that time, the national society indicated that it felt defenseless because of the failure of public services in charge of civil protection against disasters (Romero 2010, 2014).

These occasions, which politicized environmental issues, clearly show the social and political scope of socio-natural disasters such as heat waves associated with the occurrence of forest fires. At the same time, they could indicate valuable opportunities to introduce social and political reflections that, in turn, should promote educational, civic, and institutional reforms that are essential if these events are going to continue, repeat or increase because of global, regional or local climate changes. Urban climatology must contribute to the recognition that noticeable spatial and temporal variabilities of climates are becoming part of daily urban life, forcing the enactment of adaptation and mitigation measures, such as land use planning, appropriate urban designs, and adequate construction materials.

Among emerging questions, some relate to the identification and classification of scarce existing information, to demonstrate whether, because of faster and generalized urbanization, there is an increase in the number, frequency, and magnitude of heat waves in Chilean cities. Another emerging question concerns local causes that could complement the forecasts of global warming associated with the so-called climate change, such as heat accumulation caused by the size, shape, and functions of urban spaces that have resulted from an unlimited growth of dwellings and buildings and heavy densification that have taken place without any consideration of the environmental consequences. If existing urbanization trends continue in the near future, and changes from natural to artificial landscapes are accentuated, socio-natural disasters – such as the heat waves that caused tens of thousands of deaths in European cities in 2003 – can increase their frequency and magnitude in Latin America.

Table 9.6 shows daily maximum temperatures recorded during the last heat wave at a set of observation points installed in different communes or municipal neighborhoods in the interior of Santiago city. It shows that most of these urban areas registered values somewhat lower than those recorded in the official meteorological station of the city, which corresponds to an old park (Quinta Normal) located near the historical center. This information illustrates the spatial variability of climate data observed in different places in the city, highlighting the particular character and heterogeneity of urban climates in the so-called local climate zones

Table 9.6 Maximum daily temperatures recorded in Quinta Normal (Santiago) and differences within a set of neighborhood observation points (Hobo) between 17 and 26 January 2017

Neighborhoods days	Quinta normal DMC	Quinta normal (Hobo)	Pirque (Hobo)	Recoleta (Hobo)	San Bernardo (Hobo)	Renca (Hobo)	Santiago (Hobo)	La Florida (Hobo)	Maipú (Hobo)	San Miguel (Hobo)	Ñuñoa (Hobo)
17/01/2017	34.8	1.01	−1.53	−0.28	−0.61	0.26	−0.13	−1.03	−0.26	−0.77	−0.28
18/01/2017	36.2	0.8	−1.68	−0.31	−0.82	0.33	0.08	−1.14	−0.39	−0.84	−0.47
19/01/2017	35.5	0.54	−1.42	−0.31	−0.65	0.31	−0.07	−0.92	−0.28	−0.72	−0.34
20/01/2017	36.9	0.25	−1.89	0.15	−0.45	0.02	−0.1	−1.46	−0.52	−1.23	−0.38
21/01/2017	34.2	0.67	−1.27	−0.23	0.52	−0.12	0.19	−0.87	0.17	−0.81	−0.3
24/01/2017	34.2	0.52	−1.18	−0.26	0.28	0.08	0.11	−1.11	0.23	−0.79	−0.35
25/01/2017	37.4	0.12	−1.71	−0.02	−0.71	−0.14	−0.38	−1.72	−0.61	−1.45	−0.66
26/01/2017	33.4	0.26	−0.92	0.32	−0.66	0.22	−0.02	−0.92	−0.33	−0.81	−0.19
27/01/2017	34.3	0.44	−1.03	−0.29	−0.8	0.15	−0.16	−1.03	−0.41	−0.88	−0.22

Source: Central official meteorological station

(LCZs) (Stewart and Oke 2012; Romero et al. 2015; Smith and Romero 2016), which have been dealt in detail in a previous section. LCZs consist of a complex mosaic of urban forms whose climatic conditions constitute a synthesis of temperature, humidity, and ventilation caused by the uses and covering of lands, and the design and materiality of constructions. The issue is, however, that punctual observations obey some more specific local or micro-climatic urban features that prevent spatial generalizations. A survey of the landscapes surrounding a series of meteorological stations within Santiago city demonstrate the role played by vegetation in moderating temperature values.

Historical records of the number of summer heatwaves in Santiago can be reviewed in Chap. 11. The latter years (2015–2017) registered the hottest waves in data observed in all urban available stations (Fig. 9.19). Heat waves and hot days in summer are then a frequent feature of Santiago climates that could be interpreted as a combined result of regional and urban climates that requires special attention.

In spatial terms, hot days registered in the historical center of Quinta Normal also occurred in other neighborhoods of the city, which is an illustration of the geographical extension of such events in the urban area. The heat wave observed in the center of the city on 5, 6, and 7 January 1977 reached Santiago's International Airport and Cerro Calán, both places located at that time more than 10 km beyond the western and eastern boundaries of the city respectively. Although most heat waves cover the entire city, there are events in which some of the places record a significantly larger number of hot days compared with the rest of the city. Such is the case of Cerro Navia, a lower- and medium-class neighborhood located in the west end of the city

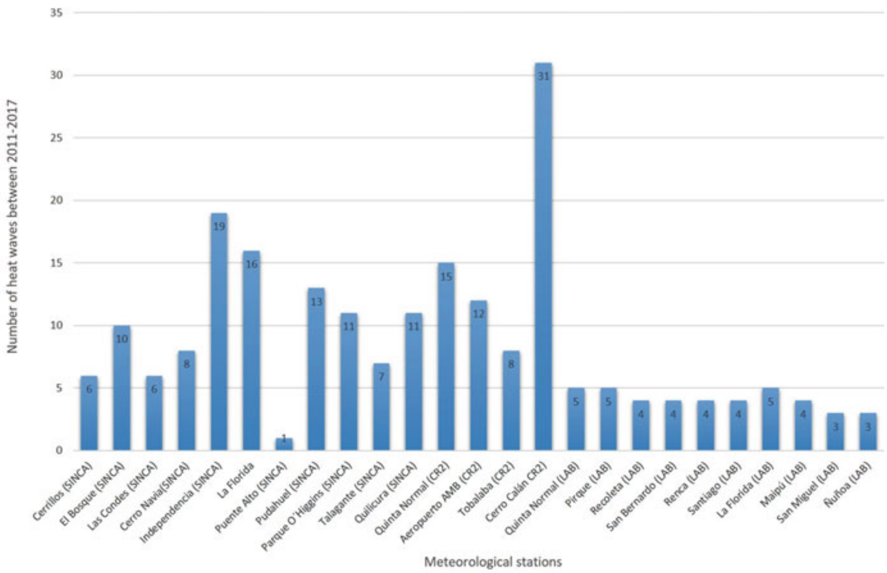

Fig. 9.19 Total number of heat waves in Santiago's neighborhoods between 2010 and 2017

that registered 13 continuous hot days between 1 and 13 January 2005. The neighborhood of Independencia, a similar social area, located on the western border of Santiago's historical center, recorded 12 consecutive hot days between 18 and 29 December 2009, and 8 days between 24 and 31 January 2015. Las Condes, a neighborhood located in the eastern section of the city, and where the upper class use to live, recorded 10 continuous hot days between 1 and 10 February 2012. La Florida, a middle-class area located on the southeastern border of the city, recorded 12 hot days between 12 and 20 March 2015.

January, February, and March 2015 were particularly hot months in Santiago. In January, heat waves spread between 8 and 12 and 24 and 28. In February, it was between 11 and 13, and in March, between 9 and 12, with some slight daily variations in certain places. In January 2016, stations of Cerro Calán and Independencia recorded six consecutive hot days (15–20), whereas in the rest, the amount of days decreased to four (La Florida and Quilicura) between 15 and 18. In February of that year, Cerro Calán registered seven consecutive hot days (between 19 and 25), which reduced to six in the rest of the stations that registered them.

The geography of the distribution of the heat waves in different Santiago's neighborhoods presents complex and different patterns owing to the huge variability of local meteorological and urban factors. As seen in the Fig. 9.20, Cerro Calán, located on an isolated hill highly exposed to solar radiation in the east of the city, recorded the highest number of heat waves: 31 in the period 2010–2017. It is followed, but with considerably fewer events, by the neighborhoods of Independencia, Quinta Normal, and La Florida. All of them occupy a peripheral position with respect to the historical center of the city. The former two are older neighborhoods, but La Florida has developed since 1980. Zones that record the least number of heat waves are located

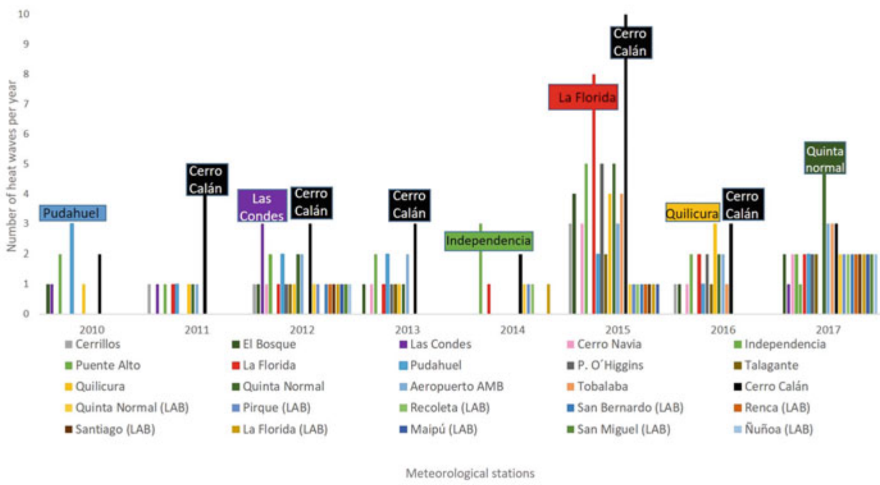

Fig. 9.20 Number of heat waves per year in Santiago's neighborhoods between 2010 and 2017

mainly at the southernmost outskirts of the city (Puente Alto, San Bernardo, and Pirque, or under particular topoclimatic features in pericentral areas such as Recoleta, Ñuñoa, Renca, Maipú, and San Miguel communes.

Spatial coverage of the number of days affected by heat waves occurred in Santiago between 2010 and 2017 showed that Cerro Calán measurements and the year 2015 appear to be exceptional events (Fig. 9.20).

Taking into consideration the elevated spatial and temporal variability of heat waves in Santiago city, the following figures are a representation of absolute maximum temperatures and average values for the period 2010–2016. Figures 9.21, 9.22, and 9.23 ratify that maximum temperatures are mainly a geographical punctual fact that responds to particular features such as large compact high-rise buildings of the modern commercial district located in the Vitacura neighborhood, large parking zones in the main national football stadium, or large shopping centers in Ñuñoa, and Macul, in addition to the landing track of the older Los Cerrillos airport.

Summer average values confirm the presence of some hot and cooler spots. In the case of the warmer area of the north eastern part of the city, it seems to be the result of modern and compact high-rise buildings occupied by international corporations. This warmer zone interrupts an area, that for the previous decades, belonged to cooler climates that characterize this eastern section of Santiago.

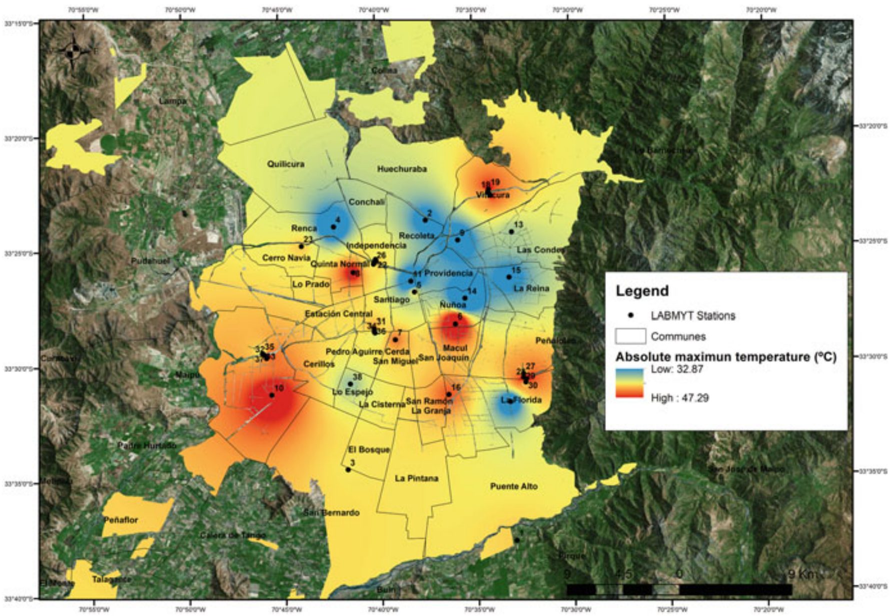

Fig. 9.21 Absolute maximum surface temperatures recorded in Santiago's neighborhoods between 2010 and 2016. (Source: Chilean National Weather Service, National System of Information on Air Quality, and the Laboratory of Environment and Territory, University of Chile)

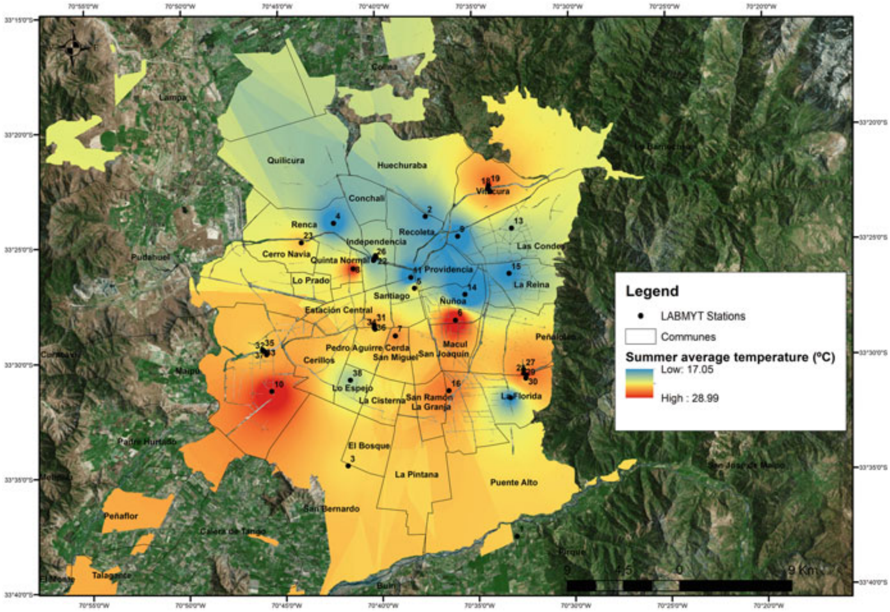

Fig. 9.22 Summer average temperatures recorded in Santiago's neighborhoods between 2010 and 2016. (Source: Chilean National Weather Service, National System of Information about Air Quality and Laboratory of Environment and Territory, University of Chile)

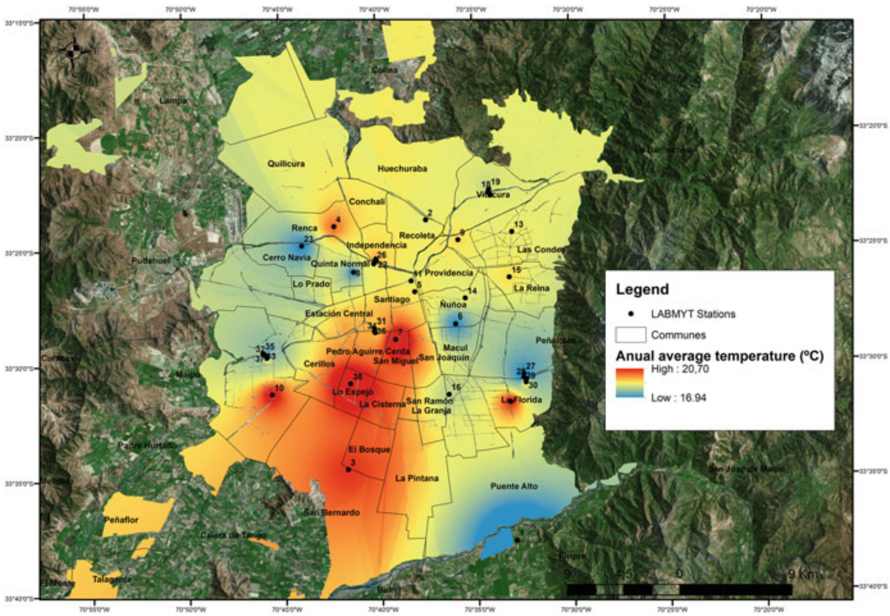

Fig. 9.23 Annual average temperatures recorded in Santiago's neighborhoods between 2010 and 2016. (Source: Chilean National Weather Service, National System of Information about Air Quality and Laboratory of Environment and Territory, University of Chile)

A cooler zone is represented by a NW-SE transect that crosses over the northern part of the center of the city, receiving the influence of the main Metropolitan Park (Cerro San Cristóbal hill) and Mapocho river that facilitates local wind circulation and interaction between the Andean foothills and the flood plain.

Advancing to the south of the city, a warmer belt that combines the local and punctual features mentioned above (stadium, airport, and shopping centers) indicate the predominance of urban landscapes with hot and medium values.

Finally, Fig. 9.23 shows the average values for the selected period. A warmer south-west corner has developed over the last few years instead of the traditional cooler corridor associated with the Mapocho riverbed and agricultural lands, which were part of the protection area of the landing track of Los Cerrillos airport. Dense dwellings and heat islands are building up this area. This warmer zone is interrupted in its advance toward the north by cooler zones developed at the western and south-eastern part of the city, owing to the influence of mountain–valley flows.

9.7 The Relationship Between Urban Climates and Air Quality: A Spatial Synthesis and Concluding Remarks

Commodification of climate and relevant socio-environmental inequalities of climate quality around and within cities are a direct or indirect result of land use planning, urban designs, and political–economic models applied in most Latin American cities. The lack of climate justice, on the other hand, means that good climate and air quality are concentrated in areas where the upper social classes live.

Taking into consideration the limited available information (which is part of the lack of knowledge that maintains environmental injustices), Fig. 9.24 shows the spatial distribution of particulate matter (PM_{10}) and winds during one of the worst air pollution events recorded on 11 May 2009 at 8 a.m. in Santiago. On that day an emergency event was declared, stopping 60% of vehicles and the bringing industries to a standstill. There was a difference between the eastern and western sections of the city of almost 200 $\mu g/m^3$. This difference is larger than the pollutant concentration observed in places located in the eastern part. Temperature differences between the two sectors only reached 1 °C, but synoptic meteorological conditions and katabatic (or mountain–valleys) airflows transported high concentrations from the richer part to the poorer part of the city.

Such a social component of air and climate quality in Santiago is partially explained because of the warmer temperatures and heat islands recorded in western areas. It is defined as a typical feature of the lack of environmental justice because at the same time and in the same space, poor dwellers are suffering from cooler mornings, which are typical of fall and winter seasons, living in badly equipped homes, without enough thermal insulation, and in dense urban landscapes installed on bare soils (Romero et al. 2010).

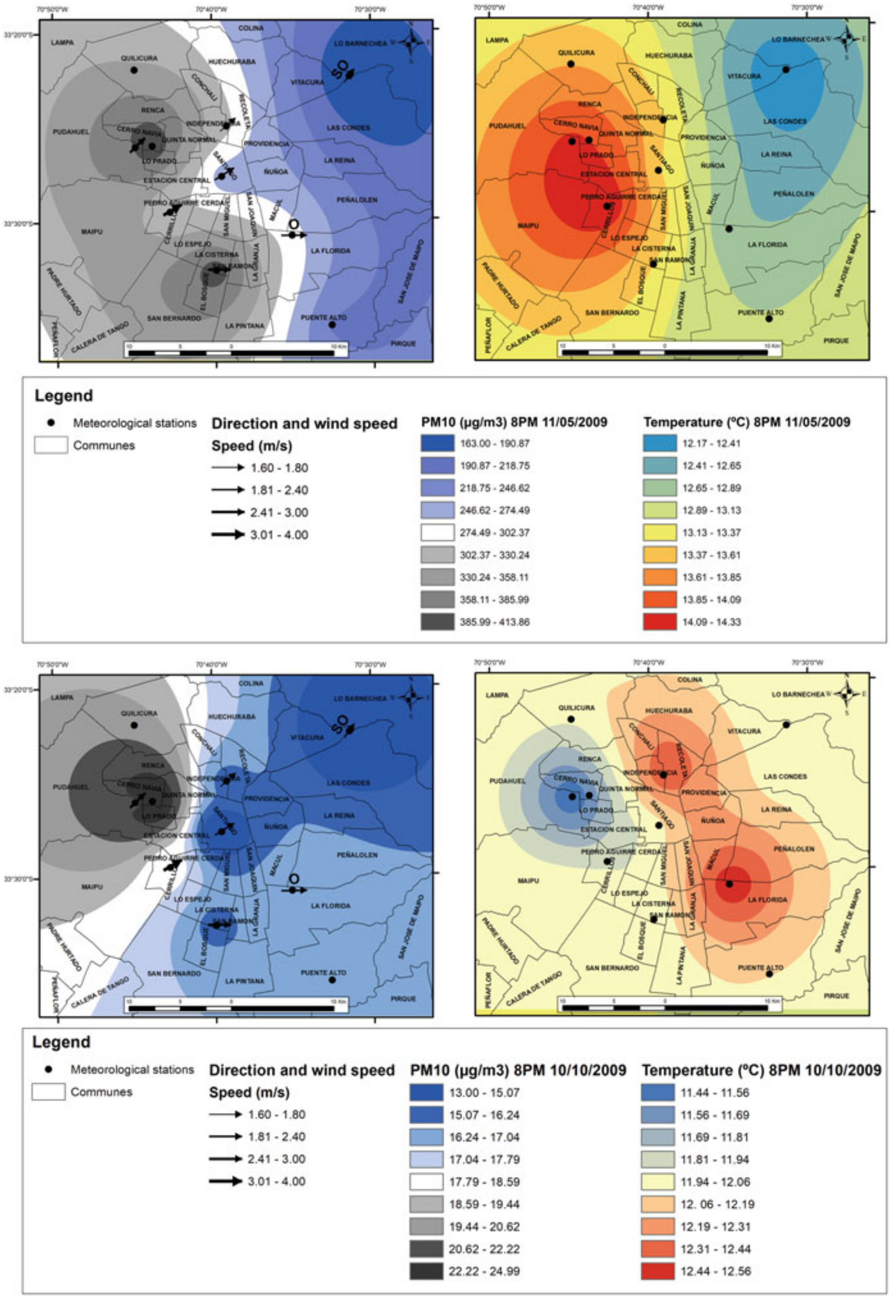

Fig. 9.24 Spatial distribution of particulate matter (PM_{10}), temperature, and winds on 11 May and 10 October 2009 at 8 a.m.

The situation was completely different during a spring day, 10 October 2009 at 8 p.m., when the air quality was good. The difference in PM_{10} concentration was only 11 μg/m^3 between the western and eastern sections. The urban thermal patterns were inverted, and the western sector presented the development of a cool island of around 1 °C, which means that anabatic floes were then blowing to the east of the city to compensate for the temperature difference.

A similar spatial pattern of the worst air pollution day and an emergency declaration in Santiago occurred on 27 June 2016. However, recorded pollutant values were much more reduced, probably as a consequence of environmental policies installed in recent years. That day, at 6 a.m., concentrations lower than 54 μg/m^3 were recorded in two clean air islets located at the north-eastern and south-eastern parts of the city. In contrast, in the western sections, values over 124 μg/m^3 covered most of the neighborhoods. The same spatial distribution was observed in the case of $PM_{2.5,}$ which has been measured in last few years. In this case, concentration differences are 20 times larger between the western and eastern sections of the city.

However, the spatial pattern and values of air temperatures are different to those observed in the critical 2009 event. In 2016, there were higher thermal values at 6 a.m. in the eastern part of the city, one located in the north-eastern place of Lo Barnechea and the other in the south east around the Puente Alto neighborhood, varying between 4.2 and 8.2 °C. The rest of the city had temperatures between 3.5 and 4.7 °C; some cooler islets (between 2.3 and 3.5 °C) were observed in Cerro Navia (NW), Santiago (center), La Cisterna (south), and La Florida (east) (Fig. 9.25).

At 2 p.m., the spatial distribution of air pollutants changed its values and locations; PM_{10} and $PM_{2.5}$ present a very similar geographical pattern. Higher values (between 33 and 40 μg/m^3 in PM_{10} and 31–50 μg/m^3 in $PM_{2.5}$) were concentrated in SW rural areas, beyond the city border, and in two islets situated in the historical center and its surroundings (Cerro Navia, Independencia, Santiago, and Recoleta neighborhoods) and at the south (La Cisterna and El Bosque neighborhoods). Minimum values (PM_{10} and $PM_{2.5}$ between 22 and 29 μg/m^3, respectively) were at this time prevalent in the south-eastern (Puente Alto) and at the north-eastern (Lo Barnechea) sections of the city. An isolated islet of lower values was located in the neighborhood of Los Cerrillos situated in the central-southern part of the city. This plot and the two eastern neighborhoods recorded cooler temperatures varying between 19.4 and 20.5 °C. The rest of the city had a warmer afternoon with temperatures between 20.1 and 21.7 °C (Fig. 9.26).

The different performance of both the western and eastern parts of the city in terms of air pollution during an emergency day consolidated during the night at 10 p.m. when minimum values of PM_{10} (23–66 μg/m^3) and $PM_{2.5}$ (16–44 μg/m^3) were recorded in the NE corner of the city (Vitacura, Las Condes, and Lo Barnechea neighborhoods). In the western part, maximum values were in Cerro

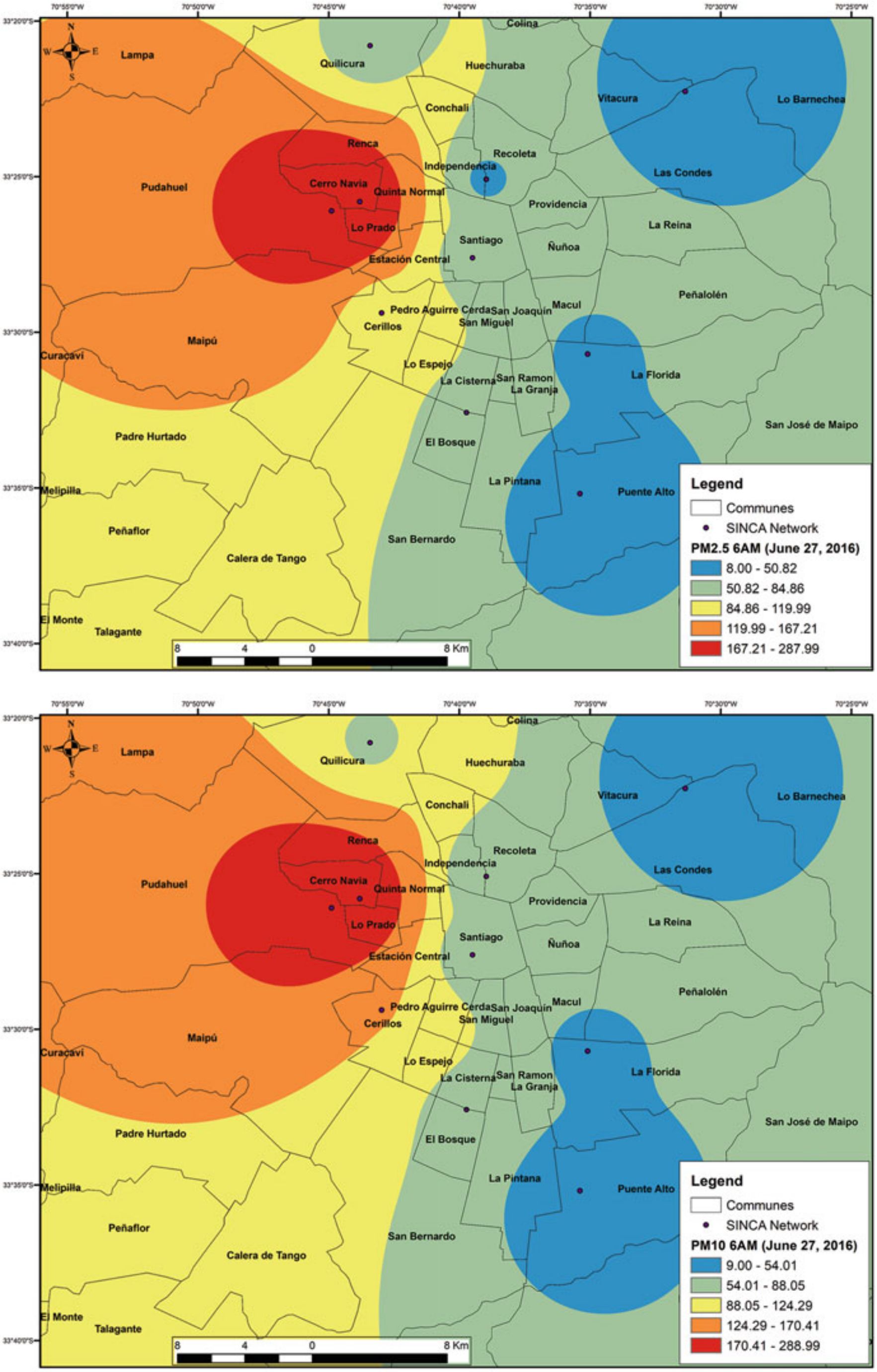

Fig. 9.25 Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) and temperature on 27 June 27, 2016 at 6 a.m.

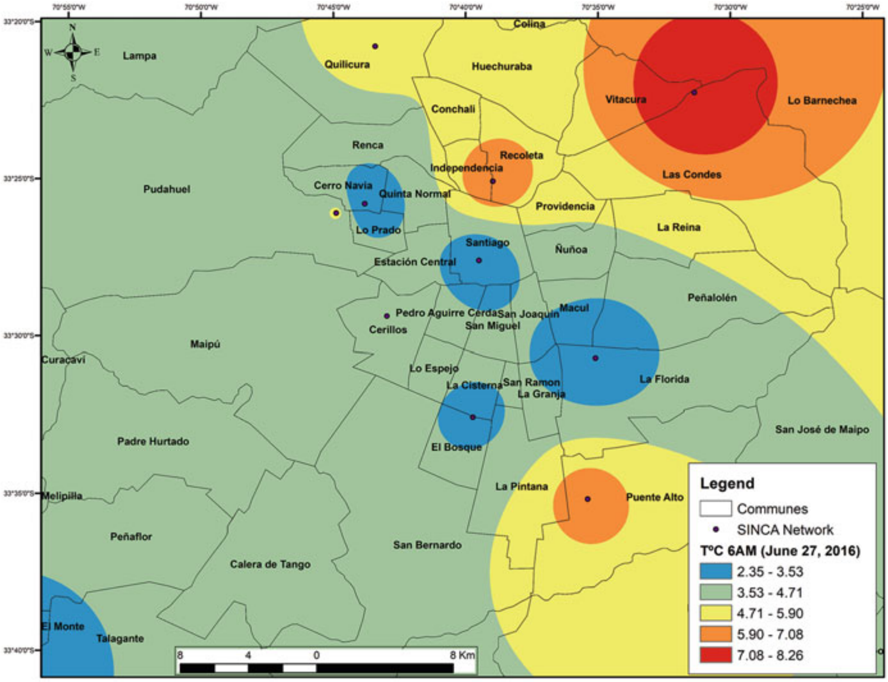

Fig. 9.25 (continued)

Navia, Lo Prado, and Pudahuel (129–177 mg/m^3 for PM_{10} and 93–132 for $PM_{2.5}$). However, a spatial feature that separated air quality in two main north–south sections was not reproduced at this time by the distribution of air temperatures during the night, as a warmer belt crossed over the city from west to east, culminating in a shape that was expanding throughout the whole day. This zone reached a temperature between 9.2 and 11.5 °C, i.e., around 2 °C warmer than the cold islets in the central-eastern parts (Santiago, Macul, and La Florida) and the south western parts beyond the urban border (Fig. 9.27).

In general terms, the representation of the spatial distribution of particulate matter – taking into consideration that interpolations are based on only 12 observation points – shows that a relevant differentiation between the western and eastern sections of the city seemed to be present during air pollution events. The NE clean air corner is a feature mentioned in previous articles and understood as evidence that urban climates show important relationships with socioeconomic spaces.

The Santiago's air cleaner zone in terms of PM and cooler zones overlaps with the richest neighborhoods mostly inhabited by socially uppermost (ABC1) and upper medium class (C2) groups classified according to their family income (Fig. 9.14).

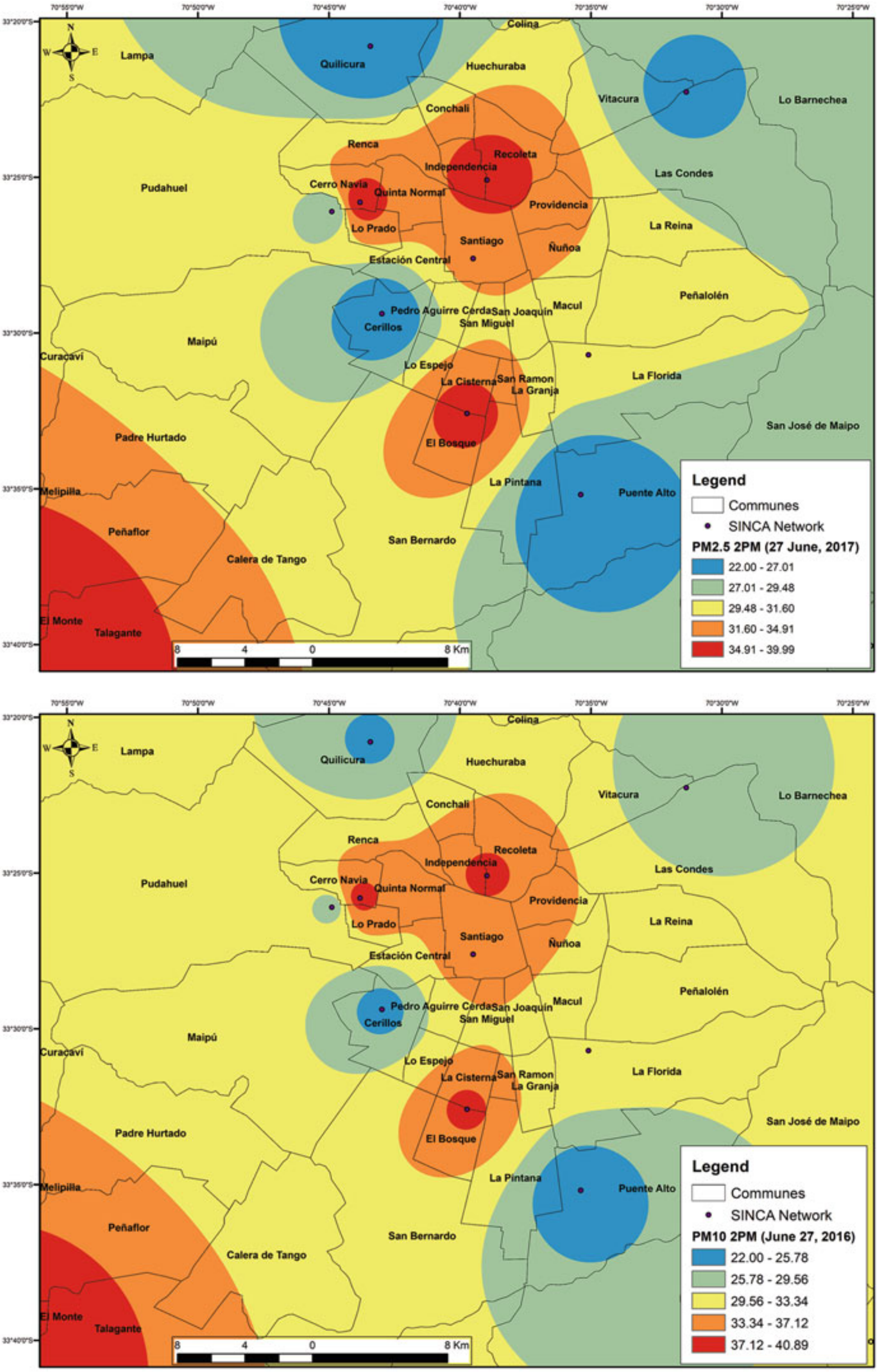

Fig. 9.26 Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) and temperature on 27 June 2016 at 2 p.m.

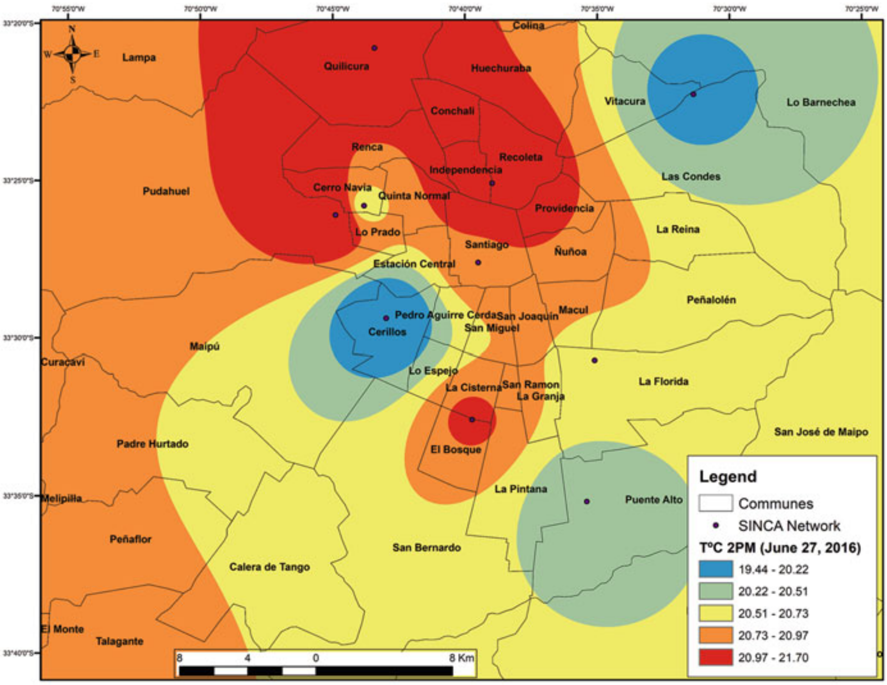

Fig. 9.26 (continued)

Conversely, air pollution and warmer temperatures tend to concentrate in neighborhoods located in the western part of the city are places where lower middle-class (C3) and poorer people (D and E) live. However, between socioeconomics and air pollution there are many other intervening and interacting variables, such as dwelling densities, vegetation cover, bare soils, building heights, construction materials, and urban design (Romero et al. 2012).

The issue is that in Latin American cities in general, and in Chilean cities in particular, most of these variables are directly associated with the socioeconomic conditions of urban societies. This means that if a truly urban sustainable development were approached, environmental components, and urban climates in particular, would improve because of economic progress, social equity, and environmental protection.

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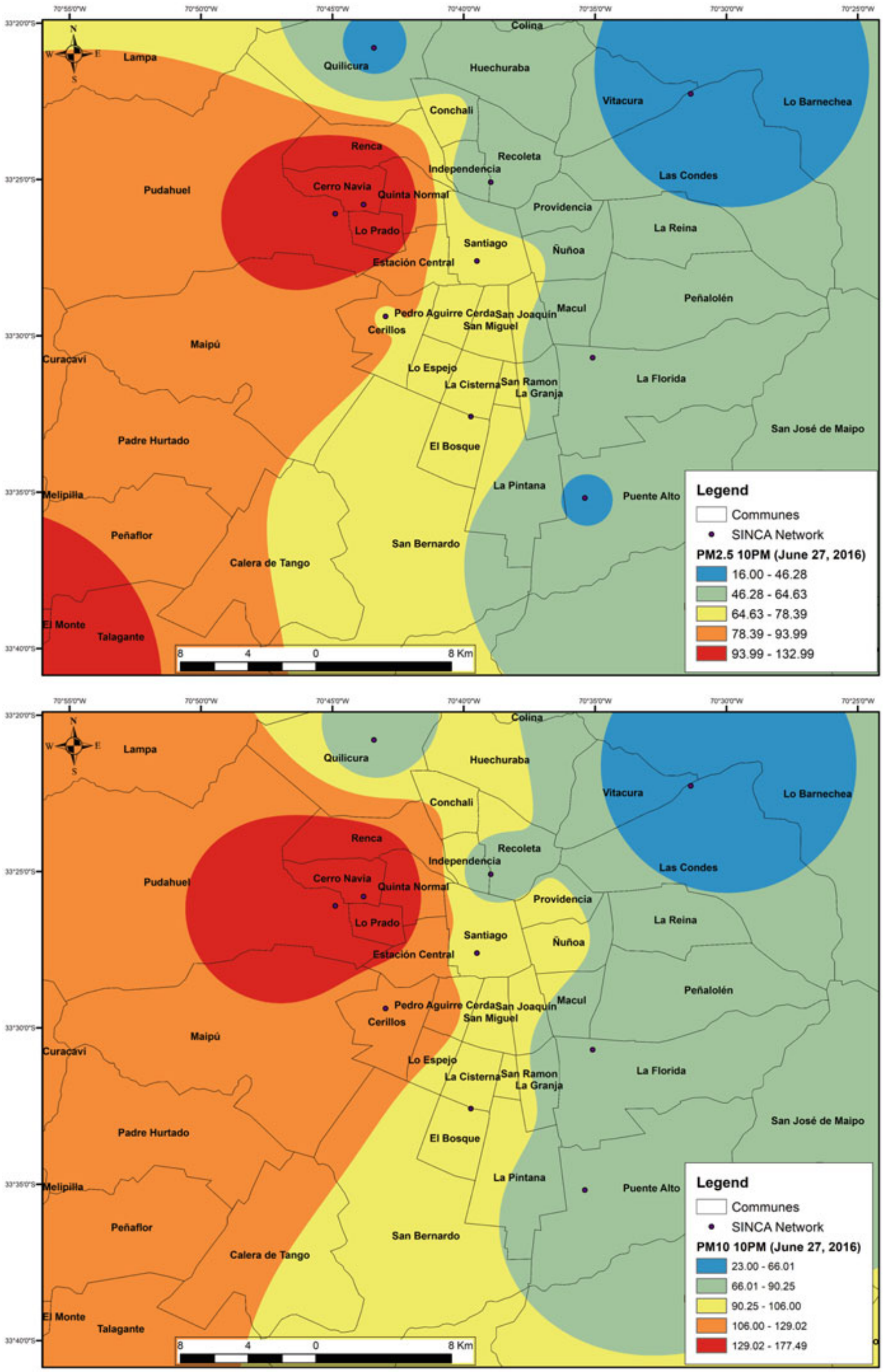

Fig. 9.27 Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) and temperature on 27 June 2016 at 10 p.m.

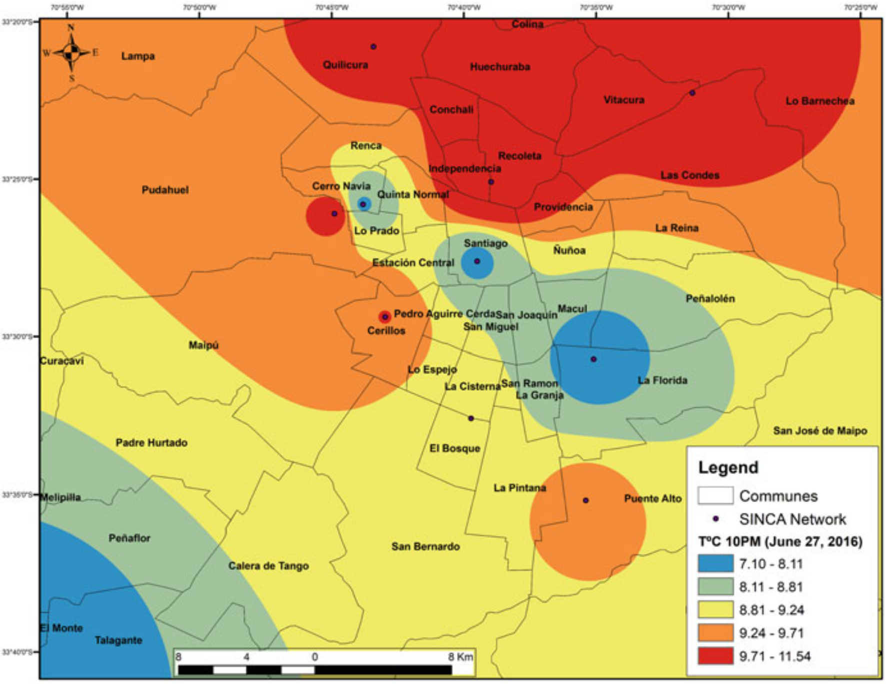

Fig. 9.27 (continued)

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Part III
Climate Disasters, Health, and Urban Resilience

Chapter 10
The Urban Climate System and the Impacts of Flooding on Rio de Janeiro, Brazil

Nubia Beray Armond and João Lima Sant'Anna Neto

Abstract Despite their individual socio-spatial paths of development, the countries of Latin America underwent similar urbanization processes. Analyzed from the geographical perspective of the spatial relationship between society and nature, the different forms of urbanization, especially in their material dimension, directly affect the creation of different climates. Based on this assumption, Carlos Augusto de Figueiredo Monteiro originally proposed, in his associate professorship thesis, the Urban Climate System (UCS) theory in Brazil with the goal of analyzing the climates of specific locations and their urbanization. Based on the work by Monteiro, combined with a climate geographical perspective, the goal of our study was to analyze the urban climate, specifically the hydrometeorological subsystem that triggers extreme events in the urban portion of Rio de Janeiro, Brazil. First, the specifics of urbanization of a Latin American metropolis underlining the particularities of its urban climate are briefly introduced. Subsequently, the UCS theory is presented, focusing on the perceptual channels and the specifics of flood events, which is followed by a characterization of the climate dynamics of the study area, including those that occur on an hourly scale. Last, the hours of highest precipitation are identified, and the ways in which social groups are related to the urban climate of Rio de Janeiro are explained.

Keywords Geographic climatology · Urban climate · Precipitation · Flooding · Rio de Janeiro

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10.1 Introduction

Owing to urbanization without the democratic allocation of adequate living spaces, in general, the poorest populations of tropical cities in Latin American socio-spatial formations (Santos 1977) are forced to live in places that lack urban infrastructure and services and are highly vulnerable to climatic impacts (Satterthwaite et al. 2009; O'Keefe et al. 1976; Cutter 1996; Cutter et al. 2003).

The visible characteristics of the landscape and elements that trigger disasters of all types have mostly resulted from a colonial past characterized by an expropriation of natural wealth and of human labor. This past transitioned into a modern period, that, in a new guise, continued the expropriation process. This is the reality of most major Latin American cities.

The oldest Brazilian cities (which include most large Brazilian cities) clearly show, based on the landscape, an uneven pattern of development of different eras (Santos 2004). Contemporary, luxurious, and bold developments are built concomitantly with self-build projects in areas susceptible to landslides and floods. Simultaneously, remnants of a pre-capitalist architecture persist from an era of plundering characterized by a slave-based economy. During that era, most of the mineral and natural wealth of the country was drained to the Portuguese Crown, which paid its debt to England with Latin American gold and silver – the foundation of the Industrial Revolution.

The Industrial Revolution led to lifestyle changes worldwide, with industrialization setting the pace of a new process: urbanization. This process was only incorporated into the dynamics of Latin American countries in the twentieth century. In the Brazilian case, the country transitioned from an agricultural–exporting country to an urban–industrial one, which was extremely important to the creation of Brazil's national identity.

Rio de Janeiro is typical of a city that underwent this accelerated urbanization process. Concomitant with the mid-1960s rural exodus, the city was transformed into a metropolis whose main economic activities transitioned from agriculture to manufacturing and finally to tourism, thereby transforming it into a city of international stature.

Similar to most of the oldest colonial Brazilian cities, its coastal location and its geological, geomorphological, pedological, climatic, and biogeographic conditions were key elements in creating the unique characteristics of Rio de Janeiro.

The period of exploration of the city's natural environment occurred in the sixteenth century, according to Galvão (1992). Identified as obstacles or facilitators, features such as Guanabara Bay, Baixada Fluminense (a lowland flood plain area on the outskirts of the city) and the coastal massifs, typified a relationship that the author defined as one of the conflicts between nature and the growth of Rio de Janeiro.

Abreu (2006), when discussing later centuries (focusing on the transition from the eighteenth to the nineteenth century), showed that the urbanization of Rio de Janeiro was characterized by the incorporation of "peripheral areas" for urban growth, during which the middle/upper classes initially moved away from the city center toward the southern area (Flamengo, Botafogo, Copacabana, Leme, Ipanema) and, more recently, toward the neighborhoods of Leblon, Barra da Tijuca, and Recreio dos Bandeirantes. Simultaneously, workers were left living on the outskirts and, after the nineteenth century, with the transition to the industrial period and the construction and consolidation of the tram and train lines, the outskirts were transformed into what would eventually become, materially, symbolically, theoretically, and conceptually, the suburbs of Rio de Janeiro (Fernandes 2011).

Earth-moving and the land reclamation of mangrove and marsh areas to expand the continental part of the city have occurred since at least the seventeenth century, particularly in the eastern portion of the city, bordering Guanabara Bay.

Previous studies (Abreu 2006; Coelho 2007; Andreatta et al. 2009) identified these changes not only as a process that occurred in the past, but also as a mark and a foundational and living characteristic of the urbanization of Rio de Janeiro. Currently, these changes continue in the same neighborhoods, mainly with construction work related to the Pan American Games (2007), FIFA World Cup (2014), and Olympic Games (2016). The constant changes in the physical space of Rio de Janeiro, usually intended to satisfy a great variety of interests (except for the quality of life of the working class), are key elements in understanding some of the main urban environmental problems of the city (Coelho 2007).

In summary, these processes produced a metropolitan area marked by different characteristics regarding the creation of urban climates, including selectivity, when considering natural dynamics (places where natural dynamics are preserved or even controlled, as opposed to places where these dynamics are ignored in construction work); unequal land valuation (in areas where upper-middle and upper-class social groups live and congregate). The concentration of high-income social groups mostly on the edge of the main beaches of Rio de Janeiro (Copacabana, Ipanema, Leblon and Barra da Tijuca) ultimately also reflect the process of segregation and fragmentation – which led part of the working class to move to places that are unhealthy or unsuitable from a social, cultural, economic, political, and environmental standpoint, either close to or far from their workplaces – and concentrated urbanization (for example, the production of urban centers with a high concentration of apartment buildings, commercial buildings, and streets that are almost provided with inadequate infrastructure).

These complex dynamics lead to an urban materiality that, if spatially analyzed, reflects the different relationships between the social groups and climatic elements. Thus, a geographic examination of the relationship between climate and society in a country such as Brazil, requires the assumption to be made that different forms of the production of geographic spaces lead to, reflect, and condition different forms of production of urban climates. In other words, a geographic study of the urban climate requires an understanding that the geographic space is socially produced according to tensions between social groups and other agents, which essentially reflects a class issue (Sant'Anna Neto 2001, 2008, 2011; Armond 2014).

Thus, different correlations of forces between groups, agents, and institutions imply a different production of space. Such complexity, combined with the coastal tropical climatic conditions and the geological–geomorphological characteristics, requires analysis of the urban climate in those locations, not only quantitatively and materially, but also considering the different lifestyles, geographic spaces, and urban climates of social groups and how they relate to them (Sant'Anna Neto 2001, 2008, 2011; Monteiro 1976, 2009, 2015; Armond 2014; Armond and Sant'Anna Neto 2017).

Accordingly, seeking to perform a better, more detailed analysis of the relationship between climate and society and its effects on urban space organization, Monteiro (1976), in his associate professorship thesis entitled "Urban Theory and Climate" (*Teoria e Clima Urbano*), proposed the urban climate system (UCS), a theoretical and methodological construct that significantly influenced geographical analyses of climate in Brazil starting with the initial publication of the theory and extending to the present day (Monteiro and Mendonça 2003).

Therefore, we used the theoretical, methodological, and conceptual legacy of Carlos Augusto de Figueiredo Monteiro to perform a geographical analysis of flooding in the municipality of Rio de Janeiro. For this purpose, the theoretical framework of the UCS was first introduced, focusing on the hydrometeorological perceptual channel and its foundations. The next step is the identification and geographic characterization of the study area, both socio-spatially and climatically, followed by a description of how the development of the various forms of urban space relate to precipitation.

10.2 The Urban Climate System and the Hydrometeorological Perceptual Channel

> *Urban climate is a system that covers the climate of a given terrestrial space and its urbanization* (Monteiro 1976).

The UCS theory cannot be addressed without a minimal understanding of the origins and foundations that led Monteiro, between the 1960s and 1970s, to formulate his geographic perspective of climate analysis specifically geared toward cities.

The trajectory of Monteiro's thought (1976, 2003, 2015) is marked by some key elements of his geological construction of climatology. Some of these principles may be summarized from his associate professorship thesis (1976):

– *Rhythm as a paradigm of analysis and the foundation of geographic climatology*: When coming into contact with climatological research produced in the early 1950s, Monteiro realized that the atmosphere, a naturally pulsating and dynamic feature, was analytically approached in terms of mean values. Dissatisfied, Monteiro consulted texts from other authors, especially Emmanuel De Martonne, Arthur Strahler, and, mainly, Maximilien Sorre, to whom he owes the fundamentals of the idea of climate rhythm, which treats the climate as a normal succession of weather types at a specific place (Monteiro 1969, 1976, 2015).

  In line with Maximilien Sorre, criticism of the separate and static notions of climate is a strong component of the argument that Monteiro ultimately produced in defense of geographic climatology. Although he recognized the importance of using mean values in studies of variability, he reaffirmed the central role of real data obtained on a daily scale (Armond 2014; Armond and Sant'Anna Neto 2017).

– *Holism in the integration of physical geography and human geography in constructing the object of geographic climatology*: The statistical approach used by meteorologists in analyses of climatic elements led Monteiro to raise the issue of the role of society, its effects, and the impacts of climate dynamics on the organization of physical space. Thus, he based the construction of the object of geographic climatology on holism in the integration of knowledge derived from dynamic meteorology, climatology, and human geography, i.e., knowledge of the lower troposphere, the layer in which society reproduces its life (Monteiro 1976, 2003, 2015).
– *Scalar analysis of climatic phenomena and their limits of specification:* Atmospheric systems, which produce time in a regional and synoptic dimension, display their own specific and differentiated performance owing to a wide range of factors. The choice of factors to consider in climate analysis necessarily depends on the phenomenon of interest. Thus, when examining thermal or hygrometric differences in urban spaces, factors such as the density, pattern, and quality of the constructed space, geo-ecological indicators of the urban site, and the spatial location of the urban space, are central to the analysis. Centers of action, air masses, and fronts are known to directly affect these differences, although they act as more generalized mechanisms in climatic characterization because the analysis is focused on other issues.
– *The city and its urbanization as agents controlling climate on a local scale:* Given the heterogeneity and specificity of the organization of social groups in urban areas, Monteiro (1976, 2003) made the theoretical choice of regarding the climate as a complex system and made the methodological choice of treating the city as:

  (1) A primordial scale of analysis
  (2) An environmental phenomenon
  (3) A study object of urban climate (Monteiro 1976, 1991, 2003)

The ways in which social groups relate to climatic elements in urban space can be analyzed through "perceptual channels," as they were called by Monteiro (1976, 2003). These channels are the socio-sensorial mediation of a more direct relationship with climatic dynamics that is produced on the regional or synoptic scale (Table 10.1).

Monteiro (1976, 2003, 2015) understood urban climates as open and dynamic systems with energy inputs, dynamics, and outputs that may be affected by various factors. The relationships between societal dynamics and climatic elements arise through the interaction of three perceptual channels: thermodynamic, physicochemical, and hydrometeorological channels.

Table 10.1 Perceptual channels and subsystems of the urban climate system

Subsystems	I	II	III
Channels	Thermodynamic	Physicochemical	Hydrometeorological
Characterization	Thermal comfort	Air quality	Meteorological impacts
Source	Atmosphere	Urban activity	Special atmospheric states
	Radiation	Motor vehicles	
		Industry	(rhythmic deviations)
	Horizontal circulation	Construction	
Traffic in the system	Operator and operand exchange	From operand to operator	From operator to operand
Mechanism of action	Transformation in the system	Diffusion through the system	Concentration in the system
Projection	Interaction	From nucleus to environment	From environment to nucleus
	Nucleus		
	Environment		
Development	Continuous (permanent)	Cumulative (renewable)	Episodic (eventual)
Observation	Special meteorology	Sanitary and special meteorology	Meteorology
			Hydrology
	(Field work)		(Field work)
Disciplinary	Bioclimatology	Sanitary engineering	Sanitary engineering and urban infrastructure
	Architecture		
Technological correlations	Urbanism		
Products	"Urban heat island"	Air pollution	Attacks on urban integrity
	Ventilation		
	Increased precipitation		
Direct effects	Discomfort and reduced human performance	Health problems	Circulation and urban communication problems
		Respiratory, ophthalmological and other diseases	
Adaptive recycling	Control of land use	Surveillance and control of pollution agents	Improvement of urban infrastructure and flood control
	Home comfort technology		
			Land use
Responsibility	Nature and man	Man	Nature

Source: Monteiro (2003)

The thermodynamic channel consists of elements expressed through the exchange of heat, ventilation, and humidity. The main source is solar radiation, which heats the atmosphere. From this energy input, elements such as types of construction materials, particulate matter and atmospheric gases, building patterns of neighborhoods and houses, combined with regional climate dynamics, are together responsible for producing more or less adequate conditions for urban life, such as urban heat, cold islands, and thermal discomfort.

In the physicochemical channel, society is the operator of the system and is an agent almost exclusively responsible for its dynamics, according to Monteiro (1976, 2003, 2015). Interactions between elements such as atmospheric circulation (notably the relationship between wind dynamics, relative humidity, and precipitation) and urban traffic and industrial activity may produce unhealthy conditions from a public health standpoint, according to the author.

In the case of the hydrometeorological channel, Monteiro (1976, 2003, 2015) asserts the predominance of climatic dynamics over human activities because precipitation is an element that, in a scalar dimension, is little affected by human influence over short time periods and at isolated points in space. However, no matter how "democratic" precipitation might be (or, stated differently, one cannot choose where it rains), the ways in which different social groups relate to precipitation reflect the social relations that produce the geographic space.

When considering that different spatial scales have different urban climate characteristics, especially regarding the resulting problems, in Rio de Janeiro, issues associated with precipitation are some of the main problems triggered by the conflicts stemming from the class-based relationship between society and nature.

10.3 Rio de Janeiro and the Geographic Complexity of the Brazilian Atlantic Tropical Climate

Rio de Janeiro has an area of 1,197,463 km^2, a population of approximately six million, and is divided into 160 neighborhoods, which, as discussed, have a complex socio-spatial composition. The city's population distribution and income structure reflect its formative history.

The city's growth began near the interior areas of Guanabara Bay and gradually advanced along two axes. The first axis, the Southern Axis, developed because of the advance of social groups with greater political and economic power; meanwhile, the growing lower social strata ultimately occupied the most central areas in search of work. The second axis, the Northern Axis, was developed mainly at the turn of the twentieth century, when industrial activity gained prominence in the city. Industrial complexes were established in the city's core and in the Northern Axis; simultaneously, company towns were constructed so that workers could live near their jobs (Fig. 10.1).

Furthermore, real estate speculation and land values prompted workers who were unable to live near the factories to buy land along the Northern Axis and to the west. The existence of the rail transport network, which enabled the working class to commute to their workplaces, also partly contributed to the growth along this axis.

The relationship between capital and labor in Rio de Janeiro is clearly marked by the city's geography. This relationship may also be identified based on the

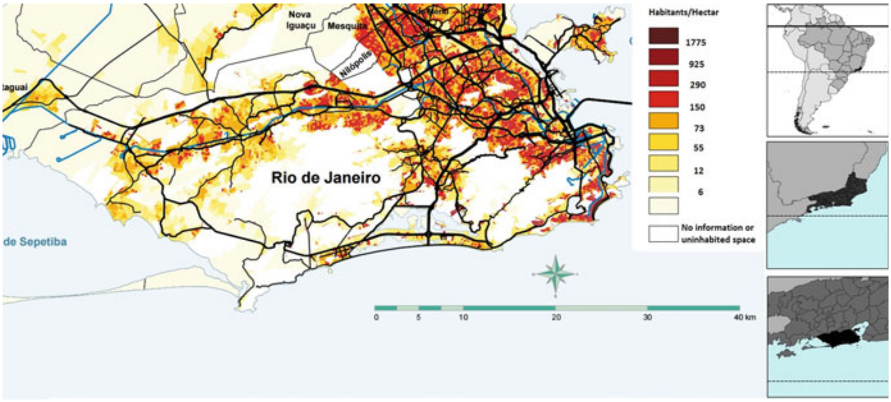

Fig. 10.1 Population density (residents per hectare) in Rio de Janeiro. Areas uninhabited or lacking data are shown in *white*. Increasing density is indicated by increasingly dark shading from *light yellow* to *dark brown*. The map clearly shows a higher population density along the Northern Axis. (Source: Jacob et al. 2014)

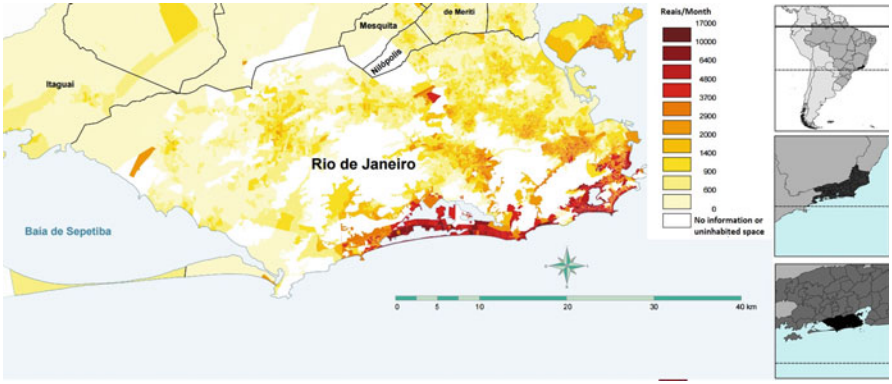

Fig. 10.2 Map of monthly income per inhabitant. The areas in *white* represent locations lacking data or uninhabited areas. The map shows monthly incomes in ascending order from 0 to 17 thousand Brazilian reais represented by shading from *light yellow* to *dark brown*. (Source: Jacob et al. 2014)

socioeconomic characteristics of the population. An analysis of monthly income per capita shows that the lowest-income population resides precisely in the areas that have been historically occupied by the working class, especially those who were once factory workers living in the central areas and along the Northern Axis (Fig. 10.2).

The social groups with the highest income per capita live along the main beaches (the so-called South Area [Zona Sul]), although the population density there is neither high nor low. The geographic location of these groups results from a historical process of occupation of this area by richer groups, which transformed

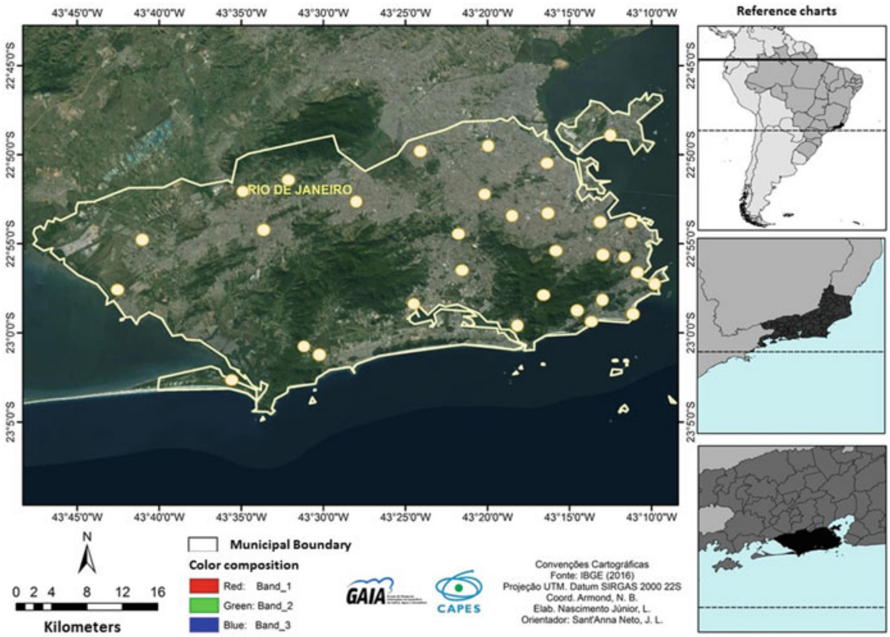

Fig. 10.3 Location of Rio de Janeiro and of rain gauges used in the analysis

this part of the municipality into an "affluent" area of the city that is highly reliant on the services provided by those living in the northern and western areas.

The complexity of the spatial development of Rio de Janeiro, which resulted from a historical and geographic process dating back to colonial periods, requires an understanding of its climatic dynamics in complex terms that differs significantly from an analysis of urban climates of cities of advanced capitalism (Oke 1978; Honert and McAeney 2011; Steffen et al. 2009).

Understanding the climatic dynamics of Rio de Janeiro demands an analysis that considers the fundamental, close relationship between the geographic factors of the climate and precipitation dynamics (Nimer 1979; Sant'Anna Neto 2005; Armond 2016). The following three factors stand out the most regarding the spatial distribution of precipitation: orography, maritimity, and latitude (Fig. 10.3).

First, the diversity of the regional weather systems corresponds to the geographic factors of the local climate (Monteiro 1969, 1971, 1976; Nimer 1979). The effect of Brazil's coastal terrain on its climate regime is considered one of the most important factors (Sant'Anna Neto 2005; Armond 2014, 2016). Atlantic tropical Brazil has an intensely steep coastline with extremely abrupt changes in elevations across short distances (Fernandes et al. 2009). In Rio de Janeiro, the elevation rises to 1,000 m above sea level within a distance of less than 20 km from the ocean (0 m). Two massifs, the Pedra Branca Massif and the Tijuca Massif, whose axes trend east−west, directly affect the distribution of precipitation in the city (De Martonne

1944; Conti 1975; Monteiro 1976; Nimer 1979; Sant'Anna Neto 2005; Armond 2014, 2016).

Precipitation maxima are located in the three main mountain ranges in the city: the Serra da Carioca (eastern part of the Tijuca Massif), the Serra do Mendanha (to the north, in the Gericinó Massif), and the Serra Geral de Guaratiba (located to the south west, in the Pedra Branca Massif), and annual precipitation totals there reach nearly 3,000 mm. The plain areas receive annual precipitation totals of 600 mm, considerably lower than those in the mountain ranges.

Associated with the local orography, the local maritimity reduces variations in local precipitation and temperature throughout the year. The coastal location of Rio de Janeiro enables the occurrence of precipitation in every month of the year (produced by both sea and land breezes) and orographic rain, and ensures air temperature stability.

Rio de Janeiro is in a transitional zone affected by tropical and polar atmospheric systems because it lies latitudinally in the tropical part of a country of continental dimensions in the Southern Hemisphere.

The municipality is almost permanently under the effects of the South Atlantic Subtropical High (SASH), with winds blowing from north east to south west. Seasonal climatic dynamics cause the advance of cold polar anticyclones toward the lower latitudes in the winter months. These anticyclones cross the South American continent along two axes: a continental axis, along which the masses enter southern Brazil; and a coastal axis, along which polar air masses move to lower latitudes along the coastline.

This northward circulation is enhanced by north western pre-frontal winds, which are replaced by south, south eastern or south western polar winds. With the passage of these high-pressure systems (polar masses that transform when reaching lower latitudes), the north and north east currents resurface in the rear.

The Atlantic Tropical Mass (aTm) is predominant, followed by cold and hot polar masses. In the summer, the aTm tends to be replaced by the Continental Tropical Mass (cTm), which is responsible for intense heat, especially in pre-frontal situations (Serra and Ratisbonna 1940; Monteiro 1969, 1971, 1976, 2015; Serra 1970; Nimer 1979; Sant'Anna Neto 2005; Brandão 2005; Dereczynski et al. 2009; Armond 2014, 2016).

The formation and movement of the Atlantic Polar Front, which represents the meeting of polar air and Atlantic tropical air (the former is stronger and weaker in the winter and summer respectively), is ultimately one of the main factors responsible for the rains throughout the south eastern region. Although the tropical conditions minimize the seasonal variations in precipitation distribution, the months from October to March, particularly the summer months, are when the precipitation totals are greatest: approximately 58% of the annual precipitation occurs in the rainy semester, and precipitation may exceed 1,200 mm in the windward and high-elevation areas.

Thus, the city has a precipitation regime characterized by a rainy summer, with precipitation totals decreasing in February. This month experiences a small decrease in precipitation, which increases again in March and then continually decreases until

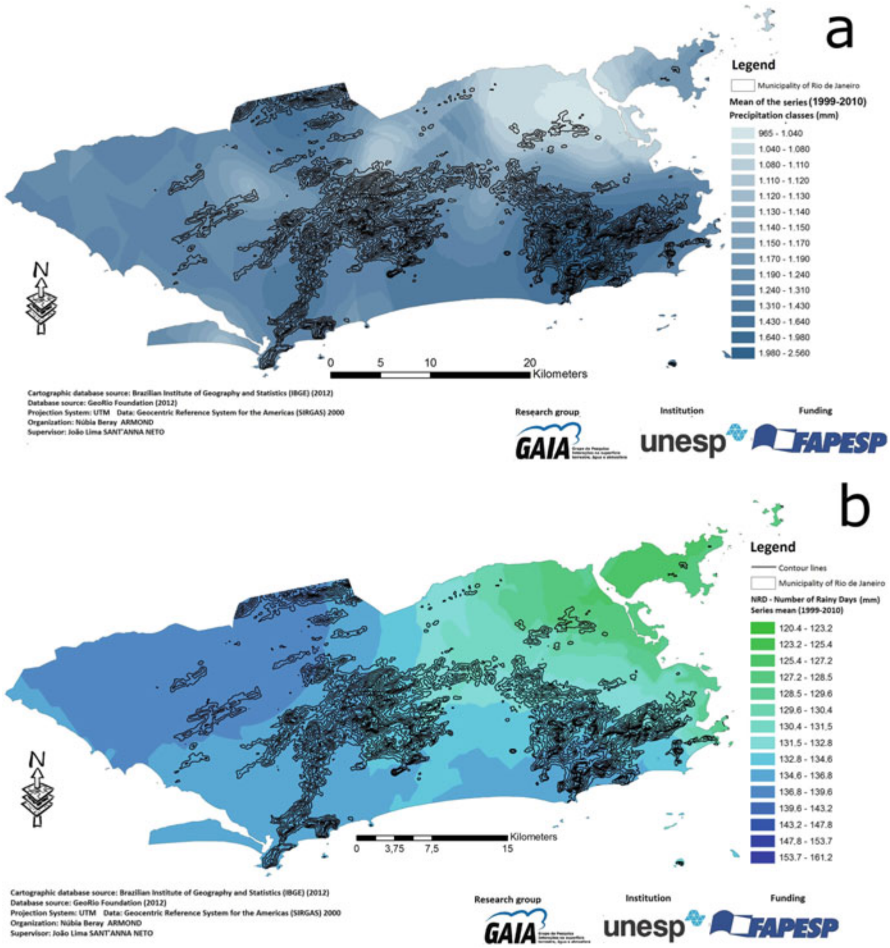

Fig. 10.4 (**a**) Mean cumulative precipitation from 1999 to 2010 and (**b**) mean number of rainy days from 1999 to 2010. (Source: Armond 2014)

August. Although the season of frontal passages begins with vigor in March and April, the lesser heating of the ground and the low humidity of the air masses preclude high precipitation. Nevertheless, exceptional precipitation amounts in fall, i.e., March and April, have been recorded (Serra 1970). The spatial distribution of precipitation, both in terms of total amounts and in the number of rainy days, is controlled by the local orographic gradient, such that the precipitation totals are greatest windward and decrease leeward (Fig. 10.4).

The windward areas of the massifs and the coastal areas receive the highest mean cumulative precipitation amounts. Conversely, a large rain shadow area stretches leeward of both massifs.

The polar systems pass over the city from south to north. The orography forces the humid air to rise, thus causing intense rains on the windward sides of the mountain ranges. Downwind, the air descends and simultaneously undergoes compression and heating (Conti 1975).

This distribution corroborates the findings of Serra (1970), who noted the importance of the terrain in controlling the spatial variation in precipitation (Fig. 10.4a). According to Serra (1970), precipitation tends to increase from Copacabana to the Tijuca Massif because of the windward location. Serra (1970) attributed the decrease in precipitation totals in the North Area (Zona Norte) to its leeward location, and certain locations receive less than 1,000 mm of annual precipitation.

Additionally, according to Serra (1970), areas in the northern part of the city and stretching to a portion of the southern coastal region are characterized by lower precipitation totals, because of their leeward location and protection from the humidity of the frontal passages. However, the author concluded that local rains with strong thunderstorm activity are the main sources of humidity in the Tijuca Massif.

This spatial distribution of precipitation totals is similar to that of the number of rainy days (Fig. 10.4b). The North Area of the city, located leeward of the Tijuca Massif, has the lowest mean number of rainy days (NRD) values and displays a slightly increasing gradient toward the West Area. Accordingly, the previously indicated roles of the frontal passages and convective complexes in rain production in the city (Serra 1970) are confirmed.

The total precipitation remains high until the end of the rainy season (March), with a gradual increase. The peaks in rainy days and monthly cumulative precipitation occur in December (the rainiest month of the summer) and in March (when the strongest fronts begin to pass over the region).

Based on a seasonal analysis, Serra (1970) noted that more than 50% of rainy days occur between October and March and that only 26% occur in winter. The average number of rainy days per year is 140.

The 24-h precipitation maxima do not necessarily follow a seasonal trend and may occur in months of the dry season. December, April, and May, in that order, are normally the months with the highest 24-h precipitation amounts. Thus, the beginning of the intensification of frontal passages coincides with extreme rains (Brasil 1992; Serra and Ratisbonna 1941; Serra 1970; Brandão 2005; Dereczynski et al. 2009; Armond 2014, 2016).

However, ways of investigating exceptional events must be put into perspective (Monteiro 1969, 1971, 1976, 1991, 2015) because a statistical analysis of 24-h precipitation totals or other high precipitation totals is not always sufficient to understand how precipitation may trigger disruptions, especially in densely and heterogeneously urbanized Latin American areas.

10.4 Hourly Precipitation and Urban Dynamics

An analysis of studies of precipitation dynamics and the thresholds for identifying extreme climate events shows that a significant fraction of the literature on precipitation dynamics relies on 24-h totals and whether or not they trigger calamitous events or generate disturbances (Konrad II 1997; Brunetti et al. 2001; Carvalho et al. 2002; Vicente 2004; Silveira 2007; Lima 2012; Colischonn 2009; Gonçalves 2003; Oliveira and Hermann 2005). Although various thresholds are used, impacts were found to start at 30 mm of precipitation over a 24-h period (Silveira 2007; Lima 2012; Gonçalves 2003; Oliveira and Hermann 2005; Brandão 2003, 2005).

However, even with precipitation totals below the mean daily threshold, impacts may occur, given the complex and varied urbanization in Latin American countries. The proportions of a 30-mm precipitation recorded in 24 h vary according to a series of factors including the hourly concentration of precipitation and the various ways in which social classes produce the geographic space in cities, enabling the emergence of different exceptional events. Thus, we chose to perform a combined analysis of the hourly dynamics of precipitation to examine in detail the diurnal precipitation patterns and the various impacts.

Studies of hourly precipitation dynamics were first performed for agricultural purposes (Kincer 1916; Pezzopane et al. 1995) and focused particularly on the relationship between hours of sunshine and hourly precipitation variations to identify the most suitable places for planting specific crops.

Pezzopane et al. (1995) sought to characterize the hourly precipitation in three cities in the state of São Paulo (SP): Campinas, Ubatuba, and Pindorama. In the summer months, higher precipitation intensities and frequencies occurred in the afternoons, whereas hourly variations in precipitation were small in the winter.

The same seasonal pattern was found in São Paulo, SP, by Alves and Galvani (2012); in Caraguatatuba, SP, by Santos and Galvani (2014), and in Rondônia by Santos Neto et al. (2014). In these studies, a homogeneous hourly precipitation distribution was observed in the winter and spring months, whereas the rains were concentrated in the late afternoons and evenings in the summer and fall.

In the coastal regions, night-time rains tend to be common because of breezes, although nonconvective rains also occur, predominantly at night. The precipitation distribution in the Bermuda Triangle is variable in the summer, with a higher frequency in the later hours of the night (Kraus 1963).

Similar results were reported by Andersson (1969) in Sweden. The author identified two patterns of hourly variations in precipitation based on two geographic climate factors: continentality (with maximum precipitation in the afternoon) and maritimity (maximum precipitation at night).

This debate was put into perspective by Wallace (1975) and Gray and Jacobson Jr. (1977), who conducted case studies and highlighted the importance of scales in what they called *dynamic* processes (genesis, or what is considered a regional scale) and *thermodynamic* processes (involving local-scale phenomena, including breezes).

Ferreira et al. (2013) found a different pattern in the eastern Amazon region. The island of São Luis (Maranhão) experiences small variations in hourly precipitation, enhanced by breezes.

Andersson (1969) reported that the highest precipitation frequencies occur at the end of the afternoon, in the evening, and at early dawn. However, precipitation extremes do not follow a pattern; the strongest rains do not necessarily occur at these times.

Nevertheless, in a tropical context such as Latin America, where demographic transitions were more rapid and followed a hegemonic rationale that reserved the spaces less susceptible to extreme weather events for the more affluent social strata, extreme rains are not the only events that may trigger impacts. Armond (2014, 2016) observed that precipitation intensity is not the determinant of extreme events. In other words, precipitation intensity alone is not a satisfactory explanatory factor for the impacts of precipitation.

Our analysis of the city of Rio de Janeiro showed that precipitation is concentrated after 5:00 p.m. and that its intensity is higher at night. A cluster analysis in the time dimension (Ward's method) was performed on the data from the rain gauges used in this study. Three groups were identified: the first, with the lowest degree of similarity, includes the dawn and early morning; the second includes the morning and afternoon; and the third had the highest degree of similarity and included the late afternoon and night-time (Fig. 10.5).

These results indicate that the terrestrial energy balance regarding the tropical climate and maritimity at a local level are important for understanding the precipitation regime.

Incident solar radiation during the day warms the surface. The air, heated by long-wave radiation emitted by the surface, intensifies convective movements, which may trigger precipitation in the late afternoon and evening (energy balance inversion). Therefore, the highest precipitation occurred at night.

Breeze dynamics contribute to this process. The air heated by the release of heat absorbed by the continent tends to rise, forming a low-pressure system. Sea breezes form in the late morning and early afternoon because water retains energy and radiates heat more slowly than land. During late afternoons and evenings, with the decrease and end of the direct incidence of solar radiation on the surface, the situation is reversed, with the formation of land breezes. The convective movements of the day may form clouds that precipitate in the late afternoon, and sea breezes may occur even at night, generating rains at dawn.

The regional dynamics of air masses may also be understood based on the complex thermodynamics system that is the atmosphere. The movement of air masses is stronger during the day. The incidence of radiation on a specific part of the Earth intensifies the heating of air, strengthening the pressure fields that form and move air masses. With the rotation of the planet, there is a deceleration of the heating of the Earth as night approaches. Thus, the movement of air masses slows or even reverses.

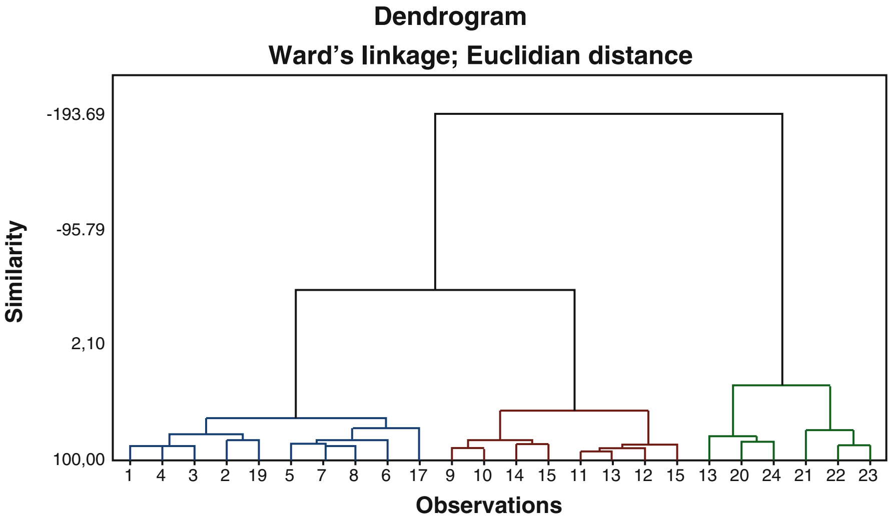

Fig. 10.5 Cluster dendrogram (Ward's method) of mean hourly precipitation between rain gauges. The numbers on the x-axis represent the hours of the day (mean of each hour considering the historical series from 1999 to 2012), and the y-axis shows the degree of similarity. Thus, three large time groups were identified: the *green*, representing the hours of highest precipitation intensity, followed by the *red* group (intermediate) and the *blue* group (lowest precipitation intensity)

Although precipitation is concentrated at night and dawn, the impacts are felt in the late afternoon. Furthermore, even if extreme events are not directly associated with the highest hourly mean precipitation, the urban geography of Rio de Janeiro allows frequent hourly precipitation thresholds to trigger disturbances in urban mobility and in commercial and service activities.

Elevation and the maritimity−continentality relationship modulate the local spatial variations. The Tijuca station receives the highest night-time total precipitation, followed by the Grota Funda and Santa Cruz stations. Both are longitudinally aligned. The Santa Cruz station is located between two massifs: the Gericinó Massif to the northeast and the Pedra Branca Massif to the southeast (Fig. 10.6).

The Grota Funda station also has the highest dawn precipitation totals, followed by the Tijuca and Vidigal stations. The Tijuca and Vidigal stations are at elevations higher than 100 m above sea level, and their precipitation patterns may indicate an enhanced breeze effect when coupled with the large differences in elevation in relation to the coast. This effect may also be present at the Grota Funda station, which, despite its elevation of 10 m, is very close to the coast and may be affected by breezes and the orographic effect (Fig. 10.7).

The Penha station, despite its high elevation, receives less concentrated precipitation at night and dawn than the other stations. Northern Rio de Janeiro is in the rain shadow (the Tijuca and Pedra Branca Massifs to the south and south west respectively contribute to this effect), according to Armond (2014, 2016).

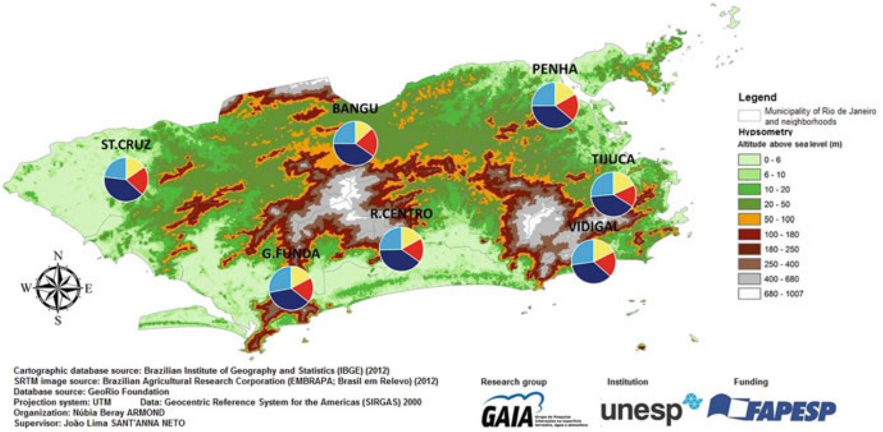

Fig. 10.6 Hourly precipitation distribution by time of day. *Light blue* – dawn; *yellow* – morning; *red* – afternoon; *dark blue* – night

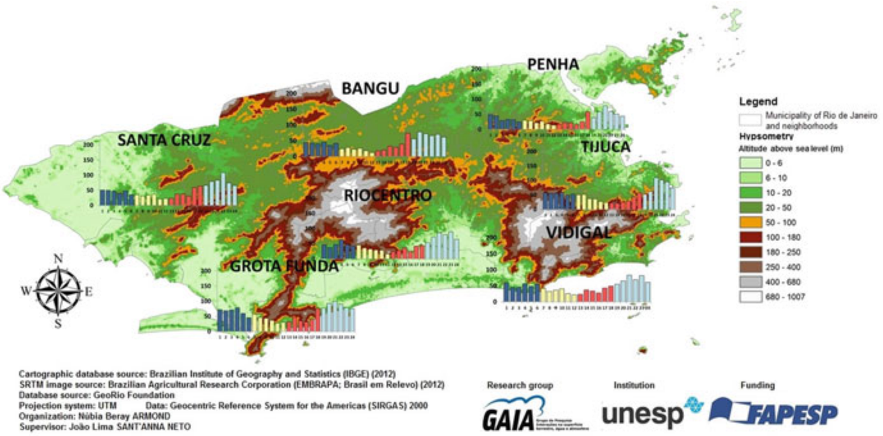

Fig. 10.7 Hourly precipitation distribution. The bar heights denote the totals during the 24 h of the day, with the colors representing the periods of the day. *Light blue* – dawn; *yellow* – morning; *red* – afternoon; *dark blue* – night

The Tijuca and Grota Funda stations recorded higher precipitation totals during the morning than the other stations. In the afternoon, the Santa Cruz and Grota Funda stations recorded the highest precipitation totals. The Penha, Vidigal, and Tijuca stations recorded the lowest afternoon precipitation totals; their location at the back of Guanabara Bay and in a rain shadow is worth noting. The Bangu and Penha stations recorded the lowest morning precipitation totals.

The hourly precipitation amounts in Rio de Janeiro show a time pattern typical of tropical climates, with rains concentrated during the night and dawn hours and sunshine in the morning and afternoon.

The occurrence of precipitation in the late afternoon significantly affects urban dynamics, especially in cities such as Rio de Janeiro. This occurrence is linked to deep morphological/terrain changes, urban hardscaping, and river channel adjustments, particularly in the central areas and on access roads, and traffic tends to be heavy after this afternoon precipitation.

Thus, local flooding and overflows from realigned water courses on which the streets and boulevards were built cause significant disruptions in the lives of city dwellers, especially in terms of urban mobility. Even if precipitation is relatively light compared with mean daily values, hourly precipitation amounts can be large.

10.5 Impacts and Exceptional Events

Precipitation, particularly precipitation that is concentrated in the late afternoon and evening, has a significant effect on the rhythm of urban life. The capitalist logic, which governs daily life, fundamentally conditions the daily rhythm of production to the work-day rhythm. The period from 6:00 a.m. to 6:00 p.m. consists of the so-called "business hours," during which most people following a formal work schedule perform their activities. In the hours immediately before and immediately after this period, the daily life of the city is marked by heavy traffic, both in the city center and in peripheral areas because of the daily commute to and from work.

The occurrence of the strongest rains in the city of Rio de Janeiro at the end of the afternoon necessarily means that people leaving their workplaces and arriving at home are vulnerable, to a lesser or greater degree and quality, to the impacts that may be triggered by the rains. These impacts necessarily depend on the differences in the historic urbanization process, which has materialized differently throughout the city.

The informal job market also causes exceptional situations, such as the trapping of cars on large boulevards because of floods, to become opportunities for specific social groups to derive income. For example, during floods, hawkers selling inflatable mattresses (which work as floats) and people willing to push cars appear in the flooded areas. These conditions reflect much more than climatic or environmental problems: they reflect problems resulting from the urban development that has occurred under a logic of inequality, typical of the capitalism of most Latin American countries.

Rio de Janeiro is known worldwide for its *favelas*, which are self-built areas located near the city center and affluent areas and which are primarily residential and lack proper infrastructure and urban public facilities. However, the city also has other specific characteristics, including the peripheral areas referred to, culturally and historically, as suburbs, i.e., places far from the center and the most affluent areas of the city, symbolically marked by the presence of railway lines built to transport workers from their residences in proletarian neighborhoods to the city

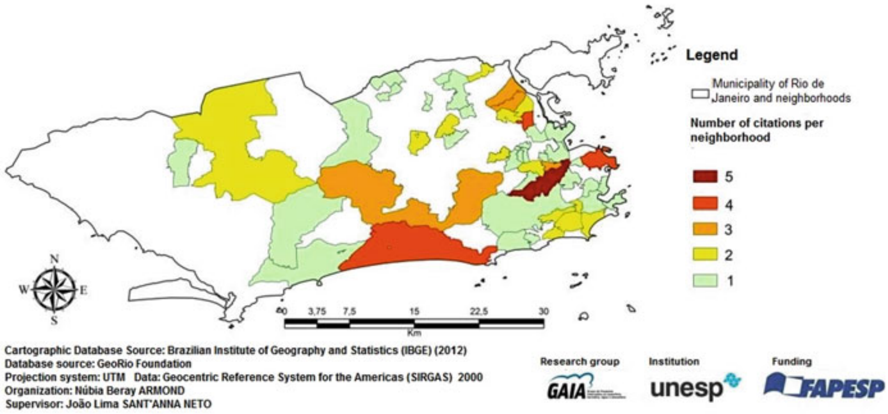

Fig. 10.8 The neighborhoods cited most frequently with regard to hydrometeorological impacts in the newspaper "O Extra." (Source: Armond 2014)

center, according to Fernandes (2011). Similarl to the *favelas*, the suburban areas are susceptible to weather events and have high socio-environmental vulnerability levels.

In the areas of the city considered affluent, the hydrometeorological impacts may range from urban mobility disturbances to power outages and falling trees. The levels of vulnerability are related much more to issues regarding loss of material goods than to situations of displacement or loss of life (Sant'Anna Neto 2001, 2008, 2011; Armond 2014; Armond and Sant'Anna Neto 2017) (Fig. 10.8).

Another problem that reflects the class-based nature of urbanization is access to leisure activities. Because the capitalist mode of production is characterized by the expropriation of workers' means of production, the only option left to workers enabling them to survive in a world mediated by mercantile relations is to sell their own labor. Thus, work becomes a socially and economically compulsory activity (Netto and Braz 2006).

Accordingly, a significant proportion of the city's workers are part of the informal job market, which affords few or no guarantee of labor rights and provides workers with few steady jobs. Much of the work is in informal trades or on a contract basis for companies, which creates a high degree of worker exploitation. Therefore, the lower strata of the working class of Latin America's cities are left with little time and very little money and thus almost no possibility of access to leisure activities.

10.6 Final Considerations

The specifics of urban climate development in Latin American cities preclude the forms of urbanization and their past characteristics from being disregarded, particularly since the colonial period. Latin American cities, including Rio de Janeiro, show, to this day, the catastrophic results of an uneven and class-based spatial relationship between society and the environment; it results likewise from the conflict of interests between social classes because of an urbanization process driven by rural exodus, rapid industrialization, and accelerated urban growth.

Cities are systems in which interactions between fixed (infrastructure) and the variable (types of time) elements are in permanent contact, thereby generating highly varied situations. Events such as floods do not affect urban residents equally because Latin American cities have uneven and unequal conditions.

In this context, climatic studies, especially geographic studies, must take into account these dynamics because their epistemic corollary involves the spatial dimension of the different forms through which the relationship between society and the environment develops.

Unevenly developed urban spaces affect different social groups unequally, creating spaces of environmental injustice. The emergence of the UCS as an eminently geographic theoretical−methodological framework was providential for Brazilian climate studies and has birthed an entire school of urban climatology in Brazil. The adoption of holistic, integrative, and complex assumptions in the analysis of the relationship between society and climate was essential for advancing geographic approaches to the study of climatic phenomena.

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Chapter 11
50-Years of Climate Extreme Indices Trends and Inventory of Natural Disasters in Chilean Cities (1965–2015)

Cristián Henríquez, Jorge Qüense, Claudia Villarroel, and Cindy Mallea

Abstract This chapter reports trends in climate extreme indices (CEI) and comfort indices for the period 1965–2015 and its relationship to historical disasters associated with hydrometeorological events for several Chilean cities. CEI analysis focused on differences in temperature trends and precipitation indices proposed by an Expert Team on Climate Change Detection, Monitoring, and Indices using RClimdex software. The disaster database had been obtained from journals, documents, and the DesInventar platform for 50 years. The results indicate that the minimum temperature increased in most parts of the country and frost events (TNn, CSDI3, and FD0) are decreasing. The heat extremes (TXx, SU30, and SU35) are decreasing in cities located in northern Chile, but increasing in central and southern Chile. The heatwaves (WSDI3 and HWN) have shown a decreasing trend in northern cities located near the coastline and an increasing trend in the rest of the cities, especially those located more centrally and in an inland position, such as Santiago and Chillán. Precipitation (RX3day, RX5day, R20mm, R50mm, and R95p) has decreased, but is more concentrated; and precipitation total (PRCTOT) and the consecutive number of dry days (CDD) are increasing according to the latitudinal gradient of cities. Furthermore, in the last 50 years, urban cities have been affected by approximately 682 natural disasters. The greatest amount of natural disasters occurred during 1991 and 1997, mainly because of precipitation. Both the extreme events and the high frequency of natural disasters show trends toward climate

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change, but these trends are strongly influenced by natural climate variability and events such as El Niño–La Niña.

Keywords Climate threats · RClimdex · Catastrophe zones · Urban areas

11.1 Introduction

The latest World Meteorological Organization (WMO) report notes that 2016 has been one of the hottest and extreme years; trends are expected to continue in 2017. The report confirms a remarkable 1.1 °C above the pre-industrial period, which is related to increasing sea surface temperatures, global sea levels, and the decreasing extent of the Arctic sea-ice and other impacts on the climate system (WMO 2016). On the other hand, the IPCC report (IPCC 2014) has a special chapter (N° 8) focused on urban areas, thus highlighting the importance of cities to the public agenda in the context of climate change. Currently, cities are home to more than a half of the world's population. According to the UN, the population will continue to grow rapidly in 2050, especially in low - and middle- income countries, which according to recent estimates, will suffer disasters of great impact related to extreme weather events.

Many effects of these extreme events, such as storms, drought, and extreme temperatures, begin to manifest in Latin American countries, especially in urban areas, where the proportion of the urban population can reach above 80% (United Nations 2015) and where large numbers of vulnerable inhabitants live. According to Hardoy and Romero-Lankao (2011, p. 158), although urban areas in Latin America and the Caribbean "are not major greenhouse gas emitters, they are hotspots of vulnerability to floods, heatwaves, and other hazards that climate change is expected to aggravate".

Studies of climate change within Chile (CONAMA 2006; CEPAL 2009) have described significant and heterogeneous changes projected for continental Chile: in broad terms, current climate models predict that Chile will experience a rise in temperatures, especially in the Andes zone, in addition to a decline in precipitation within the central-southern zone of the country and an increase in precipitation in the extreme southern zone (CONAMA 2006; MMA 2016). However, to date, there have been no studies that relate to climate extreme indices (CEIs) with disaster events on an urban scale. Despite CEIs being well documented in Latin America (Donat et al. 2013; Aguilar et al. 2005; Villarroel et al. 2006; Skansi et al. 2013), the relationship with natural disasters is not very well developed. More specifically, there is insufficient evidence for the variation in climate extreme indices on the urban scale, which is required to justify the necessary measures to adapt and mitigate for local scale climate risks. Results of this kind regarding climate models are especially relevant in a country like Chile, where over 88% of the population live in urban areas (UN 2015). According to the IPCC (2012) report, the CEIs are related to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events. These changes in extremes "can be linked to changes in the mean, variance, or shape of probability distributions, or all of these" (IPCC 2012, p. 7). It is important to mention that many extreme weather and climate events continue to be the result of natural climate variability and are strengthened by climate change. These events can be very risky because the populations exposed, such as the case of Latin American countries, are very vulnerable to economic, social, cultural, and institutional reasons. In this way, mitigations and adaptations can be difficult to implement as often, the resources of the community and local governments are scarce and limited.

Changes in global climate patterns associated with both human activity and natural climate variability appear to vary depending on a city's particular geographic and climatic context, in addition to its location, distribution size, shape, and function. In fact, the Fourth Report of the Intergovernmental Panel on Climate Change (IPCC 2007) stresses the need to achieve a transition in the structure and function of built environments to simultaneously mitigate climate change and adapt to the effects of a warming climate. Consequently, strategies of human mitigation and adaptation to extreme climatic conditions resulting from a warming climate have become one of the most formidable challenges of our time (Pizarro 2009).

The information regarding changes in trends and the empirical distribution of CEI indicators associated with temperature and precipitation with the situation of Chilean cities is still a challenging goal. The CEI has direct implications on society, especially in terms of health consequences and the occurrence of extreme natural events. During the last few decades, more extreme climate events have occurred and resulted in serious damage in Chile. In this regard, some questions arise such as: Have natural disasters associated with climate become more frequent in the last 50 years? Can trends of extreme climatic indexes be associated with climate change? Are some Chilean cities more exposed to hydrometeorological disasters than others?

Moreover, missing data also make the task of understanding the evolution of the current climate in relation to extreme events even more complex. Additionally, it is difficult to find meteorological stations inside the city that illustrate the effects of these indicators on the population.

Given this context, in this chapter we aim to explore trends in the CEIs for 15 cities that are representative of Chile's urban network, build an inventory of disaster events, and finally, both databases are compared to reveal trends and provide a ranking of cities that are more exposed to climate change.

11.2 Study Area

The 15 cities analyzed represent distinct climatic–geographic regions: from the extreme desert in the northern part of the country to the extreme cold in the south, crossing through the southern central region with different temperate climates (Fig. 11.1).

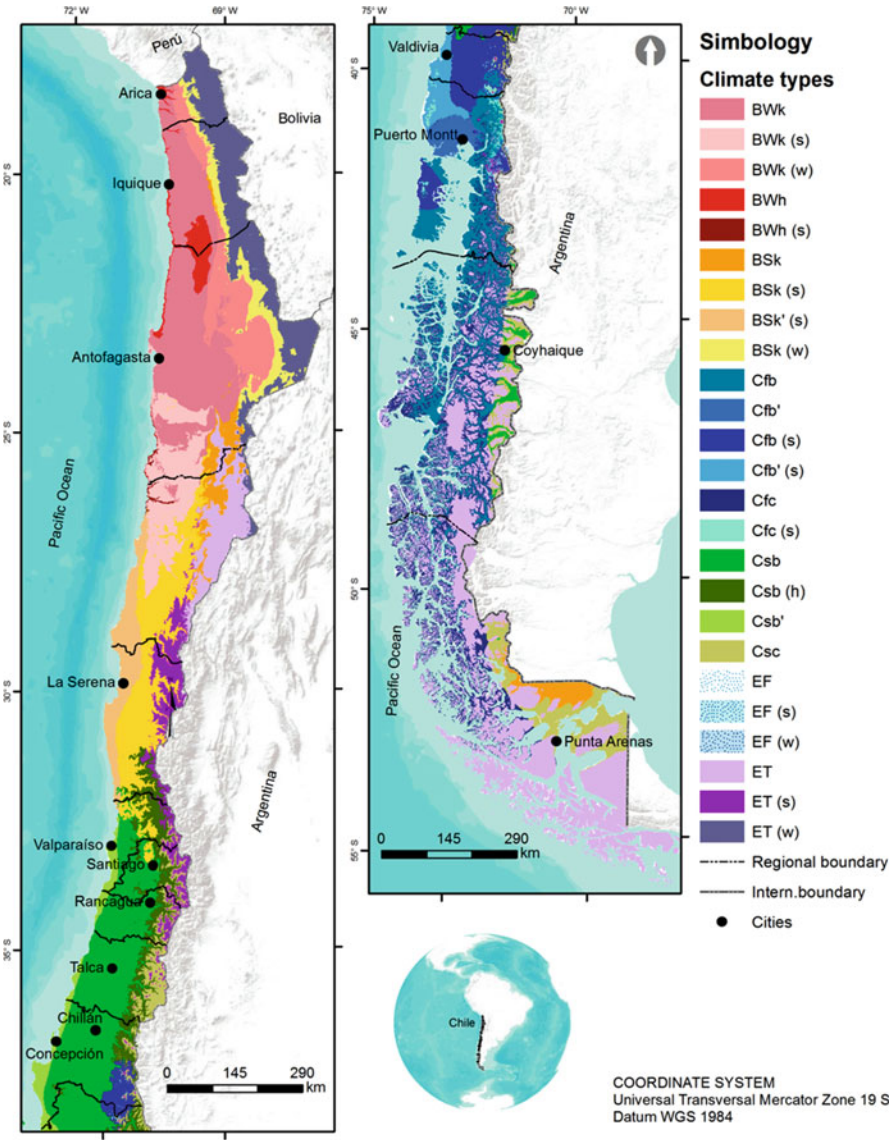

Fig. 11.1 Location of the cities studied in the Köppen–Geiger climate system. (Source: Sarricolea et al. 2017)

The climate of the country is controlled by important factors such as the Southeast Pacific Subtropical Anticyclone, the Southern Circumpolar Low Pressure, the cold Humboldt current system, the Chilean Coast Range, and the Andes Mountains. Also, an important role is played by the Pacific Decadal Oscillation and El Niño–Southern Oscillation (ENSO).

These cities together represent 60% of the urban population of the country and almost all are administrative region capitals.

11.3 Methodology

The study applies two methodological approaches. The first is based on the calculation of the climate extremes indexes for each city (Table 11.1) regarding daily maximum temperature (TX), daily minimum temperature (TN), and annual total

Table 11.1 Meteorological stations

City	Station name	Location	Height (m)	Period (years)	TMax (°C)	TMin (°C)	PRCTOT (mm)
Arica	Chacalluta[a]	18°35′–70°33′	63	1965–2015	22.1	16.3	1.8
Iquique	Diego Aracena[a]	20°74′–70°17′	52	1965–2015	21.2	15.7	0.7
Antofagasta	Cerro Moreno[a]	23°26′–73°26′	113	1965–2015	20.3	14.5	3.9
La Serena	La Florida[a]	29°54′–71°12′	142	1965–2015	18.1	10.1	82.7
Santiago	Quinta Normal[a]	33°44′–70°68′	527	1965–2015	22.8	8.5	313.1
Valparaíso	Rodelillo[a]	33°05′–71°21′	330	1980–2015	19.0	9.6	575.4
Rancagua	Rengo[b]	34°42′–70°86′	310	1970–2010	21.5	7.6	527.9
Talca	Talca[b]	35°43′–71°61′	130	1982–2015	21.1	7.9	627.8
Chillán	Bernardo O'Higgins[a]	36°34′–72°06′	151	1965–2015	20.2	6.9	1,403.5
Concepción	Carriel Sur[a]	36°47′–76°07′	12	1965–2015	17.8	8.0	1,077.0
Temuco	Maquehue[a]	38°45′–72°38′	92	1965–2015	17.8	6.2	1,158.2
Valdivia	Pichoy[a]	39°65′–73°68′	18	1965–2015	17.0	6.2	1,819.3
Puerto Montt	El Tepual[a]	41°43′–73°09′	85	1965–2015	14.9	6.3	1,706.8
Coyhaique	Teniente Vidal[a]	45°59′–72°10′	310	1965–2015	13.1	4.3	1,103.9
Punta Arenas	Carlos Ibáñez[a]	53°00′–70°84′	39	1965–2015	9.8	2.9	391.2

[a]DMC: Chilean National Weather Service, [b]DGA: General Water Directorate, TMax: annual average maximum daily temperature (ºC), TMin: annual average minimum daily temperature (ºC)

Table 11.2 List of climate extreme indices

Index	Definition
FD0	Number of frost days. Annual count of days when TN (daily minimum temperature) < 0 °C
SU30	Number of summer days. Annual count of days when TX (daily maximum temperature) > 30 °C
SU35	Number of summer days. Annual count of days when TX (daily maximum temperature) > 35 °C
TNn	Monthly maximum value of daily minimum temperature
TXx	Monthly maximum value of daily maximum temperature
WSDI	Warm spell duration index. Annual count of days with at least 6 consecutive days when TX > 90th percentile
WSDI3	Warm spell duration index. Annual count of days with at least 3 consecutive days when TX > 90th percentile
CSDI3	Cold spell duration index. Annual count of days with at least 3 consecutive days when TN < 10th percentile
HWN	Number of summer heatwaves ([a])
CDD	Maximum number of consecutive days with RR < 1 mm
RX3day	Monthly maximum consecutive 3-day precipitation
RX5day	Monthly maximum consecutive 5-day precipitation
R95p	Very humid days. Annual total PRCTOT when RR > 95p
R20mm	Annual count of days when PRCTOT ≥20 mm
R50mm	Annual count of days when PRCTOT ≥50 mm
PRCTOT	Annual total precipitation

Source: ETCCDI based in IPCC (2012)
[a]Based on DMC heatwave thresholds (DMC 2016)

precipitation (PRCTOT) during the period 1965–2015, based on the IPCC proposal in its Fourth Assessment Report (IPCC 2007). This stage considered meteorological data corresponding to stations of the Chilean National Weather Service (DMC in Spanish) and of the General Water Directorate (DGA in Spanish). It should be noted that many stations are located at airports, which best represent the peri-urban environment.

Selected CEIs are shown in Table 11.2. The software RClimdex and ClimPACT developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Aguilar et al. 2010; Alexander et al. 2013) were used. The result corresponds to the extreme indices for each year of the series and the decadal variation for each station analyzed.

Linear trends were calculated using least-squares linear regression on individual series of each indicator; significance was calculated using the Montecarlo method (bootstrap) with a 95% confidence interval. The local significance of trends was analyzed using the nonparametric Kendall's tau test (Mann 1945; Wu et al. 2011) on an annual basis for air temperature. In the present analysis, the significance level was fixed at 5%.

The second approach is based on a documented record of natural disasters associated with climate occurring in each of the selected cities between 1965 and

Table 11.3 Natural disasters associated with climate extreme indices (CEIs)

Natural disasters	CEI	Abbreviation
Frost events	FD0	F
	CSDI3	
	TNn	
Heat extremes, wildfires	SU30	HW
	SU35	
	TXx	
Heatwaves	WSDI	H
	HWN	
Extreme precipitation	RX3day, RX5day, R20mm, R50mm	EP
	R95p	
Drought	CDD, PRCTOT	D

2015. For the preparation of the cadaster of natural disasters, information from three sources was used. The first corresponds to the government decree declaring Catastrophe Zones by extreme climatic events, under Law No. 16,282 (1980–2015 period) and the second corresponds to the natural disaster database developed by the Network of Social Studies in Disaster Prevention for the 1970–2015 period (DesInventar 6 platform, http://online.desinventar.org/). To complete the 1965–1970 period, secondary sources were revised, such as a book about historical disasters in Chile (Urrutia 1993), reports from the National Emergency Office (ONEMI in Spanish) (ONEMI 2001), and scientific journals (Schneider 1968; Schneider and Peña 1975; Pizarro and Castillo 2006). As a result, the number of events per year is obtained for each commune that represents a specific city or metropolis, according to the type of disaster of climate and hydrometeorological origin. For the case of the metropolis of Santiago, all the communes of the Santiago province were considered, plus the communes of Puente Alto and San Bernardo. Administratively, Chile is divided into regions (15), provinces (54), and communes (346).

Subsequently, the CEI database and the record of disasters were compared (Table 11.3). Five (5) types of natural disasters are defined, which are related to specific CEIs. These are defined as a climate threat if the values exceed the average value of the series.

By combining the two variables, four risk categories were defined:

(1) Threat as impact: Corresponds to the years in which at least one natural disaster is associated with CEI in its category whose values are above the average of the series.
(2) Potential threat: Years where disasters do not occur, but there is a CEI record in its category whose values are above the series average.
(3) Mismatched disasters: Years in which natural disasters are recorded, but the CEI in its category has values below the series average.

Table 11.4 Relationships between climate threats and disasters

		Climate threats (CEI)	
		CEI above mean	CEI below mean
Disasters (number of events)	Presence	Threat as impact	Mismatched disasters
	Absence	Potential threat	No threat or disaster

(4) No threat or disaster: years where no natural disaster are recorded and all CEI values in its category are below the series average. For example, the city Antofagasta was affected by a mudflow disaster (May 3rd, 1991) and also the CEI associated with this disaster (RX3day = 14.1 mm) was above the average (0.6 mm). For this reason, this year qualifies as a "Threat as impact" for that type of event (red color, Table 11.4). On the other hand, for the same year the CEI CTX90pct_HWN was above the average (4 events in relation to 0.8 as average of the series), but a disaster did not occur that was associated with a heatwave by what is classified as a "potential threat" (green color).

The results obtained from both CEIs and natural disasters are compared annually to verify if they coincide, which explains why each CEI is associated with a type of recorded disaster. Finally, a table of relationships between CEI and natural disasters is generated, which considers four categories.

11.4 Climate Extremes Indices Trends

Table 11.5 shows a summary of the variations of the CEI decadal rates for the 15 cities analyzed. The values in bold correspond to significant trend values at 95% confidence and values in italics correspond to significant trends at 90% confidence. The city with the highest statistical significance in CEI trends is Punta Arenas, followed by Santiago and Coyhaique.

At a general level, in cities with 50-years records, there is an increase in the mean daily maximum temperatures and number of hot periods and heatwaves. On the other hand, most of the cities show a negative rate in the index of frost days (FD0) and cold spell duration index (CSDI3), implying a trend of increasing global temperature. Finally, with respect to rainfall (PRCTOT), there is a decrease in almost all cities, Valparaíso being the most extreme case, which shows a decrease of 108.85 mm/decade.

Table 11.5 Decadal rates of CEIs

Cities/CEI	FD0	CSDI3	TNn	SU30	SU35	TXx	WSDI	WSDI3	HWN	RX3day	RX5day	R20mm	R50mm	R95p	CDD	PRCTOT
Arica	-	**−5**	**0.49**	*−0.22*	-	−0.04	−3.06	**−4.77**	**−0.3**	0.24	*0.22*	-	-	0.09	4.23	0.2
Iquique	-	**−5.58**	**0.47**	*0.07*	-	**0.36**	0.17	0.93	−0.19	0.07	0.07	-	-	0	−7.0	0.01
Antofagasta	-	**−5.54**	**0.55**	-	-	−0.07	−1.48	−3.29	−0.21	0.33	0.33	*0.02*	-	0.55	1.71	0.34
La Serena	**−1.97**	**−14.73**	**0.98**	-	-	*0.2*	0.29	0.17	0.07	−0.33	−0.4	−0.05	-	0.98	−1.65	−0.83
Santiago	−0.49	**−3.18**	0.09	**5.39**	**0.25**	**0.24**	0.51	**2.93**	**0.2**	−0.23	−1.19	−0.01	−0.01	−2.83	1.31	−9.22
Valparaíso[a]	0.16	2.05	−0.15	0.34	−0.03	0.09	0.27	1.26	0.15	−11.45	−15.78	**−2.13**	**−1.2**	−24.03	**19.86**	**−108.85**
Rancagua[b]	−0.25	*−3.51*	−0.07	**10.27**	**−0.02**	**0.41**	0.33	**3.34**	*0.19*	*−9.68*	**−12.29**	−0.32	0.21	9.53	*7.55*	−18.46
Talca[c]	0.9	1.71	*−0.41*	3.95	**0.34**	0.56	−0.02	*3.14*	**0.33**	−8.34	*−11.21*	−0.9	**−0.45**	**−45.5**	−2.14	*−57.29*
Chillán	**−1.39**	**−1.62**	0.09	**3.92**	0.12	*0.22*	0.94	**2.76**	0.06	−3.83	−4.23	*−0.73*	−0.09	−15.86	1.19	**−55.06**
Concepción	−0.21	**−1.6**	0.09	−0.07	-	0	0.21	0.37	0.01	−2.71	*−6.68*	**−1.13**	−0.14	−13.53	2.33	**−55.82**
Temuco	*1.24*	0.72	−0.12	**1.33**	0.3	**0.57**	0.28	**2.39**	0.07	0.13	−1.94	−0.35	0.07	−0.08	**2.02**	−23.65
Valdivia	**−1.5**	*−0.8*	0.15	**1.17**	0.05	**0.62**	0.79	**2.18**	−0.01	3.03	−0.14	−0.49	−0.2	−7.55	*1.3*	*−44.82*
Puerto Montt	**1.1**	*−1.04*	**0.26**	0.06	0	*0.35*	−0.01	0.13	−0.05	−0.26	−1.48	**−1.61**	−0.05	**−31.28**	0.45	*−98.1*
Coyhaique	1.57	1	−0.02	0.5	**−0.01**	0.19	0.83	**1.69**	0.07	−3.18	**−8.86**	**−1.98**	−0.32	**−64.48**	0.91	**−91.61**
Punta Arenas	**−3.07**	**−1.33**	0.06	-	-	0.2	0.22	**1.78**	*0.17*	1.03	1.52	0.04	0.01	**8.19**	**−1.65**	5.23

Bold indicates significant decadal trends at 5% level; italics indicate 10% level
[a]1980–2015 period; [b]1970–2010 period; [c]1982–2015 period; - not applicable (less than 30 records)

11.5 Frost Events

Northern cities such as Arica, Antofagasta, Iquique, and La Serena do not show changes in CEI frost trends because there were no days with temperatures below 0 °C (FD0), owing to its climatic desert coastal condition (Atacama Desert). The cities of Santiago, Valparaíso, Rancagua, Chillán, Valdivia, and Punta Arenas show a decline in days with temperatures below 0 °C. The largest decadal decrease is shown by Punta Arenas, where, on average, they have reduced from more than 80 days to less than 70 days per year in the last decade.

The largest reduction in the number of days with minimum cold temperatures occurred mainly in the last decade (TNn). During 1967, there was a lot of frost in the cities of La Serena, Santiago, and Chillán, where they surpassed the annual average. Meanwhile, the results obtained in the cold period trends (CSDI3) are consistent with those of the other two indexes (FD0 and TNn), showing a slight decrease in these events. The only city that did not follow this pattern is Valparaíso, which showed a positive trend, increasing considerably starting from 2007.

The cities of Coyhaique and Punta Arenas show the highest number of days with frost, explained by its proximity to polar latitudes (Antarctic circle zone). The former has an average of about 60 days, and the latter an average of almost 80 days per year. The coldest days were recorded in 1992 and 2002, reaching values of −19 °C; however, from 2003, the minimum temperatures experienced a gradual increase, reaching around −7.5 °C in 2015. The rest of the central and southern Chilean cities show fluctuations between −5 °C and 0 °C. Cities located in the central and southern zone present, on average, between 20 and 40 days in a year with extreme minimum temperatures ranging between −5 °C and 0 °C. Figure 11.2 shows the time series of cold periods for each city, demonstrating significant results.

During the last 50 years, a great number of minimum temperature extreme events have been recorded. Few of them have triggered a natural disaster, although they have produced great losses in socioeconomic terms. According to historical disasters, cities located mainly in the Chilean central and southern zones are most affected by cold spells. For example, in Santiago, during the winters of 2007, 2009, and 2011, several homeless people died of hypothermia and cold-related diseases. A similar situation happened in Concepción during July 2001 where minimum temperatures remained under 0 °C for 3 days. On the other hand, Temuco and Valdivia have been affected several times by frost, in 1983, 1988, 1990, 1995, and 2007 recording temperatures below −6 °C. These did not have a great impact on the population, but left serious consequences mainly on agriculture and homeless people. A similar situation happened in the city of Puerto Montt in 1979, 1982, 1986, and 1987.

Cities located in the southern part of the country have been heavily affected by frost. In Coyhaique, during 1982, temperatures below −20 °C were recorded, which seriously damaged soil, streets, and pipelines, resulting in more than 8,000 people affected. In 1991, another severe frost event with temperatures below −15 °C left 2 people and some animals dead because of a lack of fodder and cold weather.

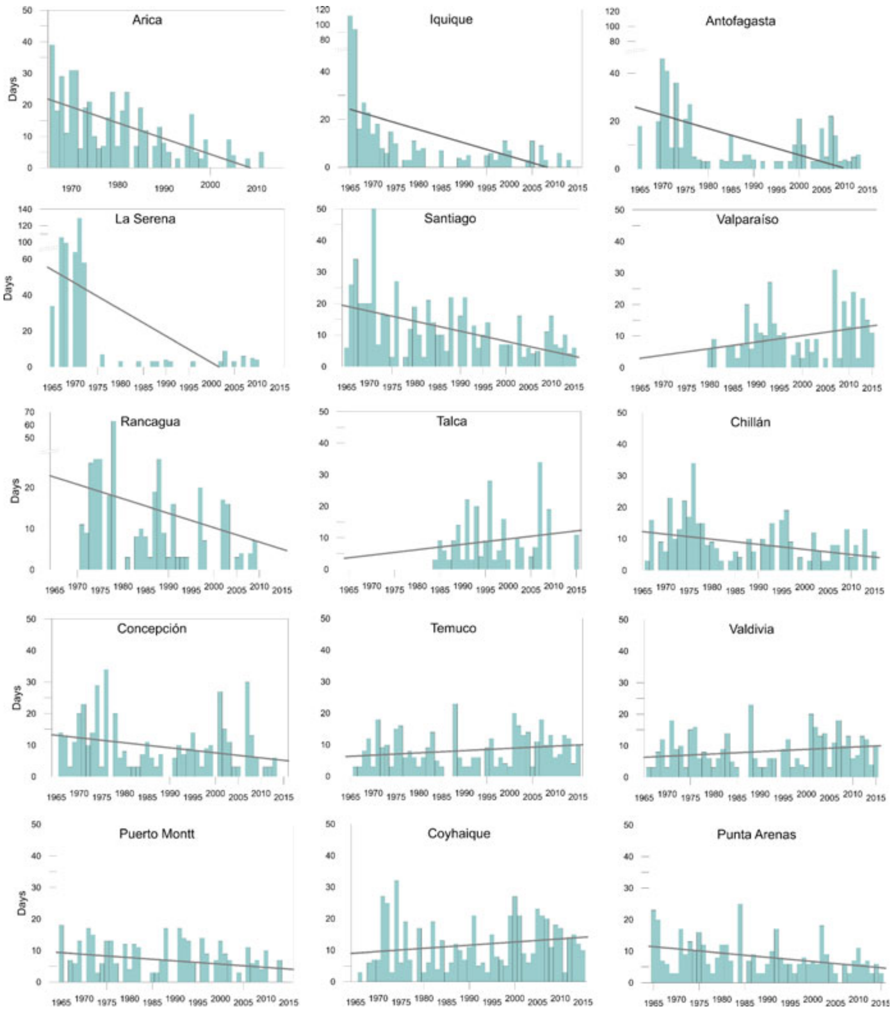

Fig. 11.2 Time series of the cold spell duration index (CSDI3)

Between 80 cm and 1 m of accumulated snow isolated 600 villagers. One of the most heaviest frosts occurred in June 2002, when temperatures registered −19.2 °C, leaving two dead and more than 50,000 people affected. The Regional Emergency Office (OREMI) activated the alert and coordination of the support network with public services and the Armed Forces. Accumulated snow made pedestrian and vehicular traffic difficult, and produced power outages and household pipelines rupturing because of frozen water. The international border crossings were impassable. On July 1st, 2002, the commune was declared a Catastrophe Zone by the Government of Chile (LA RED 2015).

Heavy frosts with temperatures below −10 °C particularly in 1971, 1973, 1977, 1995, and 1997, also occurred in Punta Arenas, which left serious damage, loss of human life, and had a vast impact on agriculture.

11.6 Extreme Heat and Wildfires

Northern cities, located in the coastal desert of Atacama and characterized by the cooling effect of the Humboldt marine current, show only a few events with temperatures above 30 °C (Fig. 11.3) and none above 35 °C. Despite this trend,

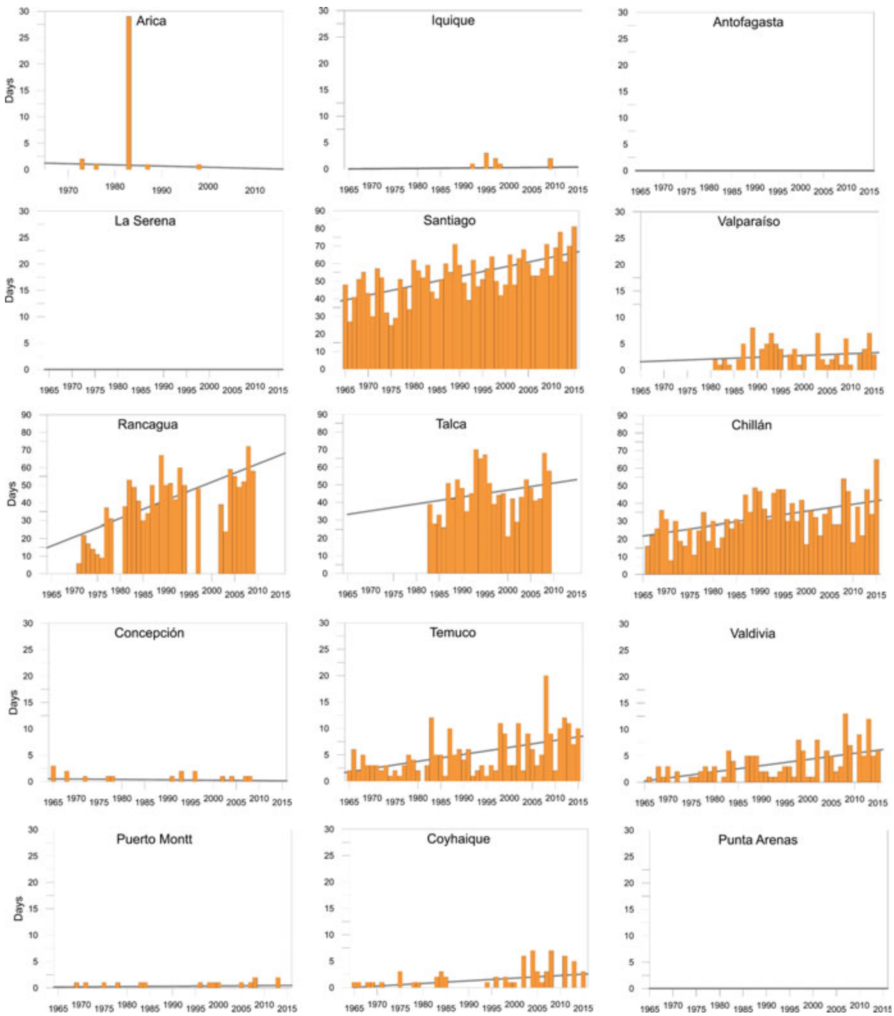

Fig. 11.3 Time series of the number of days above 30 °C (SU30)

the maximum annual temperature (TXx) shows mostly positive results, but only Arica shows a decrease in the TXx. In contrast, in Iquique, the temperature has risen from little more than 27 °C to just over 29 °C.

In the central zone, the cities of Santiago, Rancagua, Talca, and Chillán show the most significant rise in the number of days, with temperatures above 30 °C and 35 °C, increasing to a mean of 4 days per decade. With regard to the maximum annual temperature, positive trends are also shown. For example, the city of Talca shows the highest increase, which exceeds 0.5 °C per decade.

All cities in the southern zone show positive trends in the number of days with higher temperatures (SU30) and in the maximum annual temperatures (TXx). Temuco is the city that shows the largest increment in maximum temperatures, reaching a record of 38.6 °C in the last decade. The city of Valdivia also shows an increase in maximum temperatures. In the 1960s, the maximum temperatures were around 30 °C on average, and by the end of that decade, the average peak values were around 34 °C.

The city of Valparaíso, on the other hand, shows a gradual increase in the number of days with temperatures above 30 °C, mainly in the last decade, where temperatures have risen to almost 34 °C in the Rodelillo station. Wildfires are the second most frequent type of disaster in this city. At the end of January 1991, high temperatures and strong winds caused a forest fire that devastated scrub, grassland, and native forest. However, the wildfire of April 2014 was the biggest fire in Valparaíso's history (Sarricolea and Úbeda 2016), resulting in 15 deaths, 500 injured, 10,000 people affected, 1,140 hectares burned, 2,500 homes destroyed, 17,000 evacuees, 8,500 people who left their homes, and 750 in shelters (Comisión Senado 2015). The highest temperature of that day was recorded as 31.9 °C by the Rodelillo station, and the prevailing winds of that hour were 70 km/h, causing the flames to spread over populated areas of Valparaíso. Global and local climate conditions such as dry periods, low moisture content of air and soil, strong winds, and high temperatures in the summer season, in addition to the wood production from the plantations near urban areas and irregular topography, are responsible for the ignition and spread of wildfires.

Numerous studies concur that the main effects of climate change in central southern Chile are associated with a decrease in precipitation (CONAMA 2006), which would result in an increment in the frequency of wildfires and the surface area affected (González et al. 2011). In this regard, recent international initiatives, such as New Generation Plantations and early certification as defined by the Forest Stewardship Council (FSC), aim to promote and regulate the proper management and sustainability of forests and plantations. In Chile, according to González et al. (2011), policies are needed to promote the territorial planning of rural landscapes and, in particular, the diversification of the forestry sector so that it can meet the challenges posed by climate change and promote healthier forests, in terms of its long-term productivity, diversity, and resilience (Sarricolea and Úbeda 2016). Although the mega-wildfire of January and February 2017, that affected the VI, VII, and VIII regions of the country, is outside of the scope of this analysis, it should be emphasized that it was the worst current wildfire event and was related to heatwaves.

11.7 Heatwaves

The CEI heatwave trends of northern cities are heterogeneous: Arica and Antofagasta show negative results in both indices (WSDI3 and HWN), demonstrating a decrease in the number of both heatwaves and warm periods, decreasing by almost 5 and 3 days per decade respectively. In the city of Iquique, the number of heatwaves has decreased slightly, but the hot period trends have increased, clearly demonstrated by the year 1997, when the warm periods lasted for 175 days. The city of La Serena, on the other hand, shows a rise in the trends for both indices, but does not show very large variations over time.

In the central zone, trends in both the hot periods and the number of heatwaves are positive. The cities of Santiago and Chillán also show significant increases, culminating in 2015 with an average of 35 warm periods. The cities located in southern Chile show mostly positive trends in both indicators, approaching an average increase of 2 days per decade. Meanwhile, Valdivia and Puerto Montt are the only cities that exhibit a decrease in the number of heatwaves; however, the results are very close to 0.

In relation to the warm periods, based on the annual count of 3 consecutive days, it is clear that northern cities (low latitude) show the greatest variations and have the highest values. Arica, Iquique, and Antofagasta in both 1983 and 1997, exceeded 100 events with warm periods, which indicates that the maximum temperatures during those years were well above normal. The cities located in the south of central Chile show an irregular trend, but they do not exhibit very extreme values. In most cities since 2008, trends have been constantly increasing.

Although the results at a general level show a clear increase in the maximum temperatures and number of heatwaves in the cities, only three heatwaves have been defined as a natural disaster in the last half century. Chillán is the city that has had the hottest records (two events in 1978 and 2008), representing cities located in the central zone of Chile. Since 2015, the DMC has defined (DMC 2016) heatwaves by taking into consideration monthly temperature thresholds for different cities across the country. The purpose is the creation of a warning system to inform society about these events and its health risks, particularly in terms of cardiovascular and respiratory diseases, and eventual deaths, especially among the elderly (MINSAL 2016). Figure 11.4 shows the time series of the number of summer heatwaves of the cities.

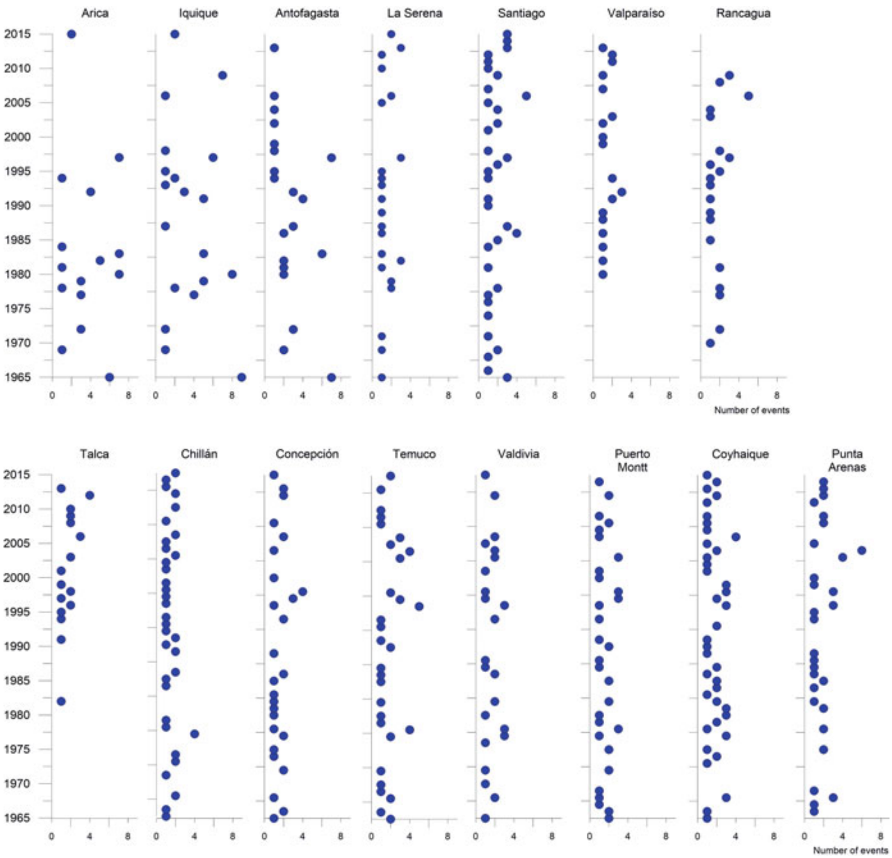

Fig. 11.4 Time series of the number of summer heatwaves (HWNs)

11.8 Extreme Precipitation

Only three cities (Arica, Iquique, and Antofagasta) show positive values in Rx3day and Rx5day CEI tendencies related to extreme precipitations. They correspond to cities located in the Atacama Desert, although the results are very close to 0, because the rainfall events are very exceptional events. Only Antofagasta shows one event (2015) where the rainfall exceeded 20 mm (Fig. 11.5).

Valparaíso and Valdivia show a decrease in maximum precipitation for 5 days (RX5day), which reached almost 16 mm per decade in Valparaíso. This means that in addition to decreasing rainfall, it is mainly concentrated in a shorter period of time. Although La Serena, Santiago, and Concepción show negative trends, there is no great variation in decadal results. Therefore, the intensity of the precipitation of these cities has remained relatively constant. The cases of Rancagua, Talca, Chillán, and Coyhaique are different as they show a decrease of almost 1 mm per year. In

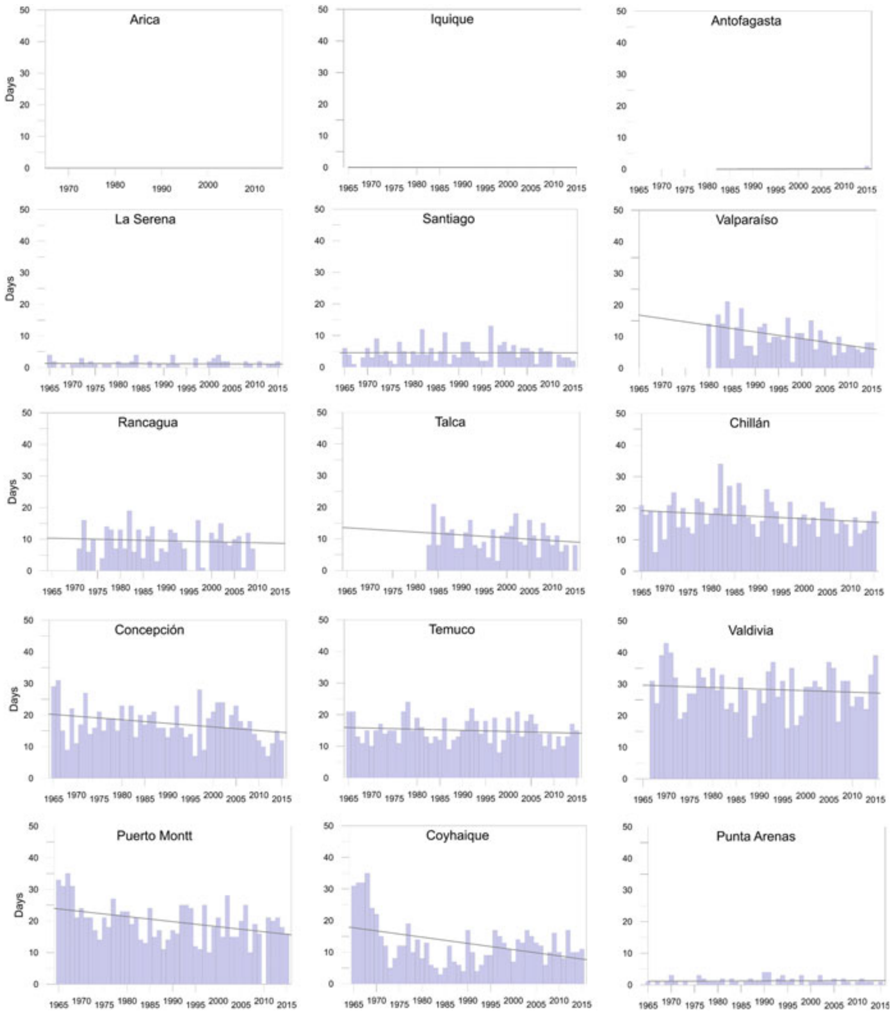

Fig. 11.5 Time series of the number of days with annual total precipitation (PRCTOT) ≥20 mm (R20mm)

Valparaíso, the rainfall events of 5 years have decreased by more than 16 mm per decade. Therefore, the amount of rainfall in short periods has been reduced by almost 70%.

With respect to the total annual amount of daily precipitation higher than 95% of the data (R95p), the cities analyzed show a decrease of 12.41 mm per decade on average, being the CEI that shows the greatest variation. On the other hand, the number of days per year in which precipitation exceeds 20 mm (R20mm) shows that Rancagua and Punta Arenas are the only cities with positive trends. The decadal increase in both cities surpasses 8 mm. Events of intense precipitation in short periods of time could trigger disasters such as floods, flash floods, mudflows, and landslides.

However, in general, rainy days that are over the 95 percentile (R95p) present a 14-mm decrease. Coyhaique and Punta Arenas have contrasting results. On the one hand, the first shows the largest national decrease, amounting to almost 65 mm, whereas the second shows an increase in intense precipitation.

One of the most important precipitation events occurred in May 1965, where storms of wind and rain affected most of the country, from the Atacama to Aysén regions. Housing, public works, agriculture, electrification, and forests were damaged. Successive frontal systems left about 100 dead, 15,000 victims, bridges destroyed, interrupted roads, landslides, isolated populations, lack of food, and sunken ships. The Catastrophe Zone was declared by the National Center for Civil Protection from the Atacama to Aysén regions (ONEMI 2001).

In the city of Arica, located on the coast of Atacama Desert and with an average annual rainfall of 0.5 mm (Sarricolea et al. 2017), natural disasters associated with precipitation have also occurred, triggering floods and mudflows. An example of this was in 1973 when the city was declared a Disaster Zone due to heavy rainfall, causing severe flooding that affected more than 500 persons. A similar situation occurred in 1983, 1986, and 1988, when although the rainfall did not exceed 10 mm, it caused considerable damage because Arica is used to having no precipitation at all. The same happened in 1995, 1996, and 1997, when intense summer rainfalls affected more than 4,000 persons.

Iquique and Antofagasta, cities also located in the desert, have not directly received precipitation, but they have been affected by rainfalls recorded in higher areas, triggering large floods and mudflows from the mountains. For example, in Iquique, February 1972, more than 10,000 persons were affected by the heavy rainfall (LA RED 2015). In 2008, a new event left more than 8,000 affected people. In Antofagasta, on 17 and 18 of June 1991, a strong wind and rainstorm affected the city where a sudden and violent rain fell between 00:30 and 03:30 hours, accumulating between 14 and 42 mm in three pluviometric stations (Garreaud and Rutllant 1996), causing minor mudflows and flooding between 2:00 and 3:00 h and a strong landslide around 4:00 (Vargas et al. 2000). It is important to mention that the precipitation amount recorded at the Universidad Católica del Norte, located within the city, was almost three times higher (47 mm) than that recorded at the Cerro Moreno station, located at the airport at 26 km northward. The city was declared a Catastrophe Zone and 91 persons were dead, 16 missing, 715 injured, 65,000 suffered damages, and 190,000 were affected (LA RED 2015).

La Serena also recorded intense rainfall in 1983 and 1987. In the latter year, rainfall reached 124.8 mm in 41 hours, producing floods that damaged streets and homes (ONEMI 2001).

In the capital of the country, Santiago, rainfalls have produced major damage, especially in communes located in the Andean foothills, where human settlements have been unwisely located in the vicinity of ravines and rivers. Examples of this occurred in 1970, 1972, and 1978, when heavy rainfall caused serious floods that affected thousands. The year 1972 was one of the rainiest, affecting more than

10,000 persons. In 1980, floods had a great impact on the city, affecting more than 40,000 persons in Las Condes commune, interrupting the supply of drinking water. In 1982, there was a flood of great magnitude that caused major problems in different areas of the cities, with 123.6 mm of rain falling in 96 h, causing several sectors of the Mapocho River to overflow (ONEMI 1982), resulting in more than 11,000 affected persons (Urrutia de Hazbun 1993). On May 3rd, 1993, there was a large flood in *Quebrada de Macul*, leaving 26 dead, 85 wounded, 8 missing, 32,654 persons materially affected, 3,486 of whom suffered damage to their homes. The year 2002 was one of the rainiest winters in the capital city of Chile with a rainfall of 211.8 mm in less than 72 hours (EMOL 2002). Hundreds of streets and houses were flooded, school classes were suspended, and there were multiple electric power outages, leaving a total of 12 dead, 11 injured, more than 30,000 homeless, and 170,000 affected.

Valparaíso is the city that has been most affected by heavy precipitation. In 1984, 1987, 1991, and 1992 there were rainfall events associated but with less impact. During July 1984, rains caused floods and landslides over 300 hectares, cutting of 11 roads and affecting 300 persons (ONEMI 2001). In the winter of 1987, rains left 85 homeless and 75 homes damaged, resulting in being one of the strongest recorded storms (ONEMI 1995).

In Rancagua, significant disasters caused by heavy precipitation have also occurred. In June 1974, intense rainfall gave rise to many floods, school classes were suspended for 3 days and a Catastrophe Zone was declared. The city was isolated because roads were cut, bridges were in danger of collapse, the Cachapoal river flooded, and houses and streets were damaged, ultimately affecting 10,000 people (Urrutia 1993). A similar event happened in May 1986, where it rained more than 130 mm in less than 3 days, flooding streets and city houses and affecting 1,500 inhabitants (ONEMI 2001).

Heavy rainfall has also affected the Biobío region, generating major disasters such as floods and landslides. In Chillán, more than 1,000 mm of water had fallen only in July 1980, flooding the slums of the city and leaving hundreds of affected people (ONEMI 2001). In May 1981, more than 100 mm of rain fell in less than 48 h, generating a major disaster that resulted in multiple landslides, and flooding: 1,200 people and 300 homes were affected (Urrutia 1993). During the first days of July 1984, there was a great storm that poured down more than 150 mm of water in 4 days. The disaster led to roads and bridges being cut off, multiple fallen trees interrupting the electricity supply, and numerous floods, leaving 204 homeless and 44 evacuees (LA RED 1994). During July 2006, there were bad weather fronts in the Biobío region that left flooded houses, overflowing channels, flooded streets, and power outages, which affected the cities of Chillán and Concepción, and a Catastrophe Zone was declared in the provinces of Ñuble and Biobío (El Mercurio 2006).

The cities located to the south of the country, although they have a type of temperate rainy weather, they have also been severely affected by storm waters. In Temuco and Valdivia, during the month of June 1976, more than 190 mm of rainfall accumulated in less than a week, which left a total of 2 dead and 62 affected (ONEMI 2001). In July 1982, more than 120 mm of rain fell during 72 h, causing flash floods and flooding, coupled with strong winds that blew the roofs off of several houses and caused the collapse of trees and street posts. In total, 350 people were affected and 1 person died (ONEMI 1982). A similar event occurred in 1993 when the heavy rainfall (146 mm), on June 26th, left 500 victims, 400 evacuees, and 100 damaged homes (ONEMI 2001). In 2001, 2007, and 2009 disasters occurred that affected a considerable number of people. In November 2001, intense rains caused flooding of the peripheral populations, streets, and avenues of sectors bordering the center of Temuco city. In total, there were 245,347 victims and 61,336 affected homes (La RED 2015).

On the other hand, rainstorms have been very frequent during the last 50 years in Puerto Montt, with a huge amount of precipitation and strong winds, added to the fact that the city is located on the coastal shore of the Pacific Ocean. In 1972, 1977, 1979, 1981, and 1982 there were events of large quantities of winter precipitation that left thousands affected, flooded streets and damaged homes, closing the port and cutting the railway line, generating landslides in some areas of high slope, producing rains of more than 130 mm in less than 48 h (Urrutia 1993).

To a lesser extent, the southernmost cities of Chile have also been affected by heavy rains; Coyhaique, on the one hand, recorded extreme events during 1977, when a storm of considerable size left serious flooding in the city and roads were cut off, which resulted in the isolation of hundreds of people (ONEMI 2001). A similar situation occurred in 1984 and 1985, when there were fatalities due to heavy rain and river flooding, affecting streets and peripheral areas of the city (Urrutia 1993). In 1995, 1998, and 2009, there were floods that left dozens of families without communication and needing to occupy schools for shelter.

Finally, in Punta Arenas, major events occurred in 1971, 1977, and 1979, when heavy winter precipitation left hundreds of people affected and having to be evacuated, and caused large floods and river flooding. Other events of lesser magnitude occurred in 1990, 1995, and 2012.

11.9 Drought

Unlike the results obtained in most of the other CEIs, the results of consecutive dry days (CDDs) do not show a clear pattern associated with the geographic location of cities. However, negative tendencies of total annual precipitation (PRCTOT) are present in northern, central, and southern cities (Fig. 11.6). For example, Valparaíso shows an increase in the number of consecutive dry days and a considerable gradual decrease with respect to the total annual precipitation: this relationship has been observed since 2003 and became particularly accentuated in 2007, when only 237 mm (below the annual rainfall mean of 585 mm) were recorded. From this last year, the number of consecutive dry days increased from an average of 100 to more than 200 dry days in the last decade. Puerto Montt and Coyhaique also have large variations in precipitation, decreasing by more than 90 mm per decade. In general, since 1998, in most cities the total amount of annual precipitation has

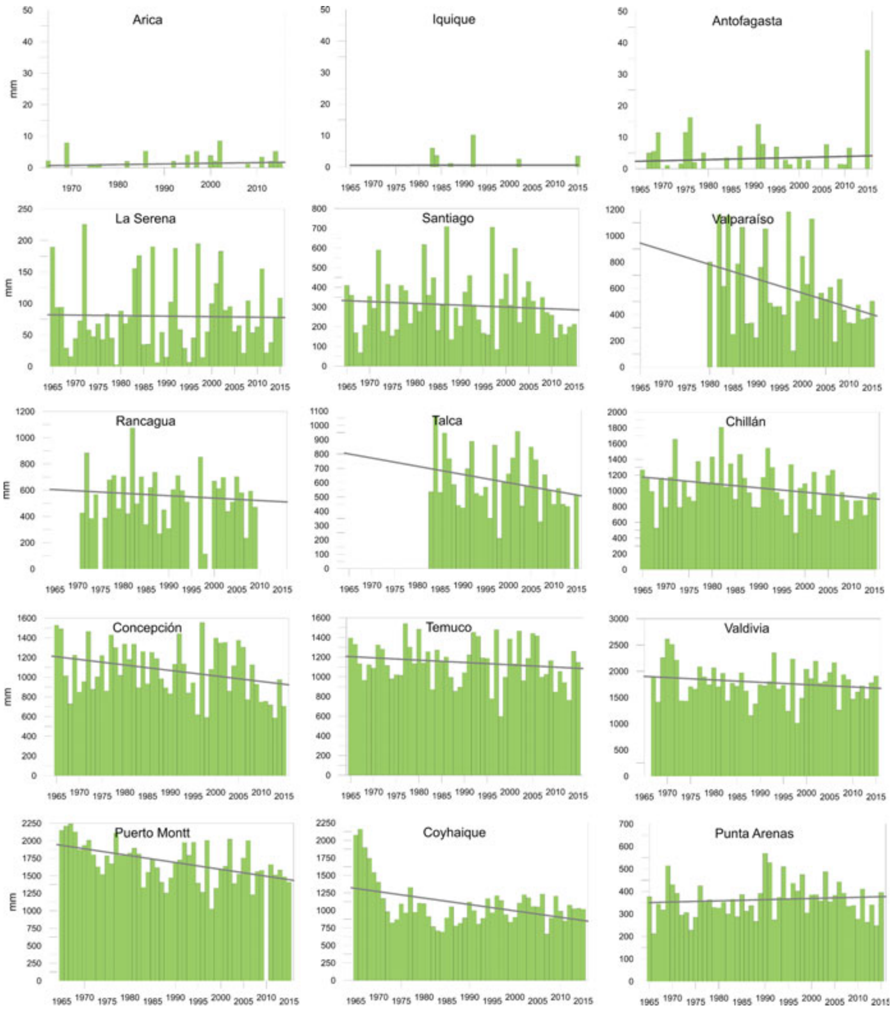

Fig. 11.6 Time series of the annual total precipitation (PRCTOT)

gradually started to decrease, and in the last 20 years, rainfall in Chilean cities has been considerably low.

Northern cities show a very small amount of rainfall, but are well above the mean. Arica, Iquique, and Antofagasta have recorded episodes where they did not receive any rain for more than 3 years. La Serena, Santiago, Valparaíso, and Rancagua have on average more than 150 consecutive dry days. The remaining cities appear to have events that fluctuate between 50 and 100 consecutive dry days, increasing gradually from 2009 onward. All of these results could have a clear influence on triggering a natural disaster such as drought (Fig. 11.6).

At a general level, the driest periods were recorded at the end of 1960s, when one of the largest rainfall deficits since 1924 occurred. The great drought of 1968 affected seven regions of the country, especially the north and central zones, causing large losses in agriculture, livestock, mining, and energy problems as this area accounted for 75% of the country's population at that time (Schneider 1968).

In the last few years, the country has also been affected by a considerable decrease in precipitation originating in what is known as the "*Mega sequía*" (Centro de Ciencia del Clima y la Resiliencia (CR)2 2015). Since 2010, the territory between the regions of Coquimbo and Araucanía have experienced a rainfall deficit close to 30%, which, together with the warmest decade of the last 100 years, has exacerbated water deficits through evaporation (Centro de Ciencia del Clima y la Resiliencia (CR)2 2015).

11.10 Climate Disasters and CEI Relationship

The inventory of the five climate disaster groups representing seven types of natural disasters mentioned in this chapter shows that selected Chilean cities have been affected by a total of 682 natural disasters (Catastrophe Zone) over the past 50 years (Fig. 11.7).

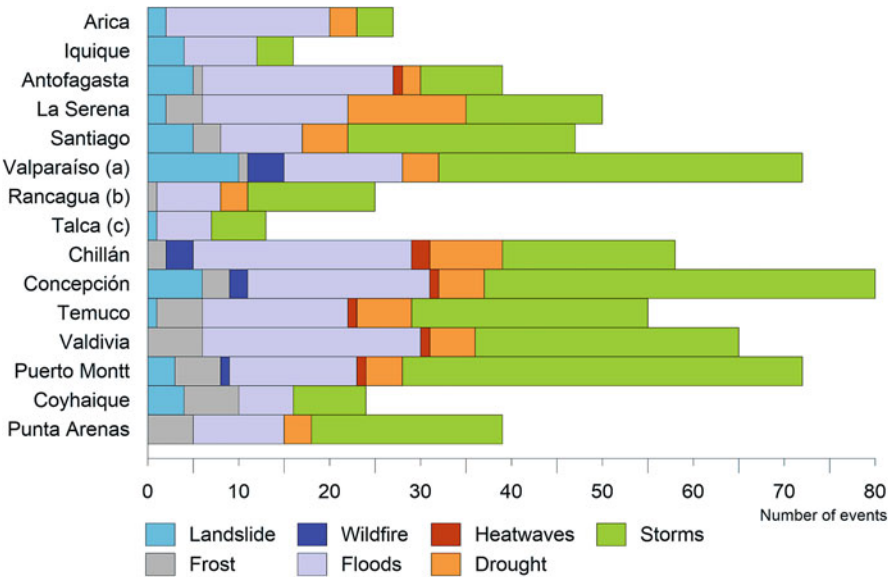

Fig. 11.7 Natural disasters distribution in Chilean cities. (a) 1980–2015 period; (b) 1970–2010 period; (c) 1982–2015 period
Note: All climate disasters correspond to socio-natural disasters (especially the wildfires). The drought records, in some cases, not match with the meteorological definition (desert cities)

Of the past 50 years of records, 2003 and 2010 were the only years in which disasters associated with climatic events did not occur. In contrast, 1991 and 1997 were the years when more disasters occurred, mainly caused by heavy precipitation. The fewest numbers of disasters were recorded in 2012 and 2013.

Concepción is the city where the greatest number of natural disasters have occurred, accounting for 80 events (10.5% of the total), followed by the cities of Valparaíso and Puerto Montt with 74 events each. In these three cities, storms are the most recurrent natural disaster and have caused serious damage to homes, streets, and ports, as all are coastal cities located in central and southern Chile. This same trend is reflected in the rest of the cities, where storm disaster has manifested itself in 40.2% of the total number of disasters, followed by floods (27.8%) and droughts (8%). This shows that both the presence and absence of precipitation in cities has had a considerable impact by causing serious material damage and affecting people.

It should be noted that disasters in Chilean cities are associated with the El Niño and La Niña phenomena, which are characterized by abnormal warm sea surface temperatures along the South East Pacific Ocean border (DMC 2015). During 1972–1973, 1982–1983, 1991–1992, and 1997–1998, the El Niño phenomenon had a severe impact on the precipitation of Chilean cities, where major disasters occurred. However, there were also years such as 1987, 1994, 1995, and 2003 where the El Niño phenomenon was present, but it did not increase the total annual rainfall in cities. On the other hand, La Niña is related to the absence of precipitation, such as in 1965, 1973, 1988, 1998, 2007, and 2011, which influenced the outset of great droughts and severely affected cities in northern and central Chile.

Figure 11.8 shows the relationship between several types of climatic threats (CEIs) and disasters per year that have affected Chilean cities. In the last 50 years, there have been 682 natural disasters and 435 potential threats. The ratio by city between CEI and natural disasters shows that 66.4% correspond to a threat and 33.4% to noncoinciding disaster. These results show that climatic threats defined from the CEI have a high probability of triggering a natural disaster. In descending order, Coyhaique, Valdivia, and Antofagasta have a higher percentage of threats occurring (about 70%). In contrast, with regard to the noncoinciding disasters, the cities of Arica, Iquique, and Santiago show a greater percentage, which surpasses 40%. Despite precipitation showing a clear decrease over time in the cities, it is the main protagonist at the moment of triggering a natural disaster, as it is the most important event in relation to the threats that occur.

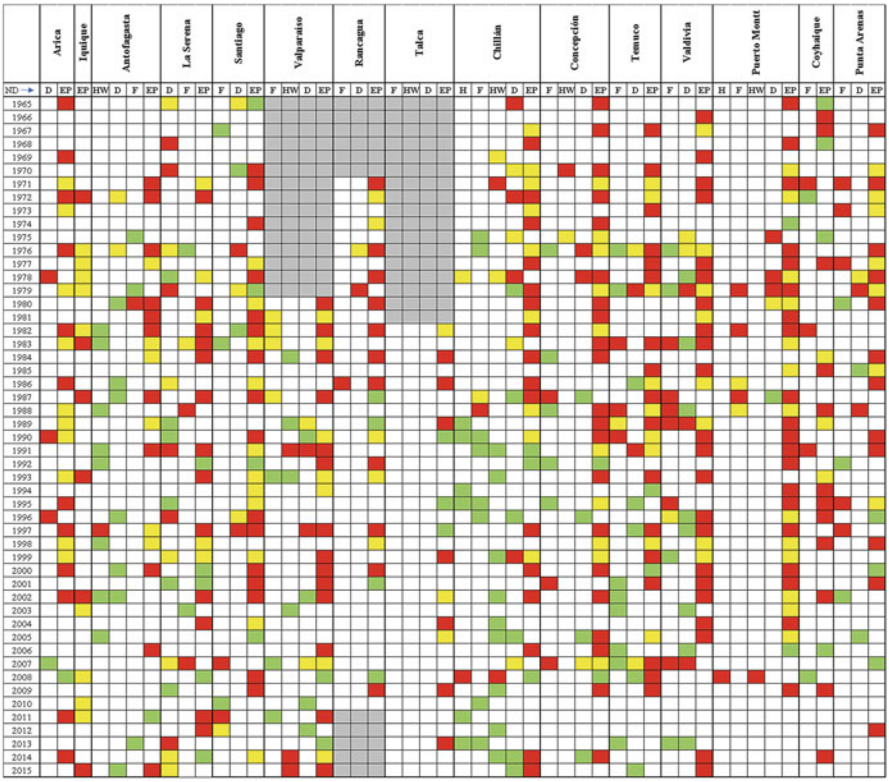

Fig. 11.8 Relationship between climate extreme indices (CEIs; threats) and climate disasters (historical records). ND, natural disasters. Colors (see Table 11.4): red, threat as impact; green, potential threat; yellow mismatched disaster; white, no threat or disaster; gray, no data

11.11 Discussion

Many cities are especially vulnerable to extreme events such as storms, floods, landslides, or wildfires, especially in the south-central zone of the country. Both inner and coastal cities are highly exposed to these events because it is where most of the population is concentrated. The city of Concepción is highlighted as the most affected by the high frequency of disasters, followed by the cities of Valparaíso and Puerto Montt.

On the other hand, climate change models (CEPAL 2009) predict an exacerbation of these hydrometeorological problems in addition to the probable addition of others, such as the effects of heatwaves, which currently do not have a considerable amount of importance, but will require greater preparation in the future.

It is important to focus efforts on these cities so that in the future, they will see themselves mostly affected by the impacts of climate change and natural climate variability to change the reactive approach to an emergency, such as the declaration of a disaster area, to a proactive and strategic approach, such as effective disaster risk management (Henríquez et al. 2016). Examples include the March 2015 events in Atacama Desert, where there were a total of 18 floods and overflows of watercourses and mudflows (ONEMI 2015a, b). Unusual oceanic and atmospheric conditions produced a heavy precipitation event, resulting from a a cutoff low-pressure system (Barrett et al. 2016). Because of a high heat event, an extreme precipitation event was produced that caused damaging stream flows from precipitation totals greater than 45 mm. This occurred in the semi-arid and hyper-arid Atacama region, causing catastrophic disasters (Barrett et al. 2016; Wilcox et al. 2016). There were 31 deaths, 16 missing persons, 30,000 displaced persons, and 164,000 people affected, in addition to widespread damage to homes, roads, bridges, and railways (ONEMI 2015a, b). Historically, in some areas of the Atacama Desert, events of heavy precipitation, landslide, and floods of small magnitude have been observed, but the event of March 2015 had characteristics that had never been registered previously (Wilcox et al. 2016). The Atacama region was the most affected, especially the cities of Copiapó, Paipote, Chañaral, Tierra Amarilla, and other localities of the region (ONEMI 2015a, b).

Another example was the great wildfire in January 2017, mentioned before, that affected thousands of hectares between the central and central southern region and, again, Catastrophe Zones were declared for the VI and VIII regions by President Michelle Bachelet (El Mostrador 2017). The most deleterious impact was the complete destruction of the forest town of Santa Olga.

This implies a great challenge for adaptation and management of the risk cycle in Latin American cities. First, in a pre-disaster phase, long-term territorial planning guidelines are required to reduce exposure and vulnerability, for example, by defining areas excluded from urban development, buffer zones against wildfires, the proposal of aquifer recharge zones to face droughts, among others. Similarly, monitoring and early warning systems need to be improved to deal with rapid-speed events such as mudflows/landslides or floods. At this point, it is essential to articulate with the agencies responsible for risk management, both at the central level and at the municipal and community levels. Finally, in a post-emergency phase, it is necessary to improve aid systems, reconstruction, recovery and, above all, increase the levels of territorial resilience through education and awareness of the population and of decision-makers, which will allow us to better face future catastrophic events (Martínez et al. 2016).

A relevant example of natural risk management corresponds to the case of the city of Manizales, Colombia. The plan includes management areas that are directly related to prevention, care, and recovery from natural hazards, mainly related to landslides detonated by heavy rains. In addition, it has incorporated the Territorial Land Use Plan (POT in Spanish) as a fundamental axis in risk management (Londoño 2007; PREDECAN 2009). The "Guardians of the Slope" program stands out, which seeks to reinforce a culture of prevention, from the knowledge of the threat and the delivery of tools, recognizing women as a central part of the monitoring program (Mejía et al. 2016).

11.12 Conclusions

The main lesson of this 50-year inventory of climate disasters and CEI trends is that cities are highly exposed to climate natural events independent of its prevailing climatic dominance, ranging from the arid extreme desert in the north to the cold southern area. It can be concluded that the changes observed in CEI associated with temperature increases and decreased rainfall are significant in almost all cities. Natural disasters are almost 50% associated with the trend of CEI that is above the series average. Other emerging threats are heatwaves that can generate strong impacts on cities that are not sufficiently prepared.

Many of the extreme events are associated with the El Niño phenomenon, especially from extreme precipitation concentrated in a short period of time. The heatwaves and droughts should be the impacts most associated with climate change anomalies. Future predictions of CEI can serve as a proxy for future risk estimation in Latin American cities.

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Chapter 12
Urban Climate and Dengue Epidemics in Brazil

Wilson Roseghini, Francisco Mendonça, and Pietro Ceccato

Abstract Dengue is currently one of the most serious worldwide public health problems. It is considered an neglected urban tropical disease by the World Health Organization, and Latin America has the ideal environment conditions for the proliferation of the *Aedes* mosquito (*Aedes aegypti* and *albopictus*), vector of the disease. Moreover, the urbanization, lifestyle, and ineffectiveness of public health policies have resulted in severe epidemics. This research focuses on analyzing the influence of the urban climate and the proliferation of dengue in three different cities in Brazil: Campo Grande, Maringá, and Ribeirão Preto, correlating climatic variables with the incidence of the disease through the use of GIS and modeling tools to understand the dynamics of the urban climate. The analysis of daily temperature showed significant correlation ($R = 0.70$ and $P > 0.99$) with the records of the disease and a delay of 7 days, just as there is a good correlation between the end of the rainy season and the epidemic peak. The results show the complexity of the disease, in a close relationship among the environment, the circulation of different serotypes, solid waste disposal, rubble, and abandoned pools, which puts its own population at risk and vulnerable to disease. An important point is that, even in different cities, the epidemic followed a similar pattern, emphasizing the importance of climate variables in an epidemiological understanding of this process. From the results, it is expected that study helps local health agencies in implementing appropriate early warning systems from monitoring and preventive control of environmental conditions.

Keyword Dengue · *Aedes* mosquito · Urban climate · Urbanization · Brazil

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12.1 Introduction

In the second half of the twentieth century, the cities of the southern countries registered an explosive growth, marked by a general degradation of quality and urban living conditions, which Santos (1993) conceived of as *corporate urbanization*. In previous decades, several studies have pointed to the genesis and aggravation of environmental problems associated with large and gigantic cities (Ramade 1987; PNUD 1997), especially the urban climate (Monteiro 1976, 2015; Monteiro and Mendonça 2004).

Among the various problems that affect the quality of life of the populations of cities, those related to human health are highlighted. Since the advent of modernity, the moment of the increasingly intense association between industrialization and urbanization, the conditions of collective health and public health have presented the most complex situations. Howard's initial studies about London have revealed the necessary link among the elements of the natural environment, the social dimension, and the built environment to understand this type of problem, especially because they have become much worse in the twentieth century (Sorre 1984).

In developing countries, the interaction between the components of the natural, the social and the built environment has created alarming situations regarding the public and collective health of populations (PNUD 1997). In these countries, the exacerbated concentrated income has generated alarming conditions for the health–disease process of the population, which is especially reflected in the high mortality and human morbidity indices.

Airborne diseases and waterborne diseases (notably) occupy a prominent place in the epidemiological framework of these countries, and the climate plays a special role in them as they form epidemic situations that have a great impact on society. Dengue, an airborne disease, is the most significant arbovirus affecting humans and currently constitutes a serious public health problem worldwide. Globally, around 2.5 billion people live in areas where dengue viruses can be transmitted. According to the World Health Organization (WHO), the current global scenario features hyper-endemic levels in many urban centers located in the tropics (WHO 2011).

Dengue is a disease classified as an arbovirus that is transmitted in Brazil by the mosquito *Aedes aegypti* (Diptera: *Culicidae*). The virus belongs to the genus Flavivirus, of the family *Flaviviridae*, and its infection is caused by four serotypes that produce serotype-specific immunity. In its most severe clinical forms, it can manifest as dengue fever, hemorrhagic fever, and dengue shock syndrome (Ministry of Health 2005).

According to da Silva (2013), any of the four serotypes can cause from undifferentiated febrile illness to the most severe forms. Infection caused by one of the four serotypes provides the individual with permanent immunity to the virus responsible for the infection, but does not confer cross-immunity so that people living in endemic areas where all serotypes circulate may have four infections during their lifetime.

Especially in tropical countries, it can be seen that the conditions of the physical and natural environment (especially climate) associated with the social–cultural environment (urbanization) and ineffectiveness of public health policies, promote the development and proliferation of the mosquito (Mendonça 2007), resulting in severe epidemics. Thus, to understand the issues of dispersion and transmission of dengue, it is necessary to address not only the behavior of infected individuals, but the correlation of all geographic and climatic features present in the urban environment.

Aedes Aegypti is the main vector of dengue in Brazil according to the Brazilian Ministry of Health and it is normally found in urban areas (officially an urban disease), whereas *Aedes albopictus* is found in rural areas.

Approximately 80% (4450) of Brazilian municipalities are in the domain of tropical climates, whereas most of the southern region of the country has a subtropical climate. In this case, Maringá is located on the border of a subtropical climate and Ribeirão Preto and Campo Grande on a tropical climate.

According to Johansson et al. (2009), temperature and precipitation can influence the incidence of dengue because the predominant vector is partly regulated by climate conditions, which provide breeding sites and stimulate egg hatching.

Temperature influences the ability of both *aegypti* and *albopictus* to survive and determines their development and reproductive rates. Increased temperatures increase the frequency of feeding, decrease the time it takes for mosquitoes to become infectious and infecting another host within their lifespan (Johansson et al. 2009).

The causes and consequences of the urbanization process, integrated with climatic variations inside an urban climate, are gaining increasing importance in the study of disease transmission and control.

The increase in human settlements in cities has created scenarios conducive to the spread of the disease vector, because many cities do not offer appropriate garbage collection resulting in construction debris and tires accumulating in properties. Abandoned houses or poorly maintained swimming pools further accentuate the problem.

Higher rates of urban population increase the flow and mobility between cities and metropolitan regions, becoming another important factor in the spread of disease through imported cases.

There is a close overlap between urbanization and changes in the local climate known as the “heat island” effect. These phenomena are detectable on a global scale; however, a more comprehensive understanding of disease transmission also demands better knowledge of the regional and local conditions of their geographical setting, in addition to the public policies and actions that have been established by society for its control.

According to Prinn et al. (1999), the interaction between natural and social aspects of human development has gained special attention from the scientific community, resulting in the development of several models to integrate them. Nonstatistic models for analyzing the urban climate were proposed by Oke (1987) and Monteiro (1976, 2015) and they have been applied in many study cases.

Mendonça (2004) integrated social and technological elements and factors to understand the urban environment as a complex system in which he includes the health of the population.

We focus on three cities in Brazil where high rates of disease and a history of serious epidemics have been reported. They are located in the central southern region of Brazil, and these cities are also key transportation hubs experiencing a large flow of people and goods, thus allowing us to study the importance of socioeconomic factors with respect to disease transmission.

12.2 Urban/Local Climate Conditions and Dengue in Southeastern Brazilian Cities

The three cities analyzed here present the formation of very similar urban climates (Roseghini 2013). The human development index (HDI) has evolved significantly over the last 20 years, even reducing poverty (Table 12.1). Incidentally, in these cities significant dengue epidemics were registered from 2000 to 2011 (see Fig. 12.2, Table 12.1), notably in Campo Grande, even the epidemics were very important in a large number of Brazilian cities since the 1990s.

In the three cities, the urban heat islands (UHIs) show different magnitudes (between 3 °C and 10 °C) and, according to Roseghini (2013), a higher intensity was recorded in the prolonged winter season (May to October). During this period of the year, the urban areas present a lower thermal amplitude than the surroundings owing to the vegetation and urban parks, because in the regional/rural zone, the radiation process is more intense owing to the reduction of the vegetation index – the thermal inertia of the soils (Mendonça 1995).

In the long summer season (Table 12.1), which is more conducive to the formation of dengue epidemics in these cities, the urban atmosphere is relatively warmer than the surroundings because of the expressive and exuberant vegetation cover. With the increase in relative humidity and precipitation in this season, the cities form environments that are highly favorable to the proliferation of dengue vector. Between January and April, the highest indices of dengue were recorded in the three cities, where the strong influence of the climate in the formation of epidemics is observed, in addition to the living conditions of the population and the corporate urbanization observed in them.

12.3 Materials and Methods

The three elements of climate (temperature, humidity, and air pressure), highly transformed within cities, are considered by the SCU – Urban Climate System (Monteiro 1976, 2015) through the use of thermodynamic, hydrometeorological

Table 12.1 Campo Grande, Ribeirão Preto, and Maringá: Population, human development index, climate, and dengue

Cities	Population (2010)	HDI evolution			Mean temperature	Annual mean rainfall	Dengue epidemics (major cases)
		1991	2000	2010			
Campo Grande	784,204	0.563	0.673	0.784	24 °C	1,450 mm	41,428–2010
						70% – October to March	(22 deaths)
					25 °C/December	(Long summer)	
					20 °C/June		
Ribeirão Preto	605,114	0.626	0.733	0.800	23 °C	1,508 mm	29,949–2010
					24 °C/December	70% – October to March	(9 deaths)
					19 °C/June	(Long summer)	
Maringá	357,774	0.608	0.740	0.808	21.9 °C	1,500 mm	7,900–2007
					22 °C/December	60% – November to March	
					15 °C/June	(Long summer)	(6 deaths)

Source: IBGE – Instituto Brasileiro de Geografia e Estatística (http://www.ibge.gov.br/). INMET – Instituto Nacional de Meteorologia – Brazil (http://www.inmet.gov.br/)

and physicochemical subsystems. For each of them, the corresponding problems are identified and addressed, each having a strong impact upon the quality of urban life, such as: UHI, thermal stress, flooding, air pollution, acid rain, etc. All these indicators are perceived differently by society, affecting human development, urban environment, and the health of the population, among others.

For the analysis of the relationship between the urban climate system (SCU) and the incidence of dengue in the Brazilian cities, a supplementary methodological perspective was also used, the SAU – urban environmental system (Mendonça 2004). The junction of these two methodologies indicate that the urban climate and dengue are the components of a socio-environmental system formed by elements of natural order (site + virus + mosquito) and social (city + disease) related to the human activities in the built environment of the city PNUD (1997). The interaction between them, in the context of corporate urbanization (Santos 1993), results in an increase in the incidence of the disease and in the intensification of urban socio-environmental problems.

The dengue data used in this study are provided by three different sources, federal (SINAN – Ministry of Health), state, and municipal departments (http://dtr2004.saude.gov.br/sinanweb/index.php).

Monthly data on the serotypes, imported cases, hemorrhagic fever, and dengue deaths were acquired for Campo Grande – Mato Grosso do Sul State, Ribeirão Preto – São Paulo State and Maringá – Paraná State (Fig. 12.1) from January 2000 to July 2011. Daily data were obtained only for the Maringá's epidemic of 2006–2007, which allowed a more detailed analysis of that event.

Much of the meteorological data used for the purposes of this study were obtained through the International Research Institute for Climate and Society (IRI) Data Library system (http://iridl.ldeo.columbia.edu/index.html), which contains a wealth of information from satellites and weather stations throughout the world.

Land surface temperature (LST) data were obtained from the *Moderate Resolution Imaging Spectroradiometer* (MODIS) sensor, on board the Terra satellite at 1 km spatial resolution. The MODIS LST is derived from two thermal infrared band channels, i.e., 31 (10.78–11.28 μm) and 32 (11.77–12.27 μm) using the split-window algorithm (Wan et al. 2002), which corrects for atmospheric effects and emissivity using a look-up table based on global land surface emissivity in the thermal infrared (Snyder et al. 1998).

MODIS LST night time 8-day composite products have been shown to be in good agreement with minimum air temperature observations for 28 stations in Africa (Vancutsem et al. 2010). MODIS night-time land surface temperatures from TERRA were used in this analysis as an estimation of minimum air temperature, because the overpass of TERRA coincides with the time of minimum air temperature over Latin America. MODIS LST day time 8-day composite products were also combined with night-time images to derive an 8-day composite mean temperature.

The rainfall estimate data were derived from the NASA Tropical Rainfall Measuring Mission (TRMM), with 25 km of resolution and 3-hourly time step. The TRMM products provide a reasonable estimation of rainfall on monthly scales, but are less skilled at correctly specifying moderate and light events at short time intervals (Dinku et al. 2008).

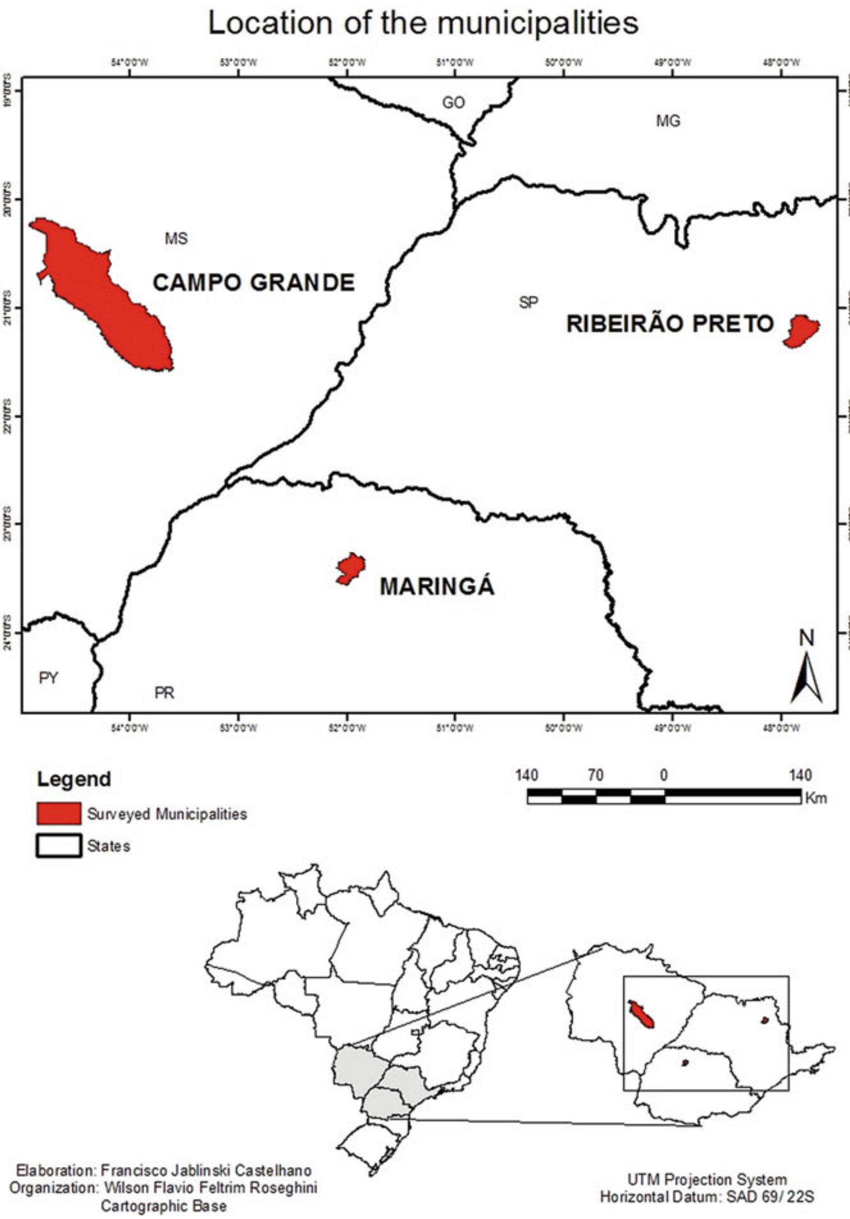

Fig. 12.1 Campo Grande, Ribeirão Preto and Maringá – Geographical localization

In addition, meteorological data from in-situ stations (rainfall and temperatures) were also acquired from the INMET – National Institute of Meteorology (http://www.inmet.gov.br/sonabra/maps/automaticas.php) and IAC – Agronomic Institute of Campinas (http://www.ciiagro.sp.gov.br/ciiagroonline), to increase the reliability and accuracy of satellite information.

Monthly and seasonal timescales of dengue epidemics in relation to climate (rainfall and temperature) were first analyzed by comparing time series of absolute values and anomalies between dengue and climate factors. The value that defines epidemics is 100 cases and above per 100,000 inhabitants, a parameter accepted by the Brazilian Ministry of Health and Pan American Health Organization (OPAS 2007).

We also conducted this study based on rhythmic analysis (Monteiro 2001), which uses the analysis of daily weather data elements such as temperature and precipitation. According to the author, the technique of rhythmic analysis of the climate is capable of representing, owing to its fine temporal scale (daily), the interaction of the elements and factors within a regional geographic reality, aiding in the understanding of various social and environmental problems, such as dengue.

However, we used here a tailored approach to the study of rhythm climate in which we considered only the temperature and rain on a daily scale, associated with the data of dengue notifications, allowing a sense of the dynamics of the urban climate and the epidemic.

Owing to the difficulty in acquiring daily data on dengue, statistical analysis was performed only for Maringá during the epidemic of 2007, seeking to understand the importance of weather patterns (rain and temperature) on the dynamics of the disease.

12.4 Seasonal Timescales

Time series analysis of dengue incidences (Fig. 12.2) indicate that there is a synchrony between the epidemics of Campo Grande and Maringá occurring with an average delay of 1 month between the epidemic peak of both, probably because of the population and economic flow between the two cities.

It can be seen in Fig. 12.2 that the occurrence of other serotypes creates new epidemics because of the lack of immunity in the population. We can identify the end of the epidemics of type 1 and type 2 in 2001 and the beginning of serotype 3, which peaked in 2006/2007. Following the occurrence of type 1 after a gap of almost 10 years, which resulted in infection of the population who had not contracted the virus at the beginning of the decade.

Analysis of the relationship between rainfall and dengue incidences indicates different periods for the peak of the dengue epidemic (Fig. 12.2).

Figure 12.3 shows the annual cycle of precipitation and dengue incidence averaged over the years 2000–2011. It is interesting to note that although the peaks of epidemics occur in different months, the three cities have similar rainy seasons (December to March), with maximum precipitation in January.

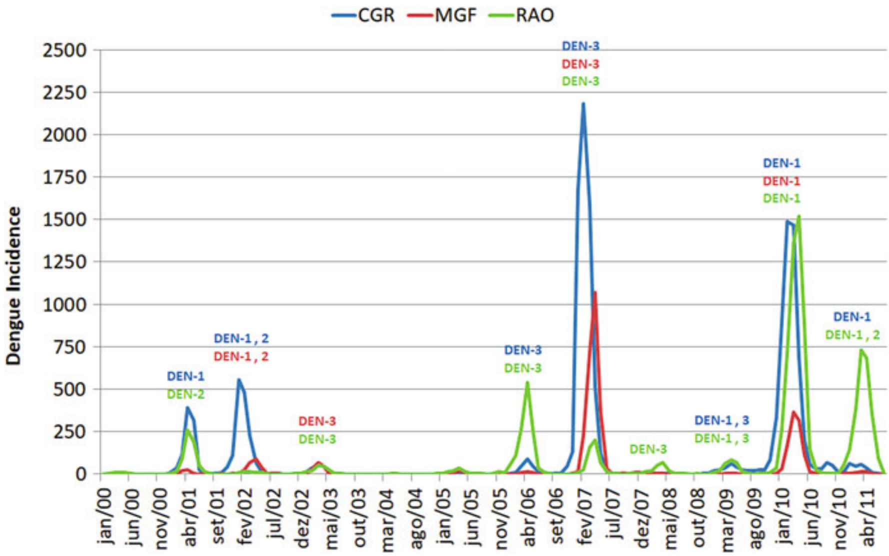

Fig. 12.2 Epidemics and serotypes in the city of Campo Grande (CGR), Maringá (MGF) Ribeirão Preto (RAO) for the period 2000–2011. (Source: SINAN, State Departments of Health, Ministry of Health. DEN-1, 2 and 3 indicate serotype 1, 2, and 3. Unit: cases per 100,000 habitants)

According to Lowe et al. (2010), seasonal climate forecast could have potential value in helping to predict dengue incidence months in advance in southwestern Brazil.

This finding is observable in all three of the cities analyzed, but with a lag of up to 1 month to the epidemic peak to Campo Grande (February) and 3 months to Maringá and Ribeirão Preto (April), perhaps explained by the difference between the beginning and end of the rainy season in each city.

It is interesting to note, when analyzing the rainy season preceding the epidemic, that they have in common the same "ideal" value of rainfall in the period. The optimal value of rainfall normally coincides with the major epidemics that have occurred (Figs. 12.4, 12.5, and 12.6).

In Campo Grande and Maringá, the occurrence of their largest epidemics coincided with years of accumulated rainfall in the 3 months before the epidemics of 500/600 mm. The serotypes were plotted only to show their succession during the episodes.

In the case of Ribeirão Preto, the "range" of total precipitation for the period was not as specific as for previous cities, but the largest outbreaks were always found to fall within the range 500–700 mm.

Figure 12.7 represents the spatial analysis of TRMM anomalies averaged for the rainy season periods (December to March) during two important epidemics and 1 year non-epidemic in the three cities studied.

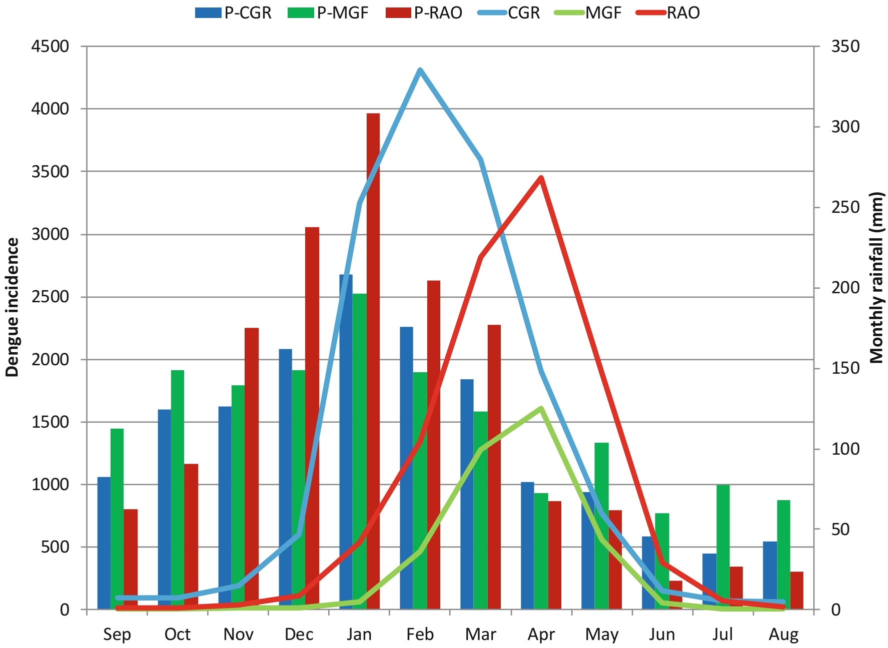

Fig. 12.3 Identification of the monthly patterns of peak epidemics (lines), and TRMM rainfall (bars) in Campo Grande (CGR), Maringá (MGF), and Ribeirão Preto (RAO), between 2000 and 2011

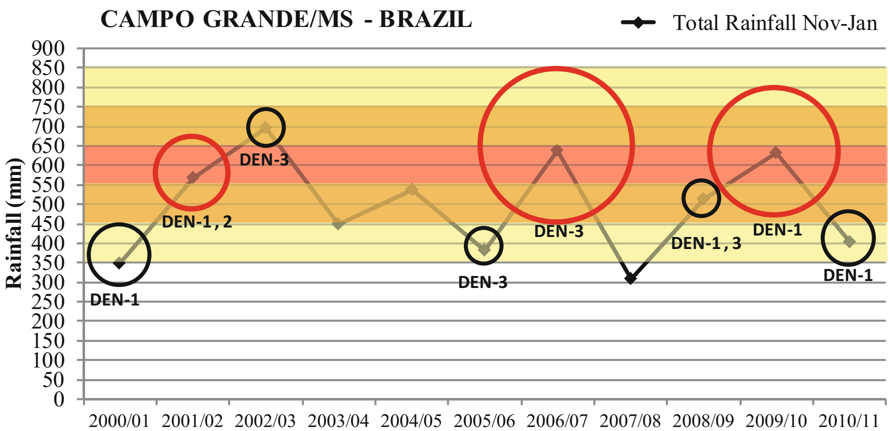

Fig. 12.4 Total rainfall for the period November to January for Campo Grande, highlighting the epidemics and the main circulating serotypes (red circles = larger epidemics, black circles = smaller epidemics). (Source: INMET and SINAN)

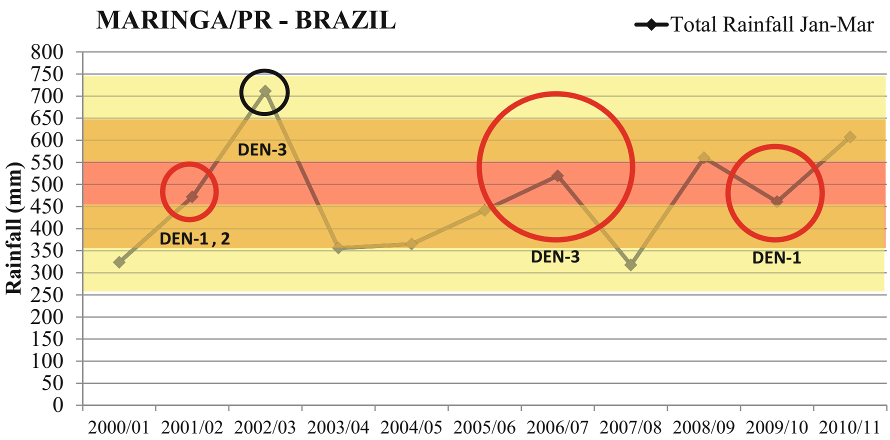

Fig. 12.5 Total rainfall for the period January to March for Maringá, highlighting the epidemics and main circulating serotypes (red circles = larger epidemics, black circles = smaller epidemics). (Source: INMET and SINAN)

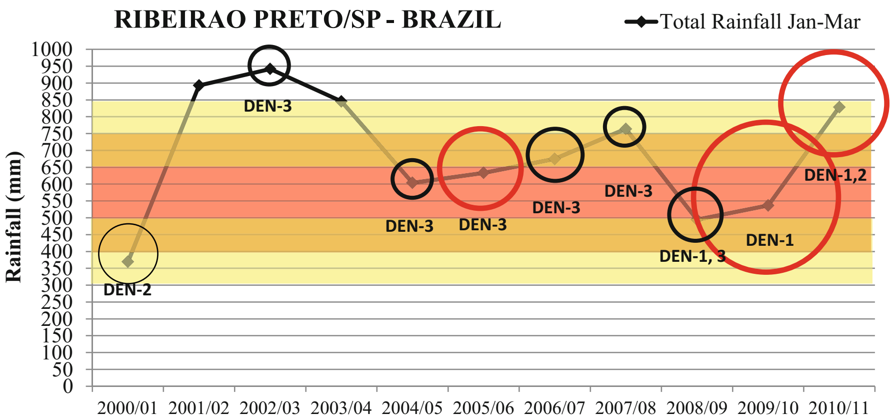

Fig. 12.6 Total rainfall for the period January to March for Ribeirão Preto, highlighting the epidemics and main circulating serotypes (red circles = larger epidemics, black circles = smaller epidemics). (Source: IAC and SINAN)

It can be seen in Fig. 12.7a, b that there is a predominance of positive anomalies of rainfall across the area when the largest epidemics occurred. In Campo Grande and Maringá (2006–2007 and 2009–2010) the two epidemics were due to the introduction of a new serotype Den-3, in 2006 and the return of Den-1 in 2010. Ribeirão Preto had its biggest epidemic in 2009–2010. In 2003–2004 (Fig. 12.7c) negative anomalies of rainfall across the study area coincided with a non-epidemic period for the three cities.

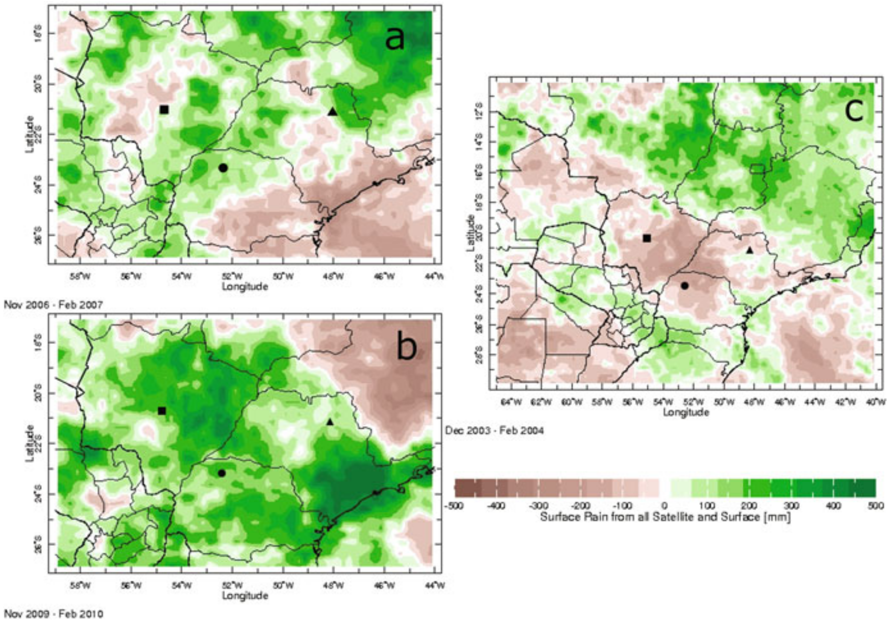

Fig. 12.7 December to March precipitation anomalies for the rainy season), according to TRMM data, for the epidemics (**a**) 2006–2007 and (**b**) 2009–2010, and (**c**) the non-epidemic 2003–2004. CGR (square), MGF (dot), and RAO (triangle)

Those results show that epidemics occurred after positive rainfall anomalies in the region. However, positive rainfall anomalies also occurred with non-epidemics, implying that the serotype circulation might be an important factor. The following monthly analysis explores in more detail the relationship between monthly rainfall and temperature anomalies with dengue epidemics.

12.5 Monthly Timescale

On a monthly timescale, no significant correlations were found between precipitation anomalies and dengue incidence (Table 12.2).

Despite the fact that we do not observe good correlations between rainfall anomalies and dengue epidemics on a local scale in the three cities, our analysis shows that good rainfall must occur in the region during the period December to March to have epidemics, but it is not a sufficient condition. We observed that large epidemics occur when new serotypes are introduced into a non-immune population. This was the case in the large epidemics of 2006–2007 with the new serotype DEN-3 and 2009–2010 with serotype DEN-1 occurring 10 years after the last epidemic in Maringá and Campo Grande (Figs. 12.8, 12.9, and 12.10).

Table 12.2 Correlations between monthly rainfall anomalies and dengue cases with no lag, 1, 2 and 3 months of lag

	No lag	1-month lag	2-month lag	3-month lag
Campo Grande	0.03	0.03	0.07	0.08
Maringá	−0.03	0.04	0.04	0.09
Ribeirão Preto	−0.09	−0.05	0.01	0.06

Source: rainfall estimates from the IRI Data Library and dengue by SINAN

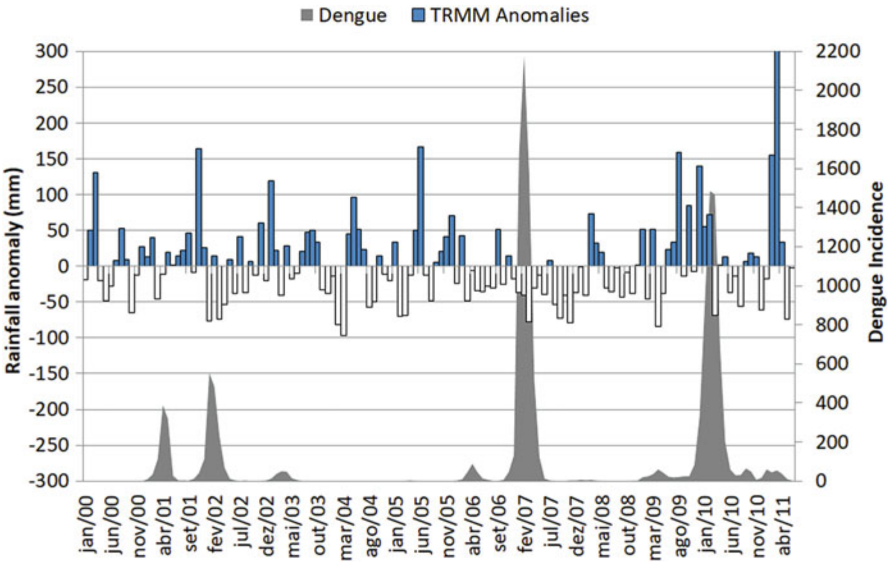

Fig. 12.8 Monthly rainfall anomalies in Campo Grande and dengue incidence. (Source: TRMM rainfall estimates from the IRI Data Library and dengue by SINAN)

In Ribeirão Preto, we observed a large epidemic in 2010 after positive rainfall anomalies and the introduction of the serotype DEN-1. However, the epidemic in 2011 was less than 2010 probably because the total rainfall exceeded the ideal range, especially during March 2011 when heavy rainfall might have washed the breeding sites (average March rainfall is 176.8 mm and March 2011 was 472.3 mm).

The relationship between temperature (measured from MODIS LST day/night) with dengue incidence indicates that no significant correlation was found (Table 12.3) between positive anomalies and increased reporting of dengue fever within the period.

The same lack of relationship between temperature anomalies and dengue epidemics can be observed in Fig. 12.11 (Campo Grande), Fig. 12.12 (Maringá), and Fig. 12.13 (Ribeirão Preto).

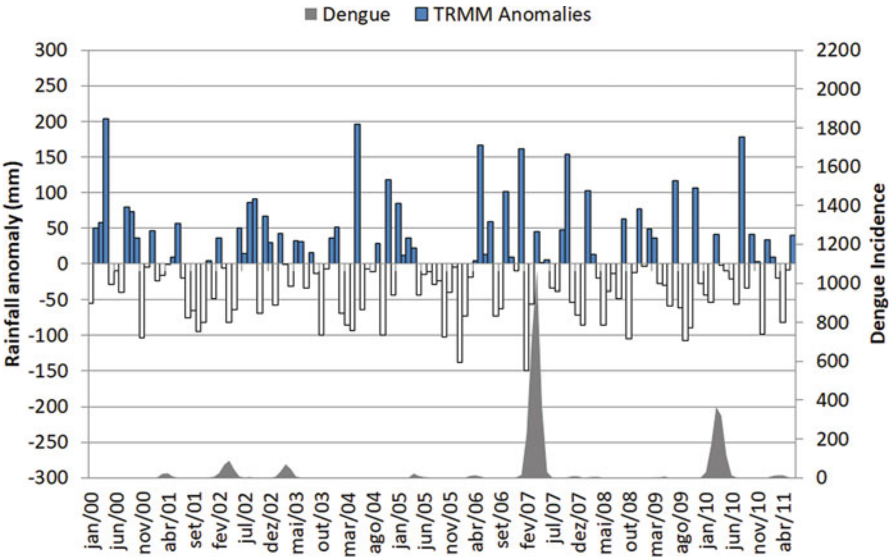

Fig. 12.9 Monthly rainfall anomalies in Maringá and dengue incidence. (Source: TRMM rainfall estimates from the IRI Data Library and dengue by SINAN)

12.6 Daily Timescale

The results of a rhythm analysis (was focused only on temperature and rainfall) on a daily timescale (Fig. 12.14) show a clear relationship between temperature and reported cases of the disease. This rhythm analysis demonstrates a lag between temperature change and disease occurrence of approximately 7 days:

It can be evaluated in the rhythmic analysis of Maringá that falling temperatures in mid-March (14 March) led to the stabilization of the growth of dengue cases in the city.

Soon thereafter, the disease cases increased again as temperature began to rise once more. The correlation between daily temperature and dengue incidence in the following week is 0.70 ($P > 0.99$).

These findings confirm those of other studies, such as Beserra et al. (2006) and Lana et al. (2011), where the authors report the importance of temperature in the cycle of life and the action of mosquitoes, and that the lag of disease occurrence in relation to the temperature is approximately 1 week.

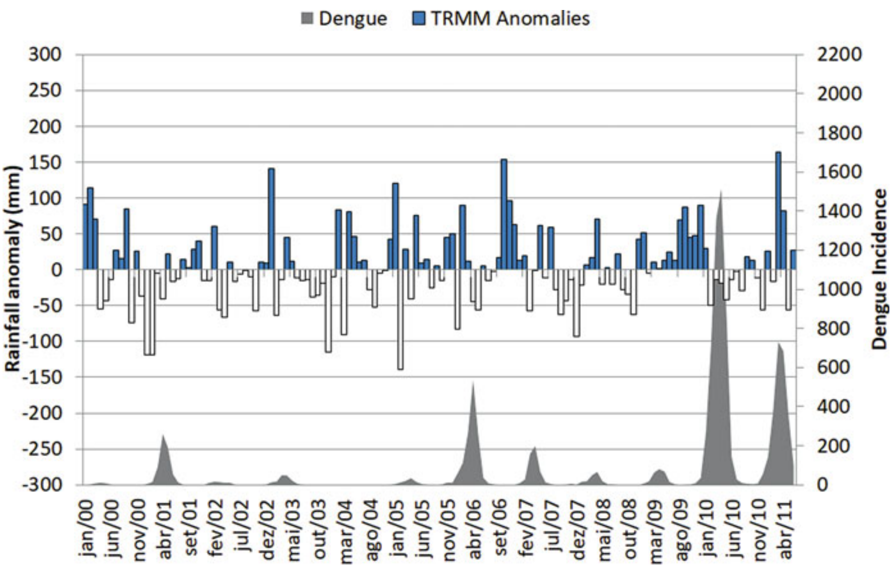

Fig. 12.10 Monthly rainfall anomalies in Ribeirão Preto and dengue incidence. (Source: TRMM rainfall estimates from the IRI Data Library and dengue by SINAN)

Table 12.3 Correlations between monthly temperature anomalies and dengue cases with no lag, and 1, 2, and 3 months of lag

	No lag	1-month lag	2-month lag	3-month lag
CGR	−0.14	−0.17	−0.22	−0.14
MGF	0.10	0.09	0.16	0.16
RAO	0.03	−0.07	−0.09	−0.13

Source: IRI Library, Terra, MODIS, and SINAN

12.7 Discussion and Conclusions

Dengue was officially conceived, in Brazil, as an urban disease. The *Aedes aegypti* mosquito adapted very well to the conditions of Brazilian urbanization. Most of the population live in cities (85%) and the importance of analyzing the urban environment – especially the urban climate – as one of the main factors to the formation of dengue epidemics in the country is evident.

The SCU – Urban Climate System, and the SAU – Urban Environmental System – constitute excellent methodological propositions for the development of studies of the interaction between the urban climate – especially temperature and humidity, and urbanization for the understanding of the dynamic transmissible diseases such as dengue. These methodological perspectives are in relation to the various elements and factors that contribute to the formation of epidemics, which demonstrates the multidisciplinary and multi-causal nature of this type of study.

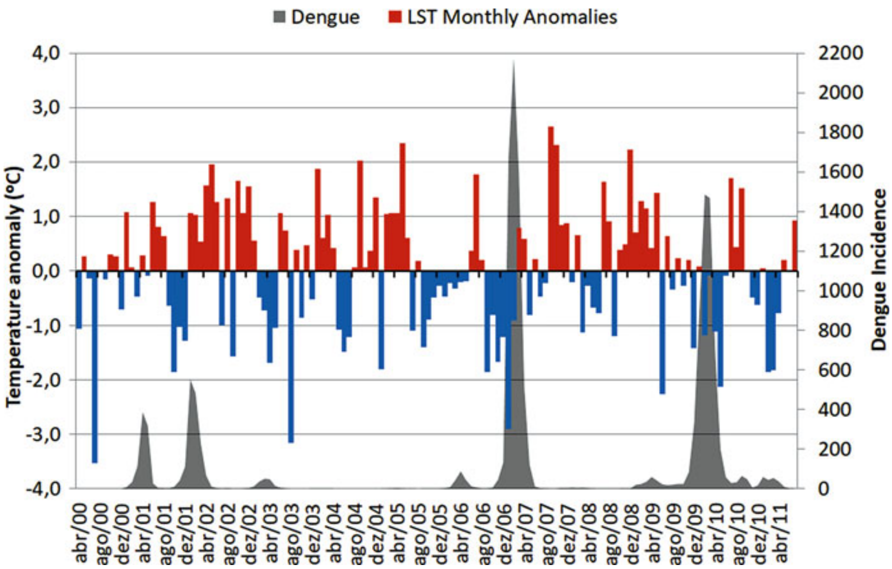

Fig. 12.11 Monthly temperature (land surface temperature [LST]) anomaly and dengue incidence for Campo Grande. (Source: IRI Library, Terra, MODIS, and SINAN)

The refined weather analysis (rhythmic analysis) made it possible to identify the formation of specific weather types for the outbreak of dengue epidemics in the cities analyzed. Considering the conditions of the tropical climate and its derivations in the cities – the urban climate – it was possible to observe urban atmosphere factors, mainly because of the heat and humidity of summer, the formation of an environment that is highly favorable to the proliferation of the dengue vector in the cities.

Our analysis and results showed the importance of the climatic factors (rainfall and temperature) in addition to the serotype in the occurrence of epidemics. However, it is noteworthy that the climate conditions, together with the serotype profile, are not the only factors responsible for the temporal evolution of dengue. The immunity status of the population and other social and environmental elements must be considered as well.

Public policy, the effectiveness of dengue control programs, limited planning, and optimal resources also play a role in the manifestation of dengue. Local policies are important for controlling the disease, because through them the resources to combat dengue are made effective.

The lifestyle of the inhabitants can also be considered a condition for the manifestation of dengue. In particular, the disposal of trash and construction debris left in the backyards of houses or abandoned swimming pools can serve as reservoirs for mosquito breeding. This situation was observed in several locations within the three cities, as highlighted in Fig. 12.15a, b.

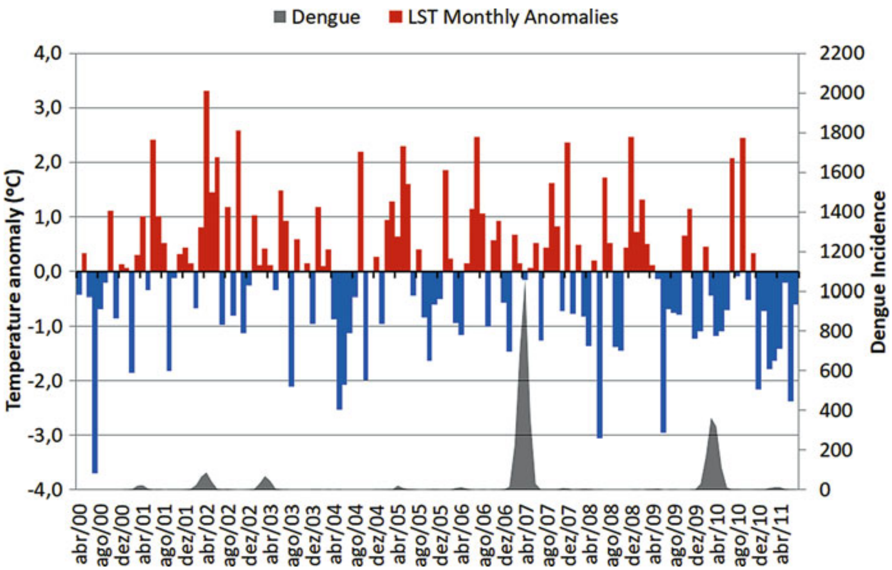

Fig. 12.12 Monthly temperature (LST) anomaly and dengue incidence for Maringá. (Source: IRI Library, Terra, MODIS, and SINAN)

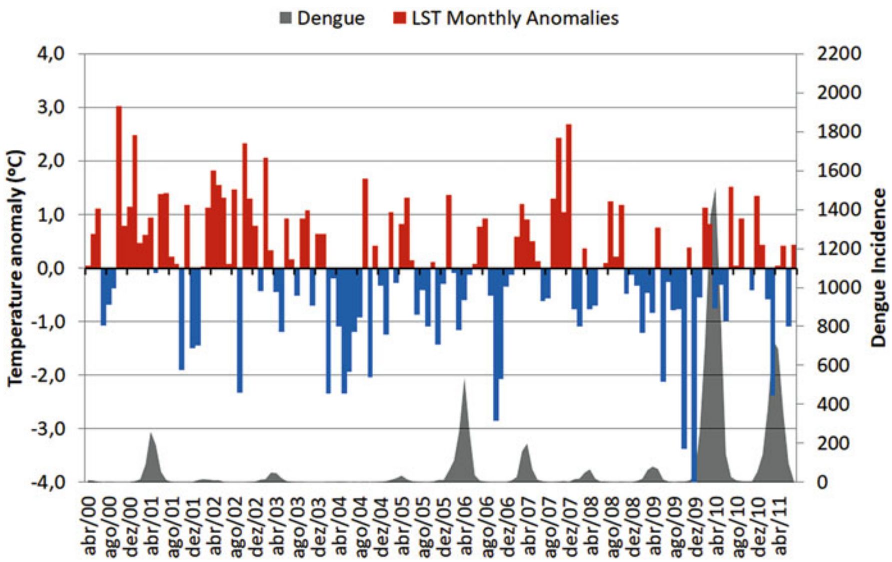

Fig. 12.13 Monthly LST anomaly by satellite (average day/night) and dengue incidence for Ribeirão Preto. (Source: IRI Library, Terra, MODIS, and SINAN)

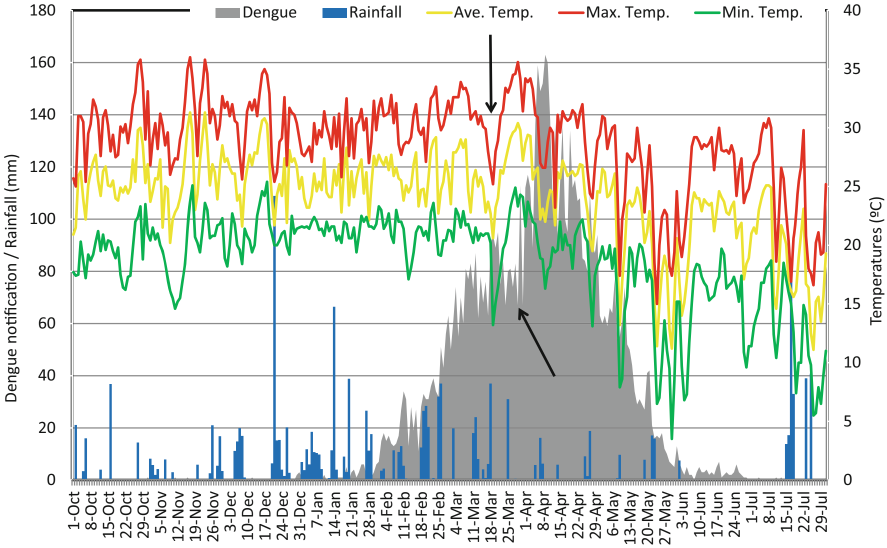

Fig. 12.14 Rhythmic analysis for Maringá (year 2006–2007). Arrows indicate the stabilization of the growth of notifications when temperatures decrease abruptly. (Source: INMET and SINAN)

Fig. 12.15 (**a**, **b**) Abandoned swimming pool and tires, a typical situation encountered in the three cities. (Source: Roseghini 2013)

Another important factor favoring the circulation of serotypes and the increase in dengue cases is the mobility of the population (inter- and intra-flow of urban commuting). Most notifications of imported cases in the three cities come from small surrounding cities, due to a lack of good health assistance, forcing the population to go to the major city in the region to find hospitals and other health care services.

Socioeconomic factors such as inequality and poverty also favor the flow of people from smaller cities to larger ones, not only in the quest for better health services, but also to work and consume.

Campo Grande, Maringá, and Ribeirão Preto are the center of their regions, and it is natural that a larger flow of people coming toward them both from neighboring towns and cities in other states.

As this is a subject of a complex nature, the dengue issue requires interdisciplinary solutions. This research showed that climate is important for the development of epidemic disease in the three cities. Dengue epidemics occur after the rainy season when there are optimal conditions of rainfall, i.e., during the period December to March.

However, we also identified that the introduction of new serotypes plays a role in the development of epidemics. This explains the continued occurrence of epidemics, because even with immunity to one viral serotype, the population may again be infected by another virus.

We also identified the importance of other factors, such as the movement of the population, the presence of breeding sites in the cities (e.g., the disposal of trash and abandoned swimming pools), and control strategies in place as factors that would require deeper analysis of their dynamics and impact on the mosquito vector and disease transmission. It challenges scientists to achieve a better understanding of the current situation and directs them to attempt to predict the factors that are likely to favor the transmission of the disease.

In light of these issues and the challenge of the problems presented, in addition to the complexity of dengue disease itself, this research required an international and multidisciplinary perspective with interaction between professionals from the areas of health, climate, and geography, which could help health care sectors to understand dengue transmission, creating early warning systems and improving disease control actions.

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Chapter 13
Green Infrastructure Planning to Tackle Climate Change in Latin American Cities

Alexis Vásquez, Emanuel Giannotti, Elizabeth Galdámez, Paola Velásquez, and Carolina Devoto

Abstract Green infrastructure (GI) offers a new perspective on the benefits of urban and peri-urban green spaces. In Latin America, the urbanization process has involved a loss of these green spaces of high environmental value. These changes have had a series of consequences on the climate of Latin American cities that have been intensified by climate change. Although the contribution of GI to urban climate regulation and to climate change mitigation and adaptation is growing in recognition, the debate has still had little influence on urban planning initiatives, with exceptions in North America and Europe. In Latin America and Africa little is known about how climate change adaptation plans incorporate the development of urban GI. This chapter explores institutional actions to develop GI as an alternative to tackle climate change in Latin American cities. A bibliographic review was conducted using the terms "green infrastructure" or "climate change." The analysis focused on identifying: responsible institutions, objectives, and the understanding and use of the GI concept. Results indicate that GI has been recently and slowly incorporated into urban planning. This scenario suggests a growing awareness of the need to plan sustainable, green, and more prepared cities to face climate change. However, planners have not considered enough the potential contribution of GI; thus, the role of GI has not been properly identified and valued in urban planning, and planning and design efforts do not maximize the benefits of GI.

Keywords Green infrastructure · Ecosystem services · Urban planning · Climate change adaptation and mitigation

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13.1 Introduction

Together with the rise of environmental concerns, since the 1960s there has been a constant need to include natural processes into urban and land-use planning practice (McHarg 1969; Hough 1995). With this in mind, the concept of green infrastructure (GI) offers a new perspective on the benefits of urban and peri-urban green spaces. According to Planning Policy Statement 12 (PPS12 2008, p.5), GI is defined as a "network of already existing or future multipurpose urban or rural green spaces that support the development of natural and ecologic processes essential for the health and quality of life of sustainable communities."

Beyond this definition, it is possible to define GI as a framework of new conceptions and methods that provide a scientific–theoretical approach to urban planning, aimed at reconciling urban growth, social wellbeing, and environmental protection. This perspective focuses on the ecological and social services offered by green spaces such as climate regulation, air purification, noise mitigation, habitat protection, and the provision of recreation, leisure, and natural areas (Vásquez 2016). Regarding this, the appreciation of the value of urban green spaces has increased in planning practice, as they encourage the development of urban nature and support the emergence of healthy cities and communities (Ahern 2007; Organisation for Economic Co-operation and Development 2016).

However, the incorporation of GI – natural or artificial green spaces – into urban planning initiatives depends on the characteristics of cities and their specific urbanization processes. According to the United Nations, 80% of the population of Latin America and the Caribbean live in urban areas and such a figure is expected to rise to 85% by 2040 (United Nations 2014). This region, which is one of the most urbanized areas in the world, experienced a rapid urban expansion over the last decades of the twentieth century, owing to massive rur-urban migration processes generated by agrarian reforms and the transformation of the labor market and industrialization processes. The fast growth of Latin American cities over this period was marked by inequality, exclusion, polarization, and centralization, and at the same time it was characterized by the emergence of one or two megacities in every country. This is the case, for instance, of Buenos Aires, Santiago of Chile, and Lima (Carrión and Dammert 2016).

The massive influx of migrants exceeded the capacity of the urban economy to absorb this new workforce (Romero 2007). Because of this, many of these new urban residents saw themselves forced to illegally occupy peri-urban areas, generating slums that are vulnerable to natural and human-induced hazards, such as floods and landslides or dumping sites and polluting industries (Vásquez et al. 2017). This situation led to the emergence of common issues such as poverty, social exclusion, socio-spatial segregation, and unequal access to goods and services (CIDES-UMSA 2011).

In addition, urbanization in Latin America is alarming in terms of biodiversity loss because of three main reasons:

(1) At a global level, the physical expansion of cities is occurring more rapidly in areas next to biodiversity hotspots (Seto et al. 2013)
(2) Latin America accounts for more than 50% of global biodiversity – 178 ecological regions – (United Nations 2014)
(3) Some of the most biodiverse countries in the world – Brazil, Colombia and Peru – are found in this region (Székely 2009)

The consequences of the urbanization process on green spaces can be better understood by considering the following Latin American cases. The Eastern hills called "Cerros Orientales" in Bogota, Colombia, have been affected by informal urbanization, despite being protected and considered part of the city's main ecological structure (Carrillo 2011). In the Metropolitan area of Caracas, the situation is similar as the city experienced diffuse growth overtaking the topographical barriers and occupying the natural mountainous land of the periphery (Cariola and Lacabana 2003). Likewise, in the Metropolitan Area of Mexico Valley, 59% of the land under protection, which includes more than 3000 species of flora and about 350 species of fauna, is threatened by rural settlements established on unsuitable land (Mollá 2006). On the other hand, at Veracruz, 90% of the mesophilic mountain forest has been destroyed, and the rest is in danger of disappearing because of its reduction and fragmentation caused by the expansion of agricultural activity (coffee and milk production) and the explosive growth of the city of Xalapa (Marchal and Palma 1985).

The replacement of these natural and artificial green spaces by urban land uses, and consequently the loss of their ecological functions and services, has had many consequences for the climate of the Latin American cities (Romero and Sarricolea 2006), such as a deterioration of air quality (Mesa and Rosa 2005), an increase in urban heat islands, an increase in thermal discomfort, and all the associated health problems.

In this context, Vásquez (2016) suggests that the benefits of GI acquire greater importance within highly uncertain contexts such as climate, social and environmental global changes. As for these events, special attention is given to climate change, which challenges cities – the main habitat of humanity – to become actively engaged in the reduction of the intensity and speed of climate change and to adapt themselves to the negative effects of global warming (Hamin and Gurran 2009).

Although the contribution of GI to urban climate regulation and to climate change mitigation and adaptation in cities is growing in recognition, this debate remains in academic circles having still little influence on local urban planning initiatives, which are mainly implemented in North America and Europe (Hellmund and Smith 2006). There are also few studies that systematize and analyze international experiences of GI focused on climate change mitigation and/or adaptation. In the same way, little is known about how climate adaptation plans incorporate the development of urban GI. This is notably true in the case of Latin America, Asia and Africa.

This chapter presents the results of a review on how different cities, especially in the Latin American case, are incorporating GI to tackle climate change.

13.2 Urban Climate Change and Green Infrastructure

Cities produce a new climate influenced by geographical features, intensity and type of human activities, in addition to the physical structure of the city. Urban climates are being affected by climate change at different intensities and forms. Although future trends depend on a set of variables, there is an agreement that the global temperature will continue to rise, generating increased water scarcity, loss of biodiversity and damages from floods and storms (Intergovernmental Panel On Climate Change 2007). The most significant negative consequences of climate change in urban environments are associated with the development and intensification of urban heat islands, air pollution, the increasing risk of floods and landslides, the rise in sea level, which may threaten coastal cities, and the exacerbation of droughts in arid or semi-arid cities.

Cities are strategic places to address climate change as:

(1) Most of the global population live in urban areas
(2) Population and infrastructure are more likely to be exposed to the negative effects of climate change in cities
(3) Directly or indirectly, cities are responsible for the emission of greenhouse gases
(4) Cities are hubs for the development of innovations and dissemination of ideas and social values

The consequences of climate change and related negative impacts on humanity are determined by the magnitude of climate change and the capacity of society to respond and take measures. Planning initiatives that guide decision-making processes about the use of urban land are progressively incorporating orientations and actions focused on climate change mitigation and/or adaptation.

According to the UN (Magrin 2015), climate change mitigation and adaptation measures are required to tackle the above-mentioned effects in all cities around the world; however, the form and implementation of these initiatives depend on the economic and social features of them. Mitigation measures are focused on reducing the emission of greenhouse gases, which directly influence the increase in global temperature, by limiting the bad practices in production processes and the management of natural resources. Adaptation measures are oriented toward the reduction of risks caused by the new climate conditions, and can be defined as a combination of "adjustments in natural or human systems in response to actual or expected climate stimuli or their effects, which moderate harm or exploit beneficial opportunities" (Intergovernmental Panel On Climate Change 2007). The urgent need to reduce gas emissions has drawn local and international attention to mitigation measures. However, the experience of recent years also suggests the need to rapidly develop a series of adaptation initiatives (Intergovernmental Panel

On Climate Change 2012; Carter et al. 2015). According to the Intergovernmental Panel on Climate Change (2007), mitigation and adaptation measures should be understood as complementary and indivisible approaches when addressing the combined effects of climate change. In this context, adaptation is essential to tackle the impacts of global warming; however, the absence of mitigation measures may lead to a situation where the effects of climate change could exceed the adaptation capacity of natural and human systems.

Many scholars and governmental organizations agree that urban green spaces, conceived as multifunctional GI, play an important role in urban climate regulation and are accordingly helping to delineate urban climate resulting from climate change. As a consequence, GI can be a key component of adaptation strategies, providing cooler microclimates, reducing the surface runoff, or increasing local air circulation (Gill et al. 2007).

Therefore, it is possible to understand GI planning as a strategy that helps cities in their battle against climate change. Such a contributions are twofold: to increase the resilience of urban–ecologic systems – thus improving their preparedness in the event of uncertain circumstances – and to provide that allow cities to address specific issues related to climate change. Vásquez (2016) lists the most important ecosystem services provided by green spaces in the battle against climate change.

Attention should also be given to the capacity of ecosystems to reduce atmospheric CO_2 emissions. Green spaces such as green corridors offer significant opportunities for nonmotorized transport (pedestrian and bicycle traffic), discouraging users from driving, and consequently, producing a decrease in the emission of greenhouse gases. Another important aspect of ecosystems is their capacity to regulate temperature, which may considerably reduce the energy used for cooling or heating purposes. Finally, ecosystems provide different sources for the development of alternative energies such as wind, hydroelectric, and bioenergy (Vásquez 2016).

The geographic and environmental setting of cities determine the ecosystem services that should be promoted by urban green spaces or the GI network to address the local effects of climate change. According to UN (Magrin 2015), Latin American and Caribbean cities suffer from the impacts of climate change such as:

(1) A 0.5 °C–3 °C increase in average temperature over the period 1901–2012, where tropical areas of South America registered the highest increase in temperature
(2) A gradual increase in rainfall in the southeastern and northern areas of South America and in the coastal zones of Peru and Ecuador
(3) A decrease in rainfall in most of the Chilean territory, northern Argentina, southern Mexico, and part of Central America
(4) A progressively late start in the rainy season in Central America, an increase in the space–time variability of rainfall, and an increase in intense precipitation events at the beginning of the season.

What is mentioned above should have a direct effect on the planning objectives of each GI system in Latin America. The problems affecting the urban areas in the region should be identified and analyzed on different scales and dimensions. For instance, some Latin American countries are expected to suffer from a reduced rainfall amount, higher temperatures, and water scarcity. These cases suggest the need to develop green spaces that may resist water scarcity events and have a proper vegetal structure and composition capable of minimizing the effects of urban heat islands.

Another important effect of climate change is the loss of biodiversity. According to the UN (Magrin 2015), land use changes have increased the loss of habitat in six biodiversity hotspots in the region: Mesoamerica, Chocó-Darién-Western Ecuador, the Tropical Andes, Central Chile, the Brazilian Atlantic Forest, and the Brazilian Closed Forest. The transformation of natural ecosystems is the main reason behind the loss of biodiversity and ecosystems within the region. Benedict and McMahon (2006) suggest that establishing a network of diverse green spaces might contribute to the protection of biodiversity, especially within the context of urban expansion processes. GI protects forests, meadows, and wetlands – regarded as hubs for ecosystem services – and promotes the preservation and development of a series of less natural green spaces such as squares, parks, cemeteries, and sport facilities, which promote the existence and survival of wild flora and fauna in urban areas. Likewise, the maintenance of linear green spaces along streams, railways or roads may enable the provision of secondary habitats for local species, improve the biological connectivity within the city, thus making accessible new habitats for species that support climate change adaptation.

13.3 Cities Taking Action Through Green Infrastructure

Despite a general consensus on the theoretical definition of GI, which is grounded in global literature, in practice, there has been a variety of interpretations of the concept (Hansen and Pauleit 2014; Hansen et al. 2014; Mell 2014; Lennon 2014; Young et al. 2014). The wide array of local "planning cultures" (Knieling and Othengrafen 2009) has greatly influenced the way in which this concept has been assimilated and understood. The initiatives associated with GI show different characteristics as they:

(1) Are promoted by multiple actors
(2) Are developed by focusing on all spatial scales, from the local to the international sphere
(3) Use different instruments, including incentives for the development of projects, strategic planning or land use regulation

(4) Have different objectives, such as storm water management, biodiversity protection, or economic revitalization (Mazza et al. 2011; Hansen and Pauleit 2014; Mell 2014)

In this regard, mitigation and adaptation strategies for climate change have been included as key objectives of GI planning only over the last years, favored by a growing concern for the effects of climate change and the adoption of global commitments. Nevertheless, the recognition of the role of GI to tackle the climate change seems still weak in practice (Gill et al. 2007; Matthews et al. 2015; Gill 2009; Kazmierczak and Carter 2010).

North America and Europe are the regions where most of the publications on GI have been produced and more plans have been developed (Davies et al. 2015; Mell 2016). This concept was first proposed in the USA by some scholars (Benedict and McMahon 2006) and then promoted by associations such as the American Planning Association and the Conservation Fund (Mell 2010). At a federal level, there is a lack of clear policies on the planning of GI and fragmentation among different planning spheres. However, the USDA Forest Service, the Federal Insurance and Mitigation Administration (FEMA) and especially the Environmental Protection Agency (EPA) have made various efforts to promote GI (Mell 2014). The EPA is also in charge of conducting policies aimed at combating climate change; however, only recently have they started to make connections between these and GI. Moreover, climate change policies are weak at the federal level, as each of the states are the main promoters of these initiatives (European Parliament 2015; National Climate Assessment 2014).

In the USA, GI plans are increasingly being implemented at a local level, from large metropolitan areas such as New York, Los Angeles, Portland, Seattle, and Philadelphia, to small cities such as Lenexa, Kansas. In line with the policies promoted by the EPA, these plans encourage the creation of GI mainly for sustainable storm water management. Through the creation of regulations and incentives, they promote the development of projects such as rain gardens, blue and green roofs, swales, artificial wetlands, porous paving, rainwater harvesting, and green streets (Rouse and Bunster-Ossa 2013; Keeley et al. 2013; Economides 2014; Environmental Protection Agency 2010).

The case of New York is a good example of how GI is understood and promoted at the local level. Over the last few years, New York planning activities have gained worldwide recognition as they have been capable of increasing its vegetation and alternative mobility considerably, among other achievements (Fontanari et al. 2014; Economides 2014; Zahmatkesh et al. 2014). In 2007, the city approved PlaNYC 2030 – updated in 2011 – which aims to be a shared vision for the future, and in 2015, the new local government launched a new plan (The City of New York 2011, 2015; Committee on Pathways to Urban Sustainability 2016). In both plans, GI is explicitly aimed at the improvement of waterways. The latter was reinforced by the implementation of the Green Infrastructure Plan in 2010, which proposes concrete actions and objectives for sustainable storm water management (NYC Environmental Agency 2010). Despite not being explicitly mentioned, other goals from the plans can be associated with GI, such as the proposal to create a park within a 10-min walk for everybody or the will to protect natural areas. Moreover, a concern for the protection of coastal areas has arisen after Hurricane Sandy (The City of New York 2013). Nevertheless, the strong focus on storm water absorption impedes the full recognition of the potentials and opportunities of GI for the provision of other ecosystem services, including climate regulation and adaptation to climate change (McPhearson et al. 2015; Kremer et al. 2016).

Europe is the other region that offers interesting planning experiences. Despite being recently introduced, the GI concept has been extensively incorporated within EU policies (Lafortezza et al. 2013). The Biodiversity Strategy (2011) and the Green Infrastructure Strategy (2013) were the most prominent initiatives in this regard. The first of these strategies "aims to halt the loss of biodiversity and ecosystem services in the EU and help to stop the loss of biodiversity by 2020." The second strategy promotes many actions to foster the implementation of GI. Unlike the USA, where GI is mainly associated with water management, in the European case, GI is generally associated with biodiversity protection. The second target of the EU Biodiversity Strategy states that "by 2020, ecosystems and their services are maintained and enhanced by establishing GI and restoring at least 15 percent of degraded ecosystems". Likewise, there is recognition that GI may play a key role in climate change mitigation and adaptation through the promotion of the sustainable use of land, water, and living resources. The latter is given to the capacity of ecosystems to sequester carbon and help people adapt to climate change (Naumann et al. 2011; Doswald and Osti 2011).

European policies created a common framework and language that may contribute to the articulation of plans and initiatives that are being developed both locally and nationally. However, the current situation is marked by heterogeneity as each national/local context has a specific planning system. According to a study conducted by Davies et al. (2015), few cities have deliberately embedded the GI concept into their planning processes; "nevertheless, it is also acknowledged that European cities have well developed strategic approaches to green space [or open spaces] planning, and that these approaches may in fact encompass many of the different principles signifying urban GI" (p. 16). Similarly, a study on 100 cases in Europe conducted by Mazza et al. (2011) concludes that "the green infrastructure concept [. . .] is not yet being implemented in an integral form" and that "the term 'green infrastructure' and its equivalents in other languages does not yet have a commonly accepted scope or definition." Nevertheless, "there is a wide range of green infrastructure projects and measures although they are not always identified as such" (pp. 13–14).

The cases of France and Catalonia exemplify two different ways in which GI has been incorporated into urban and national planning. In 2007, France launched *Le Grenelle Environnement*, a round table to debate on the main targets of a public policy on sustainable development (*aménagement durables*). Different initiatives emerged from this action. The *Trame verte et bleue française* – officially translated as Green and Blue Infrastructure – was adopted in 2009 to preserve biodiversity and maintain ecosystem services (Alphandéry and Fortier 2012). Despite France having a long tradition in the planning of urban green areas, the *trame verte et bleue* concept has led to a change in the way they are understood and planned, highlighting their multifunctionality and the necessity to link them to the regional and national scale (Mehdi et al. 2012). The implementation of a system of green areas has become a primary goal for urban planning on a regional and metropolitan scale, providing a common framework that could give a new meaning to singular projects such as the creation of eco-neighborhoods, the requalification of river banks, or the sustainable management of storm water. At the same time, it has created new challenges, as an integrated and transdisciplinary approach is necessary (Cormier et al. 2010; Toublanc and Bonin 2012; Consalès et al. 2012; Roebelling et al. 2017).

In parallel, France is making significant efforts to address climate change. The National Climate Plan invites local authorities to formulate climate action plans, which are mainly focused on the reduction of emissions, promoting energy efficiency in buildings, and sustainable mobility. Within the context of climate change, adaptation actions are rarely included in local plans and the contribution of green areas remains largely ignored (Yalçın and Lefèvre 2012; Bertrand and Simonet 2012; Rankovic et al. 2012). Despite the above, it is possible to find some exceptions, such as the case of Lyon, in which the plan includes a network of green and blue spaces as an effective contribution to the control of urban heat islands, the preservation of biodiversity, and the capture of pollutants (Ville de Lyon 2013).

Catalonia and Barcelona have a long planning tradition that has always paid careful attention to green spaces, on their different scales. In addition, during the last years, there has been great concern regarding the effects of climate change, which has led to the adoption of strategies for mitigation and adaptation (Generalitat de Catalunya 2012a, b; Ayuntamiento de Barcelona 2014). In this context, recently, the GI concept has been explicitly incorporated into urban planning. In 2013, the City Council of Barcelona approved a draft Plan on Green Infrastructure and Biodiversity, which identifies ten strategic guidelines. One of the main goals of the plan is "making the city more resilient in the face of future challenges such as climate change" (Ayuntamiento de Barcelona 2013). Among the most significant aspects in Barcelona, there is the rapid incorporation of GI and related concepts into urban plans and projects, which is reflected in a series of studies focused on the ecosystem services provided by the different types of green areas within the metropolitan and urban area. This has contributed to determining the deficit, potential, and critical points of these spaces (Baró et al. 2014, 2015, 2016; Camp-Calvet et al. 2016).

The incorporation of GI into the urban planning processes is slowly expanding to other regions of the world such as Latin America. Some Latin American cities have begun to adopt and adapt, with different levels of success, experiences developed in North America and Europe.

For example, Colombia has incorporated the concept of Ecological Main Structure into the urban and regional planning, equivalent to GI, oriented mainly toward the preservation of biodiversity (Andrade et al. 2013). However, this has not yet been adequately incorporated into the recently approved National Plan of Adaptation to Climate Change (Republic of Colombia 2016). Similarly, in Chile, some cities are developing GI plans or green corridors, such as Coronel and San Pedro de La Paz, but with a lack of attention to their climate regulatory functions and therefore their contribution to climate adaptation. At a national level, a Climate Change Adaptation Plan was adopted (Climate Change Department 2014) and the government is committed to the Paris Agreement, including the development of GI as a means of dealing with climate change. Mexico is also implementing climate change mitigation and adaptation policies at a national and local level, but with little recognition for the role of urban green areas (Hardoy et al. 2014; Sosa-Rodriguez 2014).

In the region, climate change adaptation plans have had a national character – Chile, Peru, and Colombia, and those of Uruguay and Argentina are in development – which may reflect their recent appearance. Because of this, there is a lack of adaptation plans for climate change on an urban scale in Latin American cities – in Chile it is being developed – and consequently few initiatives integrating GI to tackle climate change (these will be presented in the next section of this chapter).

However, these national policies and plans are important because they define the priorities and emphasis that determine any initiative on an urban scale. On the other hand, green space plan and planning instruments have adopted the GI principles of multifunctionality and connectivity, although the concept in general is not explicitly present, as we will see in the next section.

13.4 Latin American Experiences on Green Infrastructure Planning to Combat Climate Change

This section explores the political and institutional actions for developing GI as an alternative to tackle climate change in Latin American cities. A review was conducted to identify different planning initiatives to deal with climate change using GI. The terms "green infrastructure" or "climate change" were used for a literature search through Google Scholar, Elsevier, and the websites of institutions involved in the development plans and/or strategies in Latin American cities (websites of the Government of the City of Buenos Aires, Environment Secretariat of Colombia, Ministry of Economy of Chile, among others). The analysis was focused on the identification of:

(1) Responsible institutions
(2) The objectives of the initiatives
(3) The – either explicit or implicit – attention given to GI

Eighteen plans and strategies to tackle climate change or develop GI in different Latin American countries were identified.

First, 11 of these initiatives are focused on climate change (Table 13.1). Four out of 11 operate at a national level and are associated with climate change adaptation; from this group, the Climate Change Adaptation Plan for Biodiversity (Chile) is the only initiative that makes an explicit reference to the term GI. Five initiatives have a single city scope and just make indirect references to GI:

Table 13.1 Plans or strategies designed to address climate change (CC) and to develop green infrastructure (GI)

Plan or strategy	Country	Scale	GI	CC
Buenos Aires Action Plan 2030 (2009)	Argentina	City	R	F
Bogota Sustainable Building Program (2014)	Colombia	City	R	F
Master Plan for Sustainable Urban Development, Rio de Janeiro (2009)	Brazil	City	R	F
Municipal Policy for Climate Change Mitigation, Belo Horizonte (2011)	Brazil	City	–	F
Guidelines of the City of São Paulo Action Plan for the Mitigation and Adaptation to Climate Changes (2011)	Brazil	City	R	F
Mexico City Climate Action Program (2014)	Mexico	City	R	F
Climate Change Adaptation Strategy and Mitigation Actions of the Province of Lima (2015)	Peru	Regional	R	F
National Climate Change Adaptation Plan. (2014)	Chile	National	–	F
Climate Change Adaptation Plan for Biodiversity (2014)	Chile	National	R	F
National Climate Change Adaptation Plan (2012)	Colombia	National	R	F
Action Plan for Adaptation and Mitigation Against Climate Change (2010)	Peru	National	R	F
BIO 2030, Master Plan for Medellin, Aburra Valley (2011)	Colombia	Basin	R	R
Curitiba Master Plan (1966)	Brazil	City	R	–
Green Plan, Mexico City (2007)	Mexico	City	F	–
Green Municipal Plan, Campinas (2013)	Brazil	City	F	–
Coronel Green Plan (2012)	Chile	City	F	–
AQUAFONDO-SEDAPAL Alliance (2015)	Peru	Basin	F	–

R: reference to, *F*: focus on

(1) Buenos Aires Action Plan, 2030 – Argentina (2009)
(2) Bogota Sustainable Building Program – Colombia (2014)
(3) Master Plan for Sustainable Urban Development, Rio de Janeiro – Brazil (2009)
(4) Guidelines for its Action Plan for Mitigation and Adaptation to Climate Change, São Paulo – Brazil (2011)
(5) Mexico City Climate Action Program – Mexico (2014)

Second, there are four initiatives focused on the development of GI (Table 13.1). Out of these, there is only one that explicitly recognizes the role of GI in addressing climate change: AQUAFONDO (2016). The remaining programs do not refer to climate change (Curitiba Master Plan, Green Municipal Plan of Campinas and Coronel Green Plan), except for the case of the Green Plan, Mexico City, which defines objectives to combat climate change. However, the actions proposed by this plan to address climate change are not related to GI, but focus on measures such as the inclusion of low-energy lamps within the public lighting system, the consolidation of a Virtual Center for Climate Change, and the implementation of a Hydrometeorological Monitoring and Forecast System for Mexico City.

In general, the review identifies the presence of seven initiatives that benefit from GI to tackle climate change at a city level. This indicates the small impact of this concept on urban planning practice in Latin American countries to this day. However, this scenario suggests a growing awareness of the need to plan sustainable, green and more prepared cities to face climate change. The concern about this has increased recently promoting the development of GI and climate change plans in the last decade.

Accordingly, the GI concept has been vaguely and implicitly incorporated into several initiatives in the region. These initiatives incorporate some GI principles into planning and management of urban green spaces, to maximize the benefits to improve urban climate and climate change adaptation and mitigation. All cases where the GI is implicitly incorporated recognize its multifunctional character. Conversely, the principles of connectivity and systemic integration are generally not used. For example, in Buenos Aires and Bogota, the planning instruments are focused on the development of certain types of green spaces such as green roofs and urban trees, without considering the need for a spatial connection between them. On the contrary, in the cases of Sustainable Rio, São Paulo, Mexico City, and Lima, the instruments incorporate actions that recognize the GI as a network where specific actions become meaningful for their contribution to the system and the fulfillment of the planning objectives.

In institutional terms, these instruments have been the result of the joint work between diverse actors from the public, private and social spheres.

The case of the Mexico City Action Plan stands out as the only case that considers the creation of an exclusive fund to implement the actions. According to Delgado et al. (2012), these types of plans are usually defined and designed at political levels, but then for the implementation stage they must be negotiated with each public institution involved. This ends up subordinating the initiatives an their original goals to the particular interests and possibilities of these actions appeared during this process.

These six indentified plans and strategies address some of the main problems of Latin American cities such as the biodiversity loss. An action for this purpose includes the development of urban green spaces and green buildings (Bogota and Buenos Aires) in addition to protecting natural areas located in peri-urban zones or those remaining areas within the city (Rio de Janeiro and Lima). Aside from the role of GI providing habitat and corridors for wildlife, planners recognize that GI helps to increase the resilience of ecosystems to climate-mediated changes. The latter is especially true in plans at a national level in Chile, Colombia, and Peru.

Conversely, social and environmental inequality has not been a central part of the analyzed plans and strategies. For instance, there is a lack of planning objectives related to a fair distribution of GI and ecosystem services, and consequently a lack of mechanisms against environmental injustice.

In the following text, the six cases in which GI is used to tackle climate change are described.

13.4.1 Buenos Aires Action Plan, 2030: Buenos Aires, Argentina

An Inter-Ministerial Task Force for Climate Change promotes this initiative. This Task Force is a team composed of two representatives from the Ministry of Environment and Public Spaces, the Ministry of Economic Development, the Ministry of Culture, the Ministry of Urban Development, the Ministry of Justice and Security, the Ministry of Finance, the Ministry of Health and the Ministry of Education, the Housing Institute and the Secretariat of Social Communication. This plan is aimed at reducing greenhouse gas emissions by 30% by 2030 (in relation to 2008).

For this purpose, the plan has been structured in different chapters with associated actions, among which the chapter "Urban heat island" stands out, as it refers to the contribution of the GI in the fight against climate change (Government of the City of Buenos Aires 2010).

This chapter gives great importance to the urban heat islands and develops different strategies for their mitigation as a way of dealing with climate change. Considering this, the Plan recognizes the multifunctionality of GI in the mitigation of urban heat islands and describes a series of benefits such as:

(1) The cooling of the air temperature
(2) The improvement of the thermal insulation of buildings
(3) The capture of rainwater
(4) Acting as a habitat for native or migratory species

The urban heat island mitigation actions proposed are the creation of new green spaces through the program "Haciendo Verde Buenos Aires," the development of green roofs on public buildings and the development of urban trees (Government of the City of Buenos Aires 2010). These initiatives are financed by public resources through direct state investments, subsidies, and tax deductions, in addition to low-interest loans.

13.4.2 Bogota Sustainable Building Program: Bogota, Colombia

This program was developed upon the realization that the infrastructure, the urbanization process, and construction activities contribute to increasing the vulnerability of human settlements as the result of climate change. The program recognizes that cities account for 75% of CO_2 emissions and the construction industry is one of the productive sectors that has the greatest environmental impact in the world. Such negative impacts can be observed at each of the different building stages: design, construction, use, maintenance, demolition, and disposal. In this context, the initiative is aimed at becoming an instrument for the prevention, reduction, and mitigation of the environmental impacts generated by the construction sector. This program also seeks to contribute to the goals of the Land-Use Planning and the Environmental Management Plan (Environment Secretariat 2016a).

Developed by the Environment Secretariat (SDA) in 2014, this program values and publicly recognizes the projects that implement Eco-Urban Development and Sustainable Building approaches. In this way, attention is given to improving the environment, the quality of life of the population, and local competitiveness. The latter can be achieved through the proposal of sustainable protection and operation programs for productive sectors, thus mitigating the environmental damage caused by construction processes (Environment Secretariat 2016b).

In this context, the program sets a series of goals related to the design and development of GI. Notable among them is the objective associated with biodiversity, which “encourages the preservation of the natural environment and the increase in biological diversity” through two design strategies:

(1) The elaboration of an urban intervention plan that identifies the components of the main ecological structure as key urban components for the expansion of natural habitat
(2) The incorporation of native tree and shrub species into urban projects

These actions are expected to reduce the negative impacts of urban development on biodiversity and thus increase the resilience of ecosystems and the city as a whole (Environment Secretariat 2016b).

The implementation objective is also related to the development of GI as it proposes to “incorporate the urban project into the environment and its natural elements, encouraging the preservation and/or restoration of the natural habitat” through six design strategies:

(1) Reducing the footprints of projects
(2) Implementing the treatment of wastewater systems generated by construction activities
(3) Reducing surface runoff during precipitation events through the implementation of water retention and/or infiltration systems
(4) Taking into consideration climate variables to contribute to the improvement of habitability conditions
(5) Reducing impervious surfaces exposed to solar radiation through the creation of green spaces, water bodies, shaded areas, and the planting of trees on hard surfaces. All of these efforts are intended to generate exterior areas provided with proper habitability conditions and contribute to pollution control (Environment Secretariat 2016b).

Finally, the water-related objective deals with the increased runoff and reduced infiltration capacity of urban development, which may generate floods during precipitation events. The objective of this section is to “encourage the rational use of water in an eco-friendly manner” by means of a reduction of water consumption through the implementation of storm water and grey water utilization systems (Environment Secretariat 2016b).

All of these measures contribute to GI development and use it as a means of meeting the proposed objectives, which are focused on reducing the environmental footprint of the construction sector and producing cities trying to balance environment, society, and economy (Environment Secretariat 2016a).

13.4.3 Sustainable Rio: Rio de Janeiro, Brazil

There has been significant progress in planning in Rio de Janeiro to address climate change. This development is influenced by the city's close relationship with international milestones such as the 1992 Earth Summit and the United Nations Conference on Sustainable Development "Rio +20" (Prefecture of Rio de Janeiro 2013b).

Rio de Janeiro was a pioneer in Brazil to develop a Municipal Policy on Climate Change and Sustainable Development. Likewise, it created the Carioca Forum on Climate Change and Sustainable Development, in which representatives of the public, private, and civil society sectors participate. This instance seeks to contribute in the search for solutions to deal with the effects of climate change.

Rio has been one of the first cities in the world to develop a Greenhouse Gas Emissions Inventory under the global standard, developed by the World Resources Institute and the World Bank, among others (Prefecture of Rio de Janeiro 2013b).

In this context, the development of the Master Plan for Sustainable Urban Development, or Sustainable Rio, stands out as a municipal planning instrument that guides the actions taken by public and private institutions. This initiative was elaborated in 2014 by the Prefeitura da Cidade do Rio de Janeiro and it is the basic planning instrument of development policy and urban expansion. In addition, the Plan promotes the reduction of greenhouse gases by 20% by 2020. For this purpose, the Plan has guidelines in the following areas: municipal policies for sustainable development; municipal land planning, urban land-use planning, and urban land-cover planning; sectorial public policies and associated programs; instruments for the implementation of the Plan; municipal planning and management system; and public participation (Prefecture of Rio de Janeiro 2013a).

This initiative includes actions such as encouraging the creation of GI through the expansion of protected green areas, the creation of new urban municipal parks, and the development of the Landscape and Environment Resilience Program, which involves the reforestation and preservation of the remaining native forest and the implementation of a functional and interconnected system of green spaces. In addition, the revitalization of rivers is attempted through their protection and restoration in the form of linear parks, the creation of an agricultural green belt, and the implementation of a comprehensive model for green space management (Prefecture of Rio de Janeiro 2013a).

Among the most important advances of the Sustainable Rio Plan is the elaboration of the Urban Tree Planting Master Plan in 2015, which was aimed at the expansion, consolidation, and conservation of green areas and open spaces as an integrated and connected system.

The Plan defines urban green areas as public and private spaces with or without remaining vegetation: forests, urban parks, plazas, gardens, forest reserves, and public protected areas, among others. The contribution of these green spaces, which are implicitly conceived using the framework of the GI, lies in:

(1) Mitigating greenhouse gas emissions and increasing carbon capture and storage
(2) The protection of vulnerable areas from climate change (Prefecture of Rio de Janeiro 2015)

The Plan contributes to the fulfillment of the national objectives of the reduction of greenhouse gas emissions, to which the Prefecture of Rio de Janeiro ascribed.

13.4.4 Guidelines for the São Paulo City Action Plan of Mitigation and Adaptation to Climate Change

Since 2009, the city of São Paulo has adopted the "Municipal Law on Climate Change," which allowed important advances in this matter. In this context, the Guidelines for the Action Plan, approved in 2011 by the Municipal Climate Change and Eco-Economy Committee, present a series of initiatives defined in a participatory way by institutional and community actors. The guidelines offer proposals on issues related to transport, energy, sustainable buildings, and land use, among others (Municipal Committee on Climate Change et al. 2011).

The GI appears implicitly in the guidelines on the "land use" section where the development of a compact city is desired. For this, among other actions, the expansion and restoration of urban green areas is proposed. This includes programs to preserve natural springs and streams, the implementation of linear parks, and the progressive elimination of natural risks. Many of these actions are focused on helping to minimize the risks for the population when facing the occurrence of extreme weather events (Municipal Committee on Climate Change et al. 2011).

Among the priorities of this guideline, there are various relevant aspects to consider:

(1) The conservation of water sources and biodiversity
(2) The revitalization of the river and stream system
(3) The capture and reuse of rainwater
(4) The control of areas at risk as a priority for adaptation
(5) The expansion and consolidation of protected green areas, and the protection program for the mitigation, adaptation, and prevention of the effects of climate change
(6) The maintenance of the preservation areas as a way of combating and preventing adverse effects on the city's climate (Municipal Committee on Climate Change et al. 2011)

13.4.5 Mexico City Climate Action Program

The Mexico City Climate Action Program (*Programa de Acción Climática de México* – PACCM) 2014–2020 seeks to coordinate the actions of different actors to reduce the environmental, social, and economic risks associated with climate change (City of Mexico 2014).

Mexico City has led the planning processes to address climate change in the country of Mexico. The implementation of PACCM in the period 2008–2012 has involved the mitigation of six million tons of carbon dioxide equivalent (CDE), which means a reduction of 4.5% in relation to a business-as-usual scenario. Likewise, during this period, the issue was recognized as a priority on the agenda of the Federal District (City of Mexico 2014).

The PACCM 2014–2020 seeks to increase the adaptability of the population and contribute to the resilience of the city. For this, the PAACM has seven strategic pillars and different actions associated with each one (City of Mexico 2014).

Among the strategic pillars proposed, three of them implicitly address the GI concept and principles.

The pillar of "Containment of the urban area of Mexico City" promotes the expansion of green areas to contain urban sprawl. Among the proposed actions is the creation of a territorial planning program for the Federal District to control urban sprawl and the location of houses in areas at risk. For this, an important role is given to protected natural areas as barriers for urban growth. Other actions proposed in this pillar are the increase and rehabilitation of urban green spaces and the management of urban creeks, acknowledging them as areas of importance to mitigate air pollution and reduce the effect of urban heat islands.

The second relevant pillar is the "Sustainable Management of Natural Resources and Conservation of Biodiversity," which highlights actions such as the micro-watershed management for rural development and the recovery of vacant space on the conservation land. These actions are aimed at preparing the region for the effects of extreme precipitation events expected as results of climate change.

Finally, the third pillar is the "Native Species and Wildlife" whose actions are aimed at consolidating a regulation that protects biological diversity in addition to actions to restore ecosystems within the conservation land. These actions are motivated by the recognition that ecosystem services provided for green spaces such as aquifer recharge and climate regulation are relevant to combating the effects of climate change (City of Mexico 2014).

Public financing promotes each of these actions to fight the effects of climate change, through the Environmental Fund for Climate Change (FACC).

13.4.6 Climate Change Adaptation Strategy and Mitigation Actions of the Province of Lima

This initiative arises from the need to reduce the vulnerability of the city of Lima and its 8.5 million people to the effects of climate change.

The Metropolitan Municipality of Lima during the period 2011–2014 incorporated a climate change adaptation strategy into the city's planning and management to reduce the vulnerability of the population and the economic activities susceptible to the impacts of climate change. The Climate Change Adaptation Strategy and Mitigation Actions of the Province of Lima was prepared throughout a participatory process that included the Climate Change Technical Group of the Metropolitan Commission of Lima, international experts, public and private institutions, municipal officials, and social organizations (Metropolitan Municipality of Lima 2015).

The Strategy is an instrument that sets objectives and instruments that guide municipal decisions, and it was elaborated within the framework of the National Strategy for Climate Change Management and the Action Plan for Adaptation and Mitigation for Climate Change (Metropolitan Municipality of Lima 2015).

The contribution of the GI is included in Objective 2 of the strategy, which is "To guarantee the conservation, restoration and sustainable use of water, ecosystems, biodiversity and natural resources." The conservation and restoration of the ecosystems is sought as they are seen as part of the main ecological structure of Lima. In addition, this objective seeks the expansion of urban green by increasing the number of green areas (Metropolitan Municipality of Lima 2015).

Some of the actions proposed for this objective are:

(1) The mapping of Lima's ecosystems and the valuation of their ecosystem services
(2) The creation of a regional system of conservation areas
(3) The design and development of projects for the conservation of strategic ecosystems
(4) The promotion of riparian linear parks
(5) The design of an incentive scheme for the expansion of public and private green spaces in the most vulnerable areas and the expansion of the green coefficient in buildings

These measures involve an implicit recognition of the role of the GI in combating climate change, specifically in the management of water in both urban and peri-urban Lima (Metropolitan Municipality of Lima 2015).

Objective 3 of this strategy "Protecting vital infrastructure and services," indicates the importance of the reduction of physical vulnerability in the areas at climatic risk. Among the actions proposed is the promotion of the recovery of the riversides and riverbeds, in which the creation of GI projects contribute to securing services and infrastructure (Metropolitan Municipality of Lima 2015).

Finally, Objective 5, "Reducing the effects of climate change on food security and population health," is aimed at increasing the practice of urban agriculture and recognizing the value of agricultural valleys. This is through actions such as designing and implementing projects and initiatives aimed at conserving and increasing the areas of urban agriculture, and prioritizing the conservation of agricultural valleys and developing comprehensive strategies for their development (Metropolitan Municipality of Lima 2015).

13.4.7 AQUAFONDO–SEDAPAL Alliance: Lima, Peru

The alliance between the Lima Water and Sewage Service (SEDAPAL) and AQUAFONDO – an international water fund consisting of The Nature Conservancy (TNC), the Fund for the Americas, Grupo GEA, the Pontifical Catholic University of Peru, the Peruvian Society for Environmental Law (SPDA), Backus and Johnston Brewery, the IDB and USAID, among others – will enable the implementation of a series of Green Infrastructure Projects for the ecological and hydrological restoration and preservation of the Rimac, Chillon, and Lurin basins (AQUAFONDO 2016). These basins provide water for the Lima Metropolitan Area. The Lima Metropolitan Area is the second largest city in the world located in a desert; where the annual average precipitation is 9 mm (Water Fund 2015).

The GI is seen as a complement to the gray infrastructure and it is particularly recognized because of its contribution to the quality and quantity of water supply in urban areas. These functions of GI reduce the social vulnerability to extreme weather events generated by climate change, as the GI helps maintain the ecological health of basins and contributes to tackling various effects of climate change (Water Fund 2017).

The agreement, signed in 2016, states that AQUAFONDO is responsible for the identification and elaboration of Projects for the Provision of Ecosystem Services. Then, SEDAPAL receives the necessary documentation to validate the generation of Retribution Mechanisms for Ecosystem Services, which are included in the Master Plan elaborated by SEDAPAL (AQUAFONDO 2016). This initiative is funded by investing 5% of water charges, which should be deposited into the reserve funds of water companies to finance the cost of preservation projects. Likewise, users can make contributions through payments charged to their water bills (SUNASS 2016). This alliance is valid for 5 years and may be renewed upon express agreement of both parties (AQUAFONDO 2016).

Currently, there are two projects – which are still waiting for approval – focused on the higher Rimac basin, located in Huarochiri, San Mateo (SEDAPAL 2016). They will implement GI such as vegetation restoration, water-sowing (restoration of wetlands and percolation trenches), and water collection (microreservoirs), among others (Water Fund 2015).

13.5 Conclusions and Remarks

The concept of GI is slowly starting to be incorporated into urban planning policies and initiatives in Latin America. However, initiatives are still too few, especially compared with rapid urbanization processes, which are quickly consuming natural areas and ecosystems, and the severe effects expected from climate change in the region. Planners and practitioners have not sufficiently considered the potential contribution of GI to climate change mitigation and adaptation in cities; thus, the role of GI has not been properly identified and valued in urban planning, and planning and design efforts do not maximize the benefits of GI.

In the cases of Buenos Aires, Bogota, Rio de Janeiro, São Paulo, Mexico, and Lima, plans recognize the important contribution that GI can offer to adress climate change. Nevertheless, they do not mention explicitly GI. Instead, it was possible to identify implicit references to the concept. These results coincide with the global trend to incorporate into planning the principles of GI rather than the term as such. On the other hand, in the cases of Mexico City, Campinas, Coronel and AQUAFONDO-SEDAPAL, GI plans scarsely recognize the contribution of GI to climate change adaptation and mitigation.

The planning initiatives have been focused on the role of GI in biodiversity enhancement, urban heat island mitigation and surface runoff control. In contrast, and unlike experiences in other regions, there has been little consideration of the role of GI for spatial cohesion, for the development of nonmotorized transport systems and biological corridors. In general, the measures and objectives of this initiatives seem to be generic and do not respond to the specificity of the impacts of climate change in each city. Moreover, the experience in Latin America has focused on the conservation and development of green spaces on different scales, rather than on the development of a spatially connected system of corridors and nodes.

The low adoption of the concept of GI and the associated terminology could lead to an omission of some of GI principles that have been incorporated in urban planning in other regions, such as spatial connectivity, diversity, multifuctionality, and ecosystem services. In addition, this can act as a barrier for exchange and comparison.

Although the experiences address the biodiversity loss as a major issue, they do not consider the problems of social and environmental inequality that characterize the region. The plans and programs do not recognize the need to intervene more strongly in the poorest, more vulnerable areas that are less well-provided with GI. This becomes even more important if we consider that those areas will be the most exposed to natural disasters and the least prepared for the negative effects of climate change, such as heat islands or water scarcity. For this purpose, explicit objectives and mechanisms to mitigate inequities should be included.

Another difficulty for the development and implementation of GI plans and projects in Latin American cities lies in spatial-jurisdictional and sectorial fragmentation associated with land use planning, in addition to a power centralization that makes it difficult to consider the particularities of the different territories. In Latin

America an institutional fragmentation and an inconsistency among laws, norms, and instruments can be observed. This is expressed by the discordance between particular interventions and investments, defined by sectorial objectives.

Finally, in Latin America, the initiatives to mitigate the effects of climate change are more advanced than those related to adaptation. The GI approach provides an opportunity to balance progress in both dimensions by strengthening complementarities and relationships. The GI corresponds to an integrated approach not only with regard to its simultaneous contribution to the mitigation and adaptation to the climate change effects, but it could also contribute to guide planning and urban design in order to make cities more sustainables.

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Chapter 14
Incorporating Resilience and Adaptive Strategies to Climate Change in Urban and Territorial Planning in Uruguay

Adriana Goñi Mazzitelli, Ingrid Roche, Pablo Sierra, and Isabel Gadino

Abstract Although Uruguay undertakes many actions at the national level to tackle extreme phenomena in climate change, such as the creation of the National Plan on Climate Change, most of the attention was given to the Energy Reconversion Plan, or agriculture insurance facilities for Climate Change Disaster. In a local urban context, however, extreme climate events, mainly floods and droughts, have had less attention but concrete adverse effects on many urban areas, particularly on the most vulnerable communities (population and infrastructure) and on climate-dependent basic services and economic activities. This chapter describes the current policies and initiatives taken regarding climate change at an urban level. We can identify the birth of a new institutional framework, which is creating a methodology to create a dialogue with the main changes in Territorial and Urban Planning at an international level. The chapter also focuses on the main case studies in the capital city, Montevideo, in particular the Urban Plans for Streams and Basins, which dialogue with Local Plans for urban renewal, including climate change issues. In addition to this, a focus on the Metropolitan Plan on Climate Change shows how from a methodological point of view an innovative participatory methodology has been developed considering the necessary actor's network to be established toward the implementation of the adaptation measures. Finally, some important considerations are made, thinking critically about how to include all the new strategies to deal with climate change, resilience, and sustainable development from a long-term perspective on a multi-level scale, national, metropolitan, and local.

Keywords Montevideo city · Urban planning · Community engagement · Governance

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14.1 Introduction

Uruguay is known in Latin America for its strong political, social, and economic stability, which is supported by a legal and robust democracy. This is essential for working on public policies to reach solid results in the long term. In this chapter we describe, on the one hand, how actions and strategies in climate change and urban resilience have grown in recent years and, on the other hand, how current urban planning policies incorporate this new knowledge to create a better and more efficient effect on prevention, mitigation, and the active participation of the whole of society to deal with this issue.

The Uruguayan government participates actively in international summits in order to achieve the United Nations Framework Convention on Climate Change (UNFCCC) objectives. It declares the aim of building a sustainable, resilient, and low-carbon country, by enduring efforts and capacities, which means incorporating these topics in public policies and actions in different sectors (MVOTMA-SNRNC 2016).

Based on the executive summary of Uruguay's Fourth National Communication to the Conference of the Parties in the UNFCCC on 2016, the main topic on climate change that worried the country in 2015 was the water deficit, which had a severe impact on the agricultural sector, causing major economic losses. Although in other Latin American countries that rely on fossil fuel or other main natural sources for their economies, this problem may not be so important, for Uruguay, the agricultural sector is a central motor for its economy, and therefore a priority in climate change policies (Hareau et al. 1999).

In addition to this, the regional climate scenarios show an increase in rain-fall and temperatures, with a strong influence of the El Niño–Southern Oscillation (ENSO) phenomenon. This means that in the same year, 2015, severe floods in the Departments of Salto, Paysandú, and Artigas, north of the country, forced up to 25% of the population in these areas to evacuate their homes. This caused major losses in housing and urban infrastructure, and had a psychosocial impact on the most vulnerable population (FAO- MGAP 2013).

Since 1992, several international agreements have been ratified by the Uruguayan government in the area of sustainable development, and the government follows up international measures to avoid the negative effects of climate change. As Uruguay has no fossil fuels or minerals, the main productive sector is agricultural (Achkar et al. 2016), which means that the government focuses on creating systems to protect, mitigate, and adapt rural environments from extreme events, such as floods and droughts, hurricanes, and other periodic phenomena that the ENSO creates year after year (FAO-Project) (Bidegain et al. 2013).

The National Emergency System created during the first decade of the twenty-first century includes urban areas, helping to understand and mitigate some of the worst effects that increase with the strong winds along the coast, and floods in poor slums or deprived areas of the cities (SINAE 2013).

The Ministry of Housing, Territorial Planning, and Environment (MVOTMA) became the focal point and competent national authority in charge of enforcing the UNFCCC and the Kyoto Protocol.

Many actions were undertaken; for example, the country strengthened its domestic capacities to develop national greenhouse gas inventories, climate scenarios, and to implement pilot projects on adaptation and mitigation technologies and strategies. Between 2009 and 2014, with the creation of the National Climate Change and Variability Response System (SNRCC) and the participatory development of the National Climate Change Response Plan, the topic was brought to the forefront.

The main objective of these tools is to create an inter-institutional and cross-sectorial coordinated work, and to analyze the national and local impact of climate change-related problems and develop strategic guidelines for the year 2050 within a model of sustainable, inclusive, low carbon and climate change-resistant development.

In this period, climate change and variability has become part of national strategies and public policies, applied to sectors such as energy, agriculture, tourism, health, disasters risk, and water resource management.

As of 2015, the Administration strengthened its commitment to achieve sustainable and resilient development in the country. This can be seen in the support given to the SNRCC, in the creation of a political management position for all climate change affairs within the MVOTMA, and in the creation of the National Environmental System (SNA), the National Environmental Cabinet and the National Environment, Water and Climate Change Secretariat (SNAAC) under the higher authority of the country, the Executive Power.

The research on climate change and variability that the country started to produce has helped to promote and consolidate knowledge creation and research teams at different institutions, to start collaborative and supplementary lines of work. For example, the Interdisciplinary Network of the Universidad de la República (UDELAR), a horizontal grid integrated by:

(1) Urban Waters Planning & Management
(2) Interdisciplinary Response Center to Climate Change and Variability (CIRCVC)
(3) Interdisciplinary Center for the Integrated Coastal Management of the Southern Cone (MCISur)
(4) South American Institute for Resilience and Sustainability Studies (SARAS)

The National Climate Change Response System put together a Task Force on the Indicators of Variability and Social Vulnerability to Climate Change, which has demanded thorough interdisciplinary and cross-sectional work to draw input for further assessment of the social vulnerability of our country.

Coordination with other sectors of applied research, government agencies, and regional research centers has also occurred. As climate change studies take on a strong territorial component, several research/action lines have been developed to validate adaptation and mitigation strategies in different sectors, thus allowing for multidisciplinary and cross-sectorial efforts, engaging national and local governments, NGOs, farmers, and local urban communities.

Several institutions in the country have been engaged in meteorological and climate information generation and climate services, providing essential inputs for the different sectors in the Uruguayan economy to plan their undertakings and to protect the population.

However, there are still shortcomings both in the quality of the information produced and its utilization as the efforts have mainly been focused on: the development of a flood early warning system to forecast and manage floods in the priority cities of Durazno and Artigas (in the middle and north of the country); the development of a Climate Index Insurance in Uruguay for different sectors in farming production; the development of instruments to monitor water excess and droughts in the country; and the rollout of the National Climate Database.

Progress has been made toward the development of additional information systems, to supplement efforts to manage the impacts of climate change: the Environmental Information System (SINIA), National Environmental Observatory (OAN), National Agricultural Information System (SNIA), Information and Support System for Decision Making (SISTD) for climate risk management in agriculture, the GIS viewer of the National Emergency System, and the National GHG Inventory System are currently under development.

However, there is still a great need to discuss how to create resilient environments, as Borrego et al. (2015) state:

> The concept of vulnerability includes a complex and dynamic reality. Besides referring to the possibility that a system is negatively affected by something (a stressor), it is also a relative property defining both the sensitivity and the capacity to deal with that stress. Therefore, vulnerability cannot be defined by the stressor alone, nor can it be represented strictly by internal properties of the system being stressed. Instead, it must be considered as an interaction of these factors, expressed by the sum of several dimensions: exposure, sensitivity, and capacity to adapt (Borrego et al. 2015, p. 381).

In this context, this chapter describes the current policies and initiatives taken with regard to climate change at an urban level. We can identify the birth of a new institutional framework that is creating a methodology that wants to dialogue with the main changes in Territorial and Urban Planning at an international level. The chapter focus as well on the main case studies in the capital city, Montevideo, in particular the Urban Plans for Streams and Basins that create a dialogue with Local Plans for urban renewal, including climate change issues. In addition to this, a focus on the Metropolitan Plan on Climate Change also shows how from the methodological point of view an innovative participatory methodology has been developed, considering the necessary actor's network to be established toward the implementation of the adaptation measures. Finally, some important considerations are made, thinking critically how to include all the new strategies to deal with climate change, resilience, and sustainable development from a long-term perspective on a multilevel scale, national, metropolitan, and local.

14.2 Climate Change and Urban Planning in Uruguay

From the urban policies point of view, the creation of The Territorial Planning and Sustainable Development Law (Ley de Ordenamiento Territorial y Desarrollo Sostenible) (LOTDS 2008), gives a framework for streamlining actions and management of great importance. It allows, and has progressively enabled, several tools (National, Departmental and Sectorial Guidelines, Strategic Environmental Assessment, Local Plans, Special Plans) and initiatives to be deployed in the country, including social participation and environmental components, to ensure sustainability.

Uruguay is divided into 19 regions, called Departments. The Departmental and city governments include climate change and variability in local plans for emergency situations, technology replacement and infrastructure arrangements, among other initiatives. Specific inter-institutional areas were created and progress has been made regarding knowledge creation and the implementation of adaptation and mitigation measures.

Some of the topics we are going to develop in this chapter about climate change and urban policies in Uruguay were, on the one hand hand, the need to know exactly which type of phenomenon is affecting Uruguay's cities. To study the problem properly, information and management tools were incorporated at all levels to address for example, droughts and floods, which were previously absent in the government management of urban effects.

On the other hand, particular attention was given to coastal ecosystems, because coastal areas are central to urban development and tourism in Uruguay, and are at the same time a natural barrier against sea level increase and high wind storms (Gadino et al. 2012). This last topic was identified by academic research and social movements, but not by the touristic and real estate sector, which continues to carry out unsustainable urban development in coastal areas, in some cases with the acceptance of local governments that do not create economic alternatives to such environments (De Álava 2008).

Finally, another important topic for urban policies is the effects of climate change for the most vulnerable sectors in urban contexts, especially the flood-affected population. "The National Relocation Plan" has required the coordination of decentralized policies and programs together with the efforts of Departmental governments, to launch a new interdisciplinary approach to the topic, currently experiencing the first results (Piperno and Sierra 2015).

Uruguay is a country with a high level of rainfall, but in recent years the extreme situations between heavy rains and drought periods showed a considerable increase, as Fig. 14.1 shows.

The Program for Mapping of Flood-Prone Areas (DINAGUA-MVOTMA) was recently begun; it was proposed that cities with more than 10,000 inhabitants should have a map of their flood risk areas in the short term. This mapping forms part of the Water Information System within the framework of the Environmental Information System. The delimitation of these areas is a priority for the definition of territorial

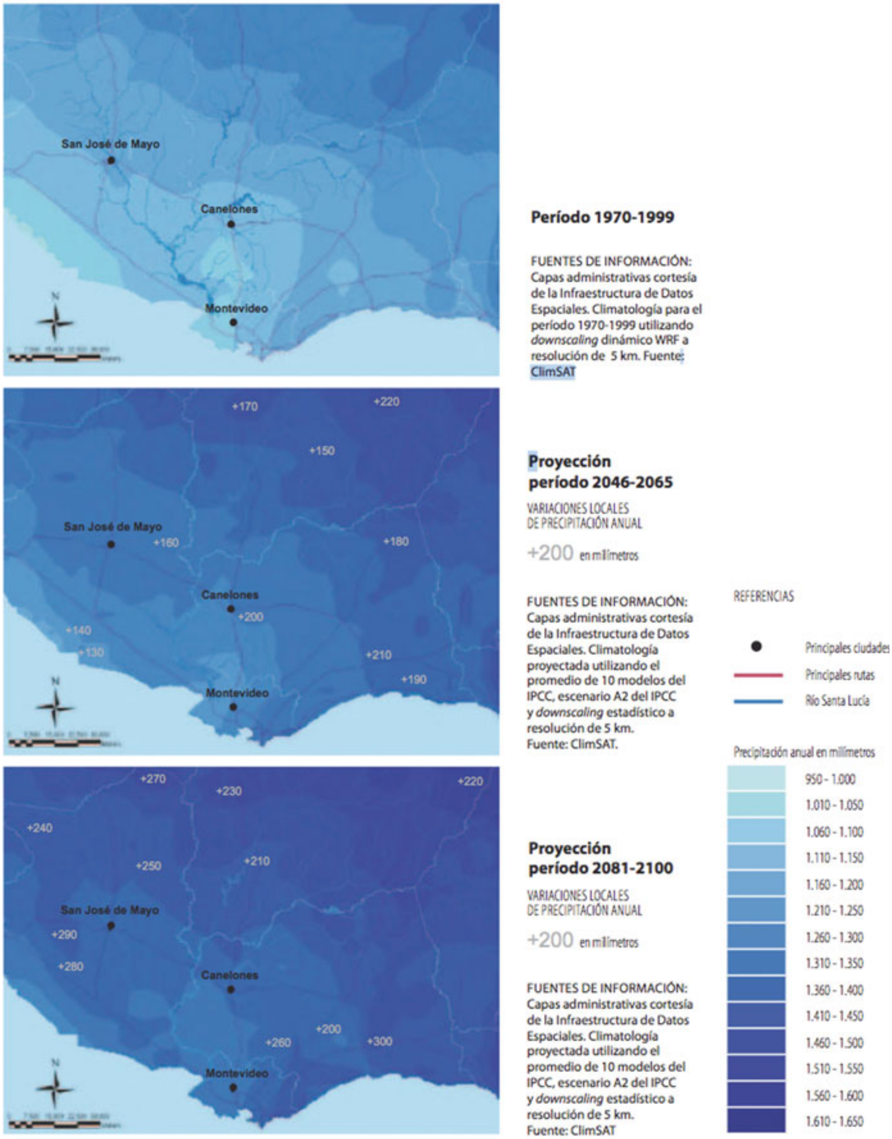

Fig. 14.1 Map of precipitation prospection scenarios. (Source: *Plan Climático de la Región Metropolitana de Uruguay*, © 2012 PNUD Uruguay)

policies, in particular for Urban Plans. In this sense, the Law on Territorial Planning and Sustainable Development, LOTDS, in article 49 states that "territorial planning instruments should guide future developments towards non-flood prone areas identified by the competent water resources state body."

The elaboration of local plans for territorial planning, responsible for the Departmental level, incorporate risk maps in a shared work between the first and the second levels of government.

The systematization of existing information on floods has been carried out under the DINAGUA-MVOTMA. The information implies a set of data processed with order and hierarchy so that they can be understood by the users. Hence, quality criteria need to be defined in terms of accuracy, consistency, timeliness, comparability, accessibility to data, metadata with information about the quality of the curves, presentation of the curves in user-friendly and usable formats, and compatibility with the mapping spatial data infrastructure.

Within this framework, the DINAGUA (National Direction of Water), performed a compilation and processing of riparian flood curves, i.e., the area occupied by water during floods. This compilation comprises the analysis of past flood events and curves resulting from hydrodynamic studies of watercourses, which estimate the flood curves. The generation of new information on river flooding implies the articulation of different actors at various levels. During the Flood Area Mapping Project, protocols were also developed to generate new information.

As Agrawala et al. stated,

> Analyses of current climatic trends reveal a warming trend in recent decades with country averaged mean temperature increases of 1.1 °C and 1.9 °C projected by 2050 and 2100. Climate models also project increased precipitation both in summer and winter, although there is considerably less agreement across climate models on such projections. The most significant impacts of climate change are projected to be on Uruguay's coastal zones, both because of the higher certainty of sea level rise and the high exposure of critical economic and natural resources on the coastline. On the other hand, many other sectors dependent on natural resources – including forestry, agriculture and livestock – offer considerable potential for mitigating climate change through carbon sequestration. Natural resource management therefore is a critical link in Uruguay's efforts to both adapt to and help mitigate climate change. (Agrawala et al. 2004).

From the urban planning point of view, the Department of Urban Planning (ITU) at the Faculty of Architecture, Design and Urban Studies, UDELAR, has made significant contributions to flood management in the country, in particular in the characterization of the vulnerability of the exposed areas, and started to work on how to incorporate climate change issues into urban and territorial planning.

14.2.1 The National Relocation Plan: Urban Planning for Reducing Social Vulnerability

From colonial times, Uruguay was organized mainly into small towns, that gradually became small, medium, and large cities, some industrial centers or ports, others cattle breeding centers or transit cities. Nowadays more than 90% of the Uruguayan population live in urban environments, which means from the point of view of territorial balance and development a historical weakness. The reasons can be found

Fig. 14.2 Flooding in Durazno City, center of Uruguay, 2010. (Source: Equipo Aguas Urbanas y Gestión de Riesgo, Facultad de Arquitectura, Diseño y Urbanismo)

in the division of land and extensive cattle breeding, which resulted in a very scarce demand for rural working population for many years. In recent years, these phenomena have been changing as the productive sector was modified by introducing intensive cattle breeding in addition to soya and eucalyptus production. The novel industries such as cellulose processing factories, and large coastal construction sites, are creating a new urban geography, where some cities continue receiving migrants, as in coastal areas, where the building industry is growing, whereas the intra- and inter-urban population flow is changing. These movements of the population affect urban contexts, although it is not the only cause; settling in informal and flood-prone areas of the cities is a typical survival strategy that continues to grow as social housing solutions are implemented slowly (Altman and Martínez 2016).

Although informal settlements and urban poverty in Uruguay are different than other countries in Latin America, as the cities grow a great deal as the result of urban plans, this does not mean that illegal occupation of land is absent. However, as soon as the informal settlements became bigger, the State started public policies of relocation or legalization of the already existing neighborhoods (Lombardo 2015).

In Uruguay, climate vulnerability from flood risks is one of the most significant climate-related impacts in the country. During the last decade, more than 67,000 people were evacuated from their homes in 60 cities across the country because of flooding (Fig. 14.2).

The country's National Resettlement Plan is relocating thousands of families out of flood-prone and polluted areas and into secure housing on secure land to help them to adapt to the effects of climate change. The National Resettlement Plan focuses on resettling families that live in extreme poverty and do not have the necessary resources to find housing alternatives or secure land on their own. The investment of USD 42 million in the resettlement plan also includes job training for family members and the reuse of former flood-prone residential land into other flood-compatible uses.

The Department governments prioritize the areas to be relocated and provide the land and infrastructures for the construction of new homes. The financing for the works and the technical equipment involved are the responsibility of the MVOTMA. The National Housing Agency (DINAVI) worked together with the National Water Agency (DINAGUA), helping in the intervention and the study of particular cases of flooding. The Neighborhood Improvement Plan, co-financed by the Inter-American Bank of Development, situated at the DINAVI, developed an operating program regulation, which was approved in 2011.

Each relocation project involves, in addition to the actions of construction and access to the housing solution, an integrated combined approach with other agencies: in particular of social policies, under the premise of guaranteeing the development of integral processes of transformation of the conditions of life, through aspects related to the generation of better work opportunities, educational offerings for early childhood, adolescents, and young people, support and orientation on the problems of drug use, domestic violence, and illegal activities.

The social housing solution can be new homes built especially for the families to be relocated in new housing developments (less than 50 housing units), or houses acquired on the market. Access to houses depends on assessments on the formality and stability of the family income and jobs, in addition to the potential to establish and build new links and feelings of identity with other neighborhoods. In addition, the acquisition of houses on the market makes use of the existing housing stock with all the services, while revitalizing the market in neighborhoods with low real-estate activity. On the other hand, this modality has also influenced an upward trend in housing, which forces the owners to regularize housing for this segment of the market, and the training of the families in a more adequate and rigorous search for a dwelling. The housing purchase instrument used for relocation projects implied the participation of the National Housing Agency in its implementation. As for the construction of new housing, the modalities have been diverse, complementing the participation of construction companies with familial self-construction, cooperative housing, and experiences of peer participation. The appropriation of the living space accompanies the transformation process itself. The diversity of results is related to: the characteristics of the resettlement (number of households and complexity of the social situations) and the different capacities of the Departmental governments for the monitoring, supervision, and involvement with each re-location project.

14.2.2 A Participatory Metropolitan Plan for Montevideo on Climate Change

The Metropolitan Plan on Climate Change for Montevideo was implemented in 2012 with the purpose of, on the one hand, focus on the specific topic of measures to be undertaken to deal with this issue and, on the other hand, make an institutional coordination among different actors and programs that in the last years deals in a fragmentary way with the climate change challenges. The aim is to work togheter towards the managment of natural resources as "commons" (Ostrom 2005).

From the urban planning perspective, the area has had a relevant quantity of planning instruments as Departmental plans of land characterization, Departmental guidelines, and regional strategies; however, the Metropolitan Area of Montevideo implies a new level of governance and coordination, which is having many problems with implementation.

Following the current international changes in the definition of urban planning units, the Metropolitan Area of Montevideo must be conceived together with the adjacent areas of the Departments of Canelones and San José regarding integrated regulation and planning, which nowadays is of very weak and secondary priority in public policies.

The Metropolitan Area does not have a specific institutional organization for the coordination of the three Departmental Governments, Montevideo, San José, and Canelones, and the 42 Municipalities (municipal councils, administrative units corresponding to the third level of Government inside each Department territory) defined by the Decentralization and Political Participation Law of 2010.

The coexistence of national, Departmental, and Municipal competences determines the absence of specific instruments of coordination; however, some instruments of territorial planning as Regional Strategies for the Metropolitan Area was already approved in addition to the Inter-Departmental Plans that have to be implemented.

This coordination was not new, as, at the end of 2005, to address this administrative weakness of the faster growth of the capital of the country, the Presidency of the Republic with the Departmental governments created the Metropolitan Agenda Program to solve various operative issues.

The Metropolitan Plan on Climate Change meets this administrative problem of coordination that almost all new metropolitan areas encounter. Therefore, the methodological approach of the Plan is based on institutional coordination and participatory planning: the main target groups of the Plan are ministries and other high authorities of regional government (from Montevideo, San José, and Canelones), which deal with climate change issues. In addition to these municipalities, citizens, entrepreneurs, environmental civil society associations, and others are involved in the different steps of the Plan.

For the elaboration of the Plan a participatory methodology was designed. Here we describe the different steps and outputs (Healey 1997).

(1) Actor mapping and working groups for a preliminary diagnosis
(2) Definition of risks and opportunities for the development related to climate change
(3) Definition of priorities with multi-criteria analysis
(4) Building of a general strategy for the adaptation and mitigation of climate change
(5) Working groups to define particular guidelines for specific topics: transport, coastal management, biodiversity, extreme events, intensive and extensive agricultural activities, energy, solid waste, built environment and health
(6) Participatory mapping of climate change impacts in the whole metropolitan area

Considering the Forester theory on deliberative practice, the current plan assumes more than a participatory approach, a well-performed consultation (Forester 1999). This means the active involvement of the different actors, without allowing these actors to take mandatory decisions, which Lussault states is the real difference between a consultation and a real process (Lussault 2011).

However, the plan was a success in the sense of sensitization of the metropolitan area governments. It also identifies the main vulnerabilities of the area, which are:

(1) The consumption of land by the informal settlements, and by the gated communities, and the free trade zones
(2) The great extension of coastal area exposed to a rise in sea level and storms
(3) The increase in temperatures with the consequence of an increase in the rain level and in extreme events as flows
(4) The contamination of potable water

14.2.3 Actions of the Metropolitan Plan of Montevideo on Climate Change

After identifying the main vulnerabilities, the participatory groups identified specific objectives to protect:

(1) Water resources
(2) Agriculture and food production
(3) Vulnerable and at-risk population
(4) Coastal zone

The program envisages actions that need to be regulated and financed by the government, for example, the sustainable management of the urban water cycle, control in the increasing presence of vectors, and reduction of risks to human health associated with the variability of temperatures.

The plan has many elements of innovation, although by now they are just good declarations, we can mention some of them here, underlining that the most interesting work of the group was to think at different levels, with different disciplines, and also involving knowledge from civil society and local governments (Fig. 14.3).

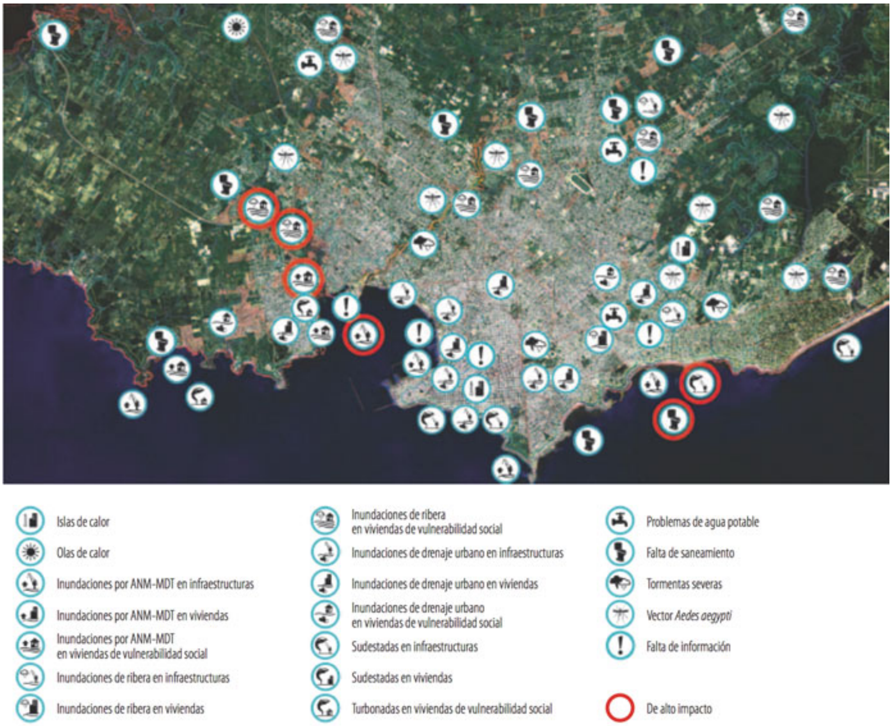

Fig. 14.3 Participatory map of climate change impacts in urban areas (Montevideo and metropolitan area). (Source: *Plan Climático de la Región Metropolitana de Uruguay*, © 2012 PNUD Uruguay)

Some of the focal points were the conviction of the need to strengthen local capabilities with regard to human health; the development of a new management model for the governance of natural resources and biodiversity, in addition to water resources in the basin; the need for better access for insurance and climate information on the rural production.

On the other hand, some modifications need to be made to the transport system to stop the current impact of carbon emissions. The proposals vary from reducing carbon emissions in the urban transport, to increasing the use of clean technologies, and increasing the efficiency in urban mobility, along with promoting active transport.

As mentioned before, the Plan considered great systems for the prevention and reduction of impact measures, such as supporting the National Policy on Sustainable Energy that is changing the matrix for low emission in Greenhouse Gases, or reducing organizational weaknesses to improve a cross strategy in the adaptation and mitigation of climate change.

Also, to work in a participatory way in the monitoring of the implementation, the Plan develops a platform for different associated policies and government directions that are related to climate change, as monitoring resources and investments do in the topic. In particular, trying to reinforce the National System on Protected Areas (SNAP), by creating a corridor of protected natural areas in each region, like an Ecological Network Corridor in the metropolitan area.

The same platform should work at a local level by making an agreement on environment management with local governments, and supporting regional working groups with all the municipalities involved. This is a very innovative proposal as local actors can exchange good practices or create synergy in asking for the coordination of central funds in related policies. In fact, this last point is related to financial resources, as the instrument is part of a Pilot Program of the United Nations; therefore, it counts on international funds to be formulated and tries to work as a coordination tool for funds in the phase of implementation.

In addition to this, the main aim of the participatory networking is to create innovative management figures such as the Basin Commission or Urban Local Plans with particular attention to the resilience aspects.

Finally, the Plan promotes what is called prompt intervention measures, to avoid serious damage to the current situation. For example, protection and recuperation of coastal morphology, dune restoration, the capture of fences of sand in critical places, and the building of ten low-impact access measures to beaches in the coastal region of Canelones. The first measures are giving excellent results, and some of the erosion that had been created in beaches and dunes by climate change is retreating, restoring the natural environments.

14.2.4 Policies and Actions in Urban Planning and Resilience to Adapt to Climate Change in Montevideo

The great population concentration at Montevideo, almost 60% of the Uruguayan population, is the result of the concentration of economic activities and opportunities. The capital city contains the Government offices, most of the industries, the main international port and airport, in addition to the financial services and commercial institutions.

According to the data of the National Institute of Statistics in the report on Poverty at the National Level, Montevideo is a Department with higher levels of poverty. In 2016, it registered that 8.3% of households were in poverty, which means out of each 1,000 households, 83 are below the poverty line.

According to Carmona and Gómez (1999), the Department of Montevideo has an important planning tradition, starting in the early decades of the twentieth century, with significant examples such as the Regulator Plan Pre-Project of 1930, the Director Plan of 1956, and the Plan Montevideo of 1998. The latter plan is a milestone in the territorial legislation of the country, initiating a process of re-appraisal of urban territorial planning in public policies that would afterward reach national scope with the passing of the Territorial Planning and Sustainable Development Law (LOTDS) N 18308 2008.

In the Plan Montevideo the sustainability is expressly included as an objective of territorial development, and although climate change is not explicit as a driving force, the recent introduction of adaptive strategies point in that direction, demonstrating the interest of the city.

The recognition of rurality as a value to preserve and the restoration of banks of structuring urban streams are relevant to this goal. The Plan Montevideo is the background of a derivative planning system in time and space that contributes to significant urban adaptation strategies (Facultad de Arquitectura IMM 2009).

The Department guidelines were reviewed after the LOTDS approval and in the context of the Revision of Plan Montevideo; the environmental dimension was identified as essential for this approach and for the relevant adaptive strategies for designing projects and interventions.

The proposal is based on six items, one of them is environmental sustainability; the document emphasizes:

> (the) preservation of environmental values, responsible use of natural resources, climate change and variability response, and comprehensive risk management. The processes that contradict environmental sustainability principles such as urban land extension, socio-territorial segregation, and lowering of life quality in consolidated city areas are critically approached (Guidelines Document, Directrices Departamentales 2012, p. 39).

In this sense, the water streams assume relevance, in particular because of the high level of housing and social vulnerability that takes place within their margins, putting them under risk for extreme events. The plans described next are examples of this phenomenon.

14.2.5 Special Plans for Urban Streams and Basins

As already stated, Montevideo is the main location in the country for incorporating new topics on urban planning. The water streams are of great importance for urban policies on climate change, in particular in the cases of informal housing at risk for floods (Conde et al. 2015).

In the land categorization, the banks of the main water streams are defined as natural rural land and restrictions for alteration of their natural condition have been established. The “green wedges” (of the main urban streams Arroyo Pantanoso and Arroyo Miguelete) are recognized as extended territorial frameworks, considered “strategic territories” that materialize the link between the natural background of the territory and the urbanization processes (Facultad de Arquitectura 1998).

Therefore, we can see the main efforts include resilience instruments and climate change measures in plans for urban streams and basins (Table 14.1). We are going to analyze in more depth here the Miguelete Stream Plan, which has already been approved and was recently implemented. In the next table, we are going to briefly

Table 14.1 Urban planning instruments that incorporate resilience and adaptability to climate change as relevant strategies together with other social and environmental policies. (Source: The authors)

	Main problems related to climate change and urban issues	Socio-ecological actions	Ecosystem services and green infrastructure	Government level of impact and participation
Plan Miguelete River (PEAM)	Great contamination of water on the river and to Montevideo Bay Environmental degradation of the watercourse Precarious housing situation Risks to the population's health	Relocation of informal settlements on the river Green Eco Place to cooperatives of waste pickers	Actions of sanitation infrastructure to avoid contamination Linear park Rehabilitation of the public spaces Vehicular, cycle, and pedestrian paths	District, Municipal, Regional
Plan Pantanoso River (in process of elaboration)	Great contamination of water due to domestic, industrial disposals and solid waste. Informal settlements occupied the banks Loss of ecosystem services of the watercourse Landscape potential loss Nondwelling large fields and wetland areas under great pressure Formal housing areas next to the stream	Main strategies Relocation of informal settlements on the river Involves an interdisciplinary team Create a hydrological model that describes the dynamics of flood pulse return that includes the climate change scenario in the design.	Main strategies Consider the area a "green wedge" where the natural framework organizes and determines the urban development along the 16 km area length of the stream Create flood area restrictions Linear parks, preservation areas, ecosystem restoration areas	Multiple institutional actors' competence, need to coordinate
Plan Casavalle Cañada Matilde Pacheco	Environmental degradation of the watercourse Precarious housing situation Extreme poverty High criminality rates Flood risk situations	Strength in inter-institutional collaboration Create technical solutions with specific focus on creating a socially resilient environment	Regenerate small stream areas that can build transversal connectivity Build quality public space Amelioration of sanitation	Creation of a participatory planning and management figure, the Council of the Casavalle neighborhood

(continued)

Table 14.1 (continued)

	Main problems related to climate change and urban issues	Socio-ecological actions	Ecosystem services and green infrastructure	Government level of impact and participation
Plan La Chacarita (in process of elaboration)	Northeastern area of Montevideo presents the highest vulnerability index of the city. Urban–rural border degradation Informal settlements Lack of urban planning Environmental degradation of the watercourse Contamination of the water Irregular settlement located on the culvert itself, Santa Teresa Settlement	Main strategies Relocation of informal settlements on the river Working on memories about the importance of the story of the neighborhood "Los Milagros," the social housing Juana de America Cooperative, and the river, which was culverted as a rainfall sewer pipe, making the stream "disappear" from the local culture	Main strategies Regenerate the lower course of the stream, located at the rural–urban inter-phase, which remains open-air with irregular occupation of the flood plains and the consequent impact of flood events (Chacarita de los Padres Settlement). Coordination and control of the existing interventions, and elaboration of the Plan of La Chacarita basin with the Departmental Government, within the context of a comprehensive plan of social connection and land-use planning	Creation of a participatory planning and management figure, the Council of the Chacarita Bassin. It was created in 2014 as an inter-institutional council with members of the City Council Government, local neighbors' council, Environmental Ministry, Social Ministry, National Education Authority, among other institutions

describe some examples: Casavalle Plan, Chacarita Plan, and Pantanoso Basins Plan (currently in development).

14.2.6 Arroyo Miguelete Stream Special Plan

The *Plan Especial Arroyo Miguelete* (PEAM) is derived from the Plan Montevideo, which recognizes the Arroyo Miguelete as a spatial axis and biological corridor of the river basin. The Arroyo physically links the Bay of Montevideo with the rural landscape areas. Symbolically, it is one of the strongest elements in the Montevideo territorial imaginary; this urban route exceeds 6-km edges; thus, the spatial recovery of Arroyo could bring to the city more than 90 hectares of public space, in addition to the transformation and urban integration of its edges (IMM, Junta de Andalucía 2004).

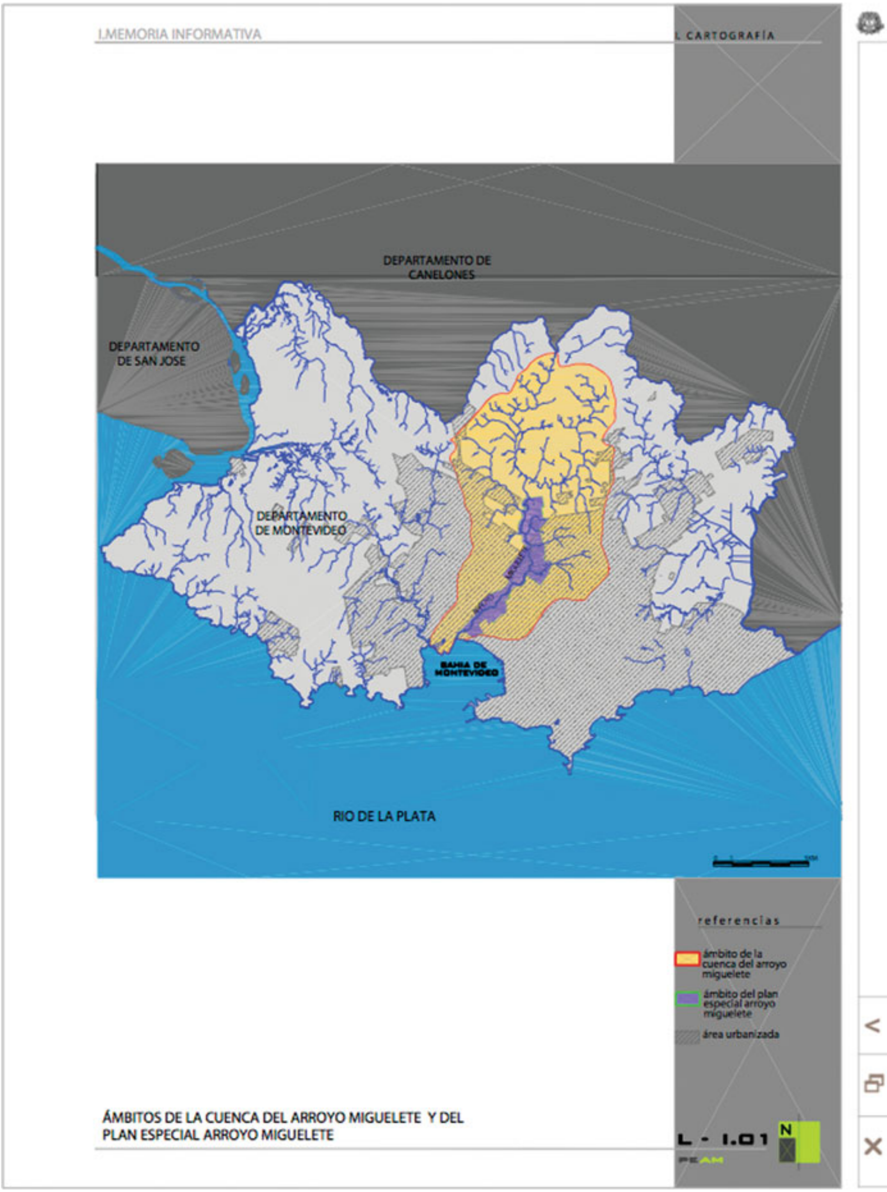

Fig. 14.4 Arroyo Miguelete, basin areas of the stream special plan. (Source: Intendencia Municipal de Montevideo)

Furthermore, the Arroyo Miguelete is conceived as a territorial unit, with the particularity of being fully contained in the jurisdictional area of Montevideo Department, which represents a unique situation that favors the management of the planned area (MVOTMA 2015) (Fig. 14.4).

The PEAM proposes to promote a sustainable urban territorial development, with a strong role for qualified public space associated with the watercourse, in which the different sections and nodes are identified as spatial units. Within the framework of the objectives and guidelines of the Plan, a management strategy has been implemented aimed at the concretion of the Linear Park, through successive interventions, with a strong impact on the banks of the stream. These include the relocation of housing and the subsequent park construction and equipment of the liberated spaces, to achieve the physical, environmental, and social recovery of the area of the basin, and enabling public tours alongside the watercourse with vehicular, cycle, and pedestrian paths.

The recovery of the environmental quality and the urban landscape on the banks of the Arroyo Miguelete is based on urban interventions of restructuring and requalification, complemented by actions on the sanitation infrastructure. In the relocation of the irregular settlements found along the Arroyo Miguelete nearby locations should be considered, but also be compatible with the previous objectives and contribute to the recovery, qualification, dynamization, and densification of adjacent neighborhoods (Fig. 14.4).

Since the diagnosis, those working on the project have contemplated the possibilities of subsistence of the families, seeking to dignify their work and improve substantially the condition of their immediate environment. For this purpose, a set of housing was complemented by the construction of a special establishment called Green Eco Place in the immediate surroundings, which should host cooperatives of waste pickers for recycling urban solid waste. The Eastern bank was specially designed to carry out the task of recycling and the classification of waste and the subsequent transfer of nonrecyclable materials to the final disposal plants of the Intendencia, establishing hygienic conditions for workers and reducing pollution of the environment. Urban control and cleaning are the responsibility of the Intendencia. Also, each house has proper premises for raising animals and hygiene measures for the new neighborhood, as long as they take care of the public common structures and the stream.

14.3 PEAM and Relocation of Informal Settlements on the River: 2004 to 2017

The middle area of the Arroyo Miguelete located at an important street intersection at Av. Batlle y Ordoñez, presents the main social problems, as it was used for an informal settlement named “25 de Agosto.” Therefore, the Arroyo Miguelete was divided into three sectors to work toward a common goal, in addition to focusing on the different actions needed for each area (Fig. 14.5).

The structural axis of the work of this section is a pedestrian Rambla and a cycle path of more than 1.5 km in length on the left-hand side. This sector of the linear park was launched in 2017.

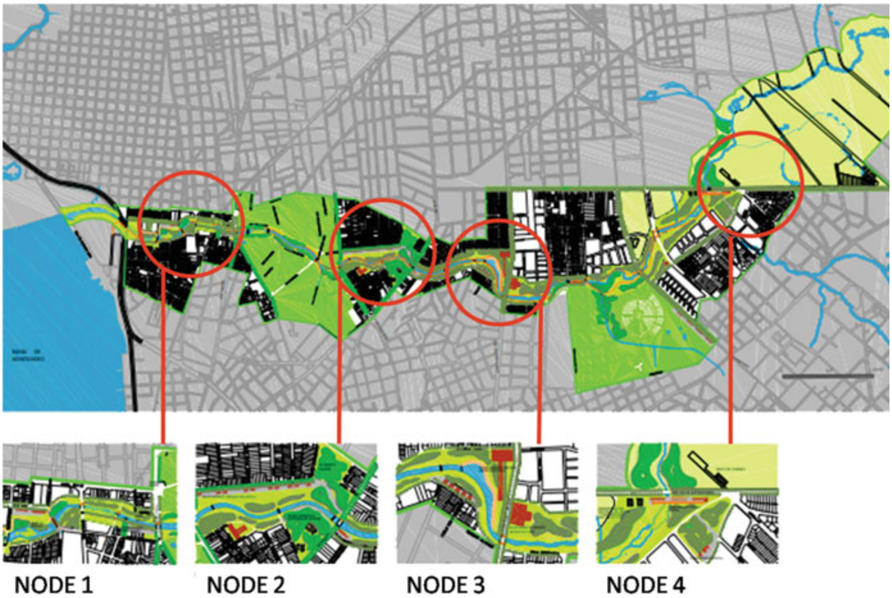

Fig. 14.5 Arroyo Miguelete stream special plan. (Source: Intendencia Municipal de Montevideo)

On the right-hand side, the project "Riberas del Miguelete" was under elaboration, including the regularization of many informal settlements with approximately 350 houses and 1,200 people (IMM 2004).

The comprehensive improvement plan, in addition to consolidating these spaces, will allow the installation of new public services to ensure the transit and circulation of people among the surrounding neighborhoods, in addition to educational, labor, and recreational opportunities aimed at reducing social fragmentation (Instituto Nacional de Estadísticas 2017). The construction of this promenade is designed to have a positive impact on the lives of the inhabitants of the surrounding neighborhoods, who will have access to a new space for recreation and enjoyment.

PEAM Section 1: Andalucía Park Once the settlement was reallocated between 2004 and 2008, an open design competition was launched for the recovered area of Andalucía Park. The Park design was supposed to follow the guidelines of the Rehabilitation of Miguelete Stream Special Plan, which included paved surfaces, ornamental gardens, landscaping, and urban furniture, incorporating public routes equipped with vehicular, cycle, and pedestrian paths alongside the banks. Andalucía Park was opened in 2008.

PEAM Section 2 Subsequently, work was carried out on the rehabilitation of the public spaces adjacent to Arroyo Miguelete between the streets Silva and Aparicio Saravia (in the northern sector of the stream), responding to the same criteria of austerity and simplicity of Andalucía Park. Work will continue on the relocation of irregular settlements and the next in line is known as "Paso de las Duranas," across the Arroyo from "Parque de Andalucía."

PEAM Section 3 Section 3 includes the Arroyo banks between the streets Bvard. J. Batlle y Ordoñez and A. Saravia. It will address problems of environmental degradation of the watercourse, in addition to the precarious housing situation, and the health of the population. The structural axis of the work of this section will be a pedestrian Rambla and a cycle path of more than 1.5 km in length.

The Plan has been carried out in several stages since 1999 and continues today. It is linked to the Sectoral Plan for Water Management and to the Master Plan of Urban Sanitation, providing for related infrastructure works according to hydrological studies, and including several planning figures and special regulations of the urban and rural Land Management Regime.

14.4 Discussion and Conclusions

The main challenge that Uruguay is trying to solve is the need for the gradual involvement of climate change and a variable approach in the Territorial Planning agenda. In recent years, Uruguay has progressed in making the environmental issues explicit. From different conceptual and methodological backgrounds (risk management, environmental policies, water resources management, climate change) the specific institutional framework has been created with the purpose of crossing policies and actions in the territory and no longer in a sectorial way. The challenge is that the current coordination of these diverse initiatives transforms into a potent platform of governance on this subject, at the national, metropolitan, and local levels (Ostrom 1990).

In the case of Montevideo, the creation of the Climate Change Work Group (GTCC) in 2010, of inter-disciplinary and inter-institutional characteristics, is a relevant milestone. This group contributed to the elaboration of the aforementioned Metropolitan Climate Plan of Montevideo. Other recent achievements have been the denomination of the former Planning Department of the Montevideo Government as the "Planning and Resilience Department," and the consolidation of the GTCC as a section of this department.

The urban dimension has achieved relevance, and adaptation has taken place as a significant strategy for making positive synergies with urban development in our country, where the climate variability is the main determinant of the occurrence of adverse events.

Also, the flood-prone urban areas have taken priority in risk management and relocation policies, considering communities that have been actively involved in the preparation processes for early warnings, the recognition of their local capacities to face extreme events, the development of solidarity in the implementation of adaptation measures, and the design of local adaptation and risk management policies within the framework of promoting a culture of prevention and enhancement of adaptive capacity.

As in all the processes, some problems have arisen between the elaboration of these new approaches and the real incorporation of them into the institutional traditional systems that govern urban areas. For example, from the DINAVI data, it is possible to assess that the relocation projects of the last 5 years have been formulated from this integral vision, but their implementation has been focused on the housing response. The multi-dimensional family problems of a high percentage of the cases were addressed by contracted technical teams with scarce institutional resources or by resorting to social proximity programs when the families fulfilled the required profile.

Something similar happened with the Metropolitan Plan on Climate Change. Although the platforms for mapping the risks and the coordination figures were decided and designed by the Plan, there is not yet any evidence that they have been implemented, or that they are in the process of being implemented.

Therefore, the future challenges are on the one hand to continue producing further knowledge and responses on climate change and the variable impact on urban contexts, although the focus on floods and the extremely vulnerable population is one of the main problems. We need to explore other urban issues in more depth, such as the city urban heat islands, or carry out further investigations related to the adaptation of the materials and constructive systems in coastal zones to potential resilience in the face of variations in storm forces, as the greatest winds that arrive at the Atlantic and Rio de la Plata coasts. On the other hand, the improvements in regulations, and the creation of norms and laws that modify the traditional adaptation practices, require more time to consolidate, perhaps by supporting more practices and gathering examples of proceedings in different urban areas of the country, university can improve the methodology for dealing with the climate change phenomenon.

Anyway, the first steps have been taken, and the efforts are well distributed and should be carried out by a great variety of actors, trying to promote collaborative scenarios to continue dealing with climate change and urban resilience issues in the future.

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Chapter 15
Assessing Climate Risk in Small and Intermediate Towns and Cities: A Preliminary Rapid Appraisal Tool and Its Application in Florencia, Colombia

Ayesha Salas Tobón and Jonathan R. Barton

Abstract Globalization and urbanization have been two forces that have spread around the world in an accelerated form and without adequate planning in the localities where their impacts are greatest. In the case of Latin America, this is especially evident in small and intermediate towns and cities. Climate change is another force that combines with globalization and urbanization, generating severe impacts and major challenges for integrated planning. In this chapter, a preliminary rapid appraisal tool is provided as a first step for climate risk assessment. The methodology includes six stages, and is developed with the goal of identifying the climate risk hotspots, and existing and potential local responses. A pilot application was carried out in the city of Florencia, in south west Colombia. The results provide inputs for the formulation of local development strategies and policies, acting as a platform for initiating climate change adaptation.

Keywords Climate risk · Climate change · Vulnerability · Urban planning

15.1 Facing Up to High Levels of Urban Climate Risk

Evaluations of the potential impact assessment of climate change have been evolving rapidly since the publication of the fourth Assessment Report of the IPCC in 2007. This has been particularly relevant for urban areas as, at the same time as the world

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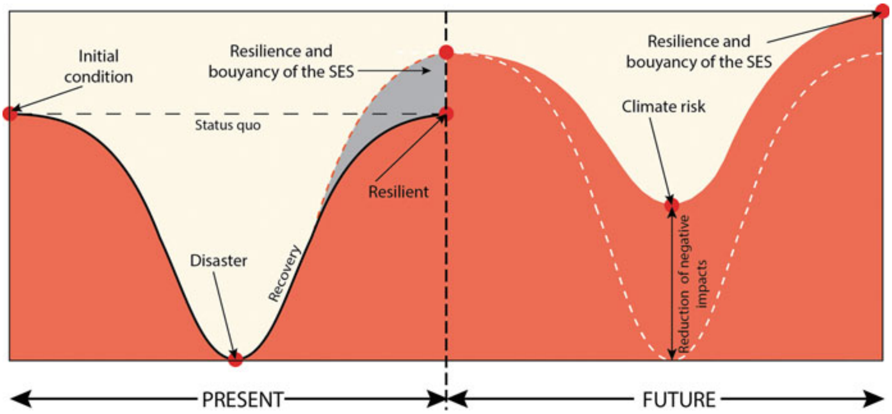

Fig. 15.1 The resilience and buoyancy of the socio-ecological system (SES). (Source: Authors)

population became more urban than rural in its settlement preferences, relatively little climate adaptation and resilience work was being developed for these towns and cities. What became clear was that all these settlements required climate action plans to increase preparedness and reduce the impacts that were being experienced (Carmin et al. 2012; O'Brien and Leichenko 2000; UNDP 2010; Stern 2007).

The rising importance of cities in the climate change debate has only been fully recognized over the past decade. Before this, adaptation was generic rather than place-specific, and often priority was given, among others, to the sectors of food production and biodiversity, rather than people more directly. Specific events during this period, starting with Hurricane Katrina in 2005, to Hurricane Sandy, Typhoon Haiyan, droughts and wildfires in Australia and California, and more recently the 2017 series of Hurricanes Harvey, Irma, and Maria, which affected the USA and the Caribbean, all indicate the importance of urban adaptation.

Climate change adaptation depends on the capacity to prepare for an impact, and the capacity to respond when those impacts occur. Factors such as adaptive capacity, the sensitivity of the social groups affected (such as age and health), and exposure, all contribute to this ability to construct resilience in the face of climate change, thus minimizing vulnerability (Adger 2006; Gallopin 2006). This resilience is a function of the buoyancy of the socio-ecological system (SES), and its ability to "ride" the impacts with least damage and loss, and to recover as swiftly as possible from them (Fig. 15.1). As it is precisely the relationship between the threat itself – whether drought, storm hazard, extreme temperatures, wildfires, among others – and the condition or vulnerability of the affected social groups (INECC and PNUD 2012), the term climate risk is appropriate. This term also reflects the fact that in a post-normal world of climate change, all climate is driven by climate change processes. The concept of risk is also useful as it is closer to how people understand their predicament in the face of other threats, whether health-related (smoking, obesity), finance-related (unemployment, debt), security-related (crime, terrorism) or environment-related (traffic, contamination, food). This chapter presents a framework for a preliminary rapid appraisal of urban climate risk (PRA-UCR) to encourage the first steps toward increasing the resilience of towns and cities.

Of particular importance in recent years was the IPCC publication on extreme events that made the connections with wider development and risk issues (IPCC 2012; Barton and Irarrázaval 2016). Instead of pursuing a specific climate change agenda, separate from these other related strands, the importance of integrated assessment was highlighted. As risk assessment in the face of disasters has a longer history, and has been particularly relevant in terms of urban development, the recognition of these links has been a significant step forward. Another relevant publication prior to the IPCC special report was the ARC3 (cities and climate change) report of the Urban Climate Change Research Network published in 2008 (see also Rosenzweig et al. 2010). Concerned with the lack of attention to cities within the IPCC, Cynthia Rosenzweig, William Solecki, and others put together a document that provided an updated overview of the situation of climate change adaptation, with a focus on informing decision-makers (Rosenzweig et a. 2011). This lack of information, and the most influential factors were later summarized in an assessment of local government capacity by JoAnn Carmin and others (2012). In this report, based on 468 responses from local government officers, 68% reported advances in this field, albeit in preparatory or early implementation phases; only 18% had actually implemented a plan. Carmin et al. (2012, 2) concluded that:

> ...the results of the survey suggest that without the commitment of local political officials and the acknowledgement of this agenda by national governments, it will be difficult to make rapid advances in planning and to move from planning to implementation. Financial and informational resources are critical, but the commitment of local officials is essential to advancing adaptation planning and implementation.

This chapter focuses on the adaptation response at a local level and bears in mind some of the limitations that were pointed out in the responses compiled by Carmin et al. in the areas of resources, commitment, communication, and information.The five most frequently cited factors for lack of progress were as follows: securing funding for adaptation; reallocating resources to adaptation work; allocating staff time to adaptation; mainstreaming adaptation; and generating interest among businesses. Faced with critical budgetary constraints in most cases, climate change adaptation is not a priority when compared with health, education, and housing, for example. However, the impacts of specific events can prove to be highly significant and costly in terms of the resources required (Stern 2007). It is for this reason that all towns and cities require plans, even if they are preliminary in scope.

Although the largest cities have made important strides over the past decade, most cities – the smaller and intermediate ones – have been slow to respond. The reasons for this are outlined above; however, this survey was directed at Local Governments for Sustainability (ICLEI) members, and for cities to be members and for there even to be a response suggests that there is a degree of awareness and related action. It would be fair to assume however that, in almost all the smaller and intermediate cities around the world, relatively little is being done however. They are subject to the vagaries of climate change and are unprepared; hence, climate risk is high, adaptive capacity is low, whereas the intensity of impacts (whether episodic or longer-term trends in temperature and precipitation) increases. This chapter proposes a low-cost first step for urban administrations in pursuit of a climate change plan. Rather than argue that only sophisticated climate assessments of potential impacts, based on more local and regional scenario work, is the first step, this tool can be implemented at an earlier stage to initiate awareness-raising among local government officers and authorities. The subject of the case study for the application of the tool is Florencia in the Department of Caquetá, Colombia.

15.2 The Predicament of Small and Intermediate Towns and Cities

City classification depends on a wide range of variables, ranging from economic growth, to population and physical size. Although the larger metropolitan areas tend to be the focus of policy initiatives and dominate academic publications and press reports, there is a much larger number of smaller settlements, which house 50% of the world urban population. A study by UNDESA in 2000 identified 1,872 settlements in Latin America of between 20,000 and 500,000 inhabitants. As the trend toward urban living continues – from 40% in the region in 1950, to 70% currently, and 90% expected in 2050 –there will not only be growth in metropolitan areas, but also in these settlements of under 500,000 people (UN-HABITAT 2012). Each country has its own metric for defining towns and cities. These typologies make comparisons difficult, especially as countries have different urban hierarchies, with one dominant, primate city (e.g., Chile, Paraguay, Uruguay) or a more distributed population (e.g., Brazil, Colombia, Ecuador), and in view of the fact that some countries have national populations that are several times larger than others; Mexico City alone has a larger population than seven Latin American countries (Fig. 15.2).

Colombia, with its population of almost 50 million, has large cities across the country, with five over one million, and 21 over 300,000. In terms of public policy

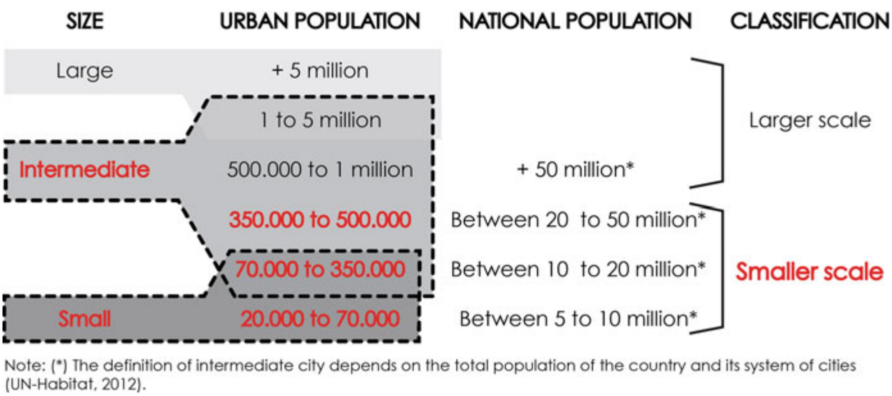

Fig. 15.2 Classification of Latin American cities. (Source: Authors)

and investment, it is the larger settlements that often define strategy and types of interventions. This is probably a relic of the explosion of these largest settlements during the second half of the twentieth century in the region (Roberts 1978). However, this trend has shifted in recent decades, with other towns and cities increasing their populations relative to the largest metropolitan areas. Despite this change in urban trends, specific initiatives for these intermediate and smaller settlements are lacking. In terms of climate change, this is notable, even though there is recognition of the need to move in this direction (BID 2014). Apart from a very small number of examples, such as Esmeraldas in Ecuador (UN Habitat 2009; Luque et al. 2012), the only settlements with climate change plans are the largest, e.g., São Paulo, Mexico City, and Bogota. In the face of uncertainty in terms of climate change scenarios, local and national politics, and budgetary constraints over the medium to long term, the case for immediate action becomes more evident. As a region with a long history of risk from disasters, and in view of the likelihood that these will become more rather than less common with climate change, there is an imperative that all settlements begin the process of mainstreaming adaptation into their local policies, programs, and projects (Betsill and Bulkeley 2007; Barton 2009, 2013; Hardoy and Romero Lankao 2011; Heinrichs et al. 2011).

15.3 Framing Urban Climate Risk

Climate risk assessment involves determining degrees of possible impacts in addition to confronting the multidimensional nature of vulnerability. Despite the conceptual ambiguity of the concept of resilience (Meerow et al. 2016), it is evident that planning involves a diagnosis of climate risk and suitable actions to confront the threats and to reduce vulnerability, whether physical, socioeconomic, or cultural. Figure 15.3 reveals the complexity of adaptation through capacity building and development planning in terms of the multidimensionality presented in the IPCC special report (2012). One of the positive observations that can be made is that the history of urban planning has focused on many of the risks that are identified as possible impacts. Given the location of towns and cities in coastal and riverine locations, for example, the threat of flooding has always been a factor in design and preparedness. In some cases, the risk has been "planned out" via major infrastructural works to channel the flood waters, whereas in others it is "planned in" via more flexible decisions that assume that flooding will take place, but that seek to reduce its damage, such as alternative uses for ground floor space. There are also evident weaknesses of both approaches, such as the vulnerability of the levee system in New Orleans when Katrina struck, or the sheer volume of water and mud in the case of Montecito, California, in January 2018.

Figure 15.3 points to the heart of the matter: the connections between local development decision-making, spatial planning, and socioeconomic factors. Where climate change factors are incorporated into physical and socioeconomic planning decisions, there is an opportunity for mainstream adaptation and incorporation into standard practices. However, there are relatively few cases where this is the case to

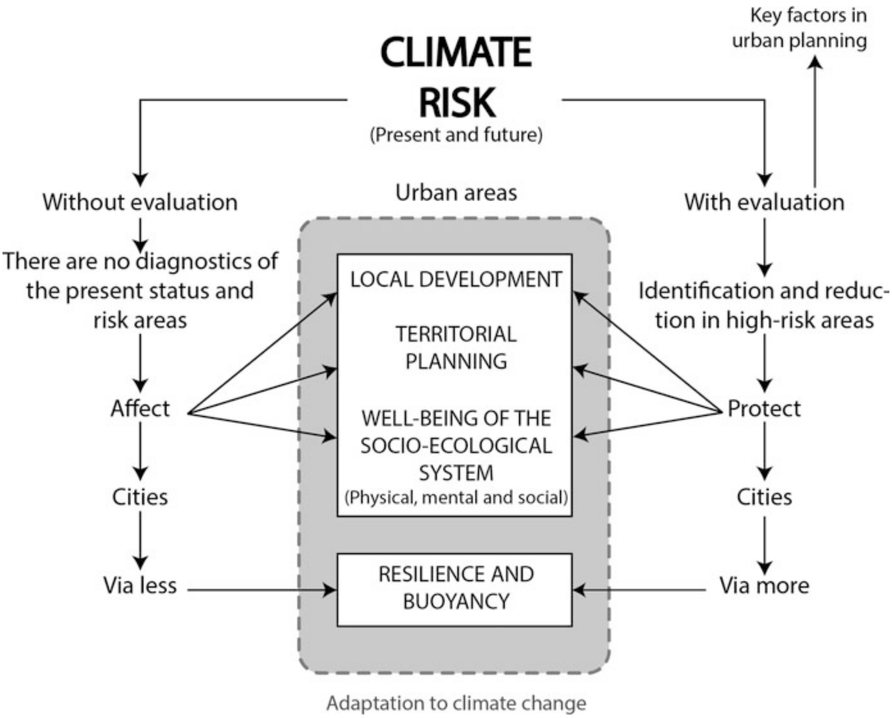

Fig. 15.3 Climate risk evaluation. (Source: Authors)

date. Examples of specific, stand-alone climate action plans are rare, and integrated, mainstreamed plans are rarer still.

Given the technical complexity of the research of Working Group I of the IPCC, based on multiple scenarios for the current century, the sense that steps cannot be taken without a downscaling of these scenarios for specific locations is understandable. However, both of the scenario methodologies used by the IPCC reveal the range of possible outcomes depending on the rate of implementation of mitigation strategies. As these are highly variable and uncertain, in spite of the enthusiasm associated with the agreement at COP21 in Paris in 2015, adaptation decisions should not be dependent on some spurious notion of certainty with regard to possible impacts. Although this argument may be used to explain a lack of protagonism, the IPCC evidence for changing patterns of extreme events, precipitation, and temperature is enough to suggest that local government planning should also accept this post-normal state of affairs and the considerable range of uncertainty with regard to impacts. Against this, there is usually a reasonably high level of knowledge of local level vulnerability in terms of sensitivity, exposure, and adaptive capacity, as this vulnerability is also present in demands for basic needs and resource allocation.

A further argument, as revealed in the ICLEI survey (Carmin et al. 2012), is that of a lack of resources, whether financial or human capital. Given that almost all local governments in Latin America find themselves with inadequate resources to combat many basic needs, the addition of climate change considerations should not be regarded as an additional burden to add to the list of unfulfilled demands. Rather, climate change should be viewed as complementary to these existing concerns, around food security, adequate housing and sanitation, employment, and health, among others. This is essentially the idea of mainstreaming (UNDP-UNEP 2011), approaching development planning with climate change viewed as a transversal consideration, in the same way that gender considerations around development have been encouraged.

The prevailing uncertainty opens up the options for more rapid appraisal methods that should be viewed as preliminary steps toward a longer-term process for developing and implementing measures to improve resilience. Rapid rural appraisal has been used since the 1980s for development planning, using eclectic methods to gain an insight into livelihoods on a community and village scale. Although incomplete, and restricted in terms of time and resources, it reveals that introductory, rapid appraisals are useful in terms of an early diagnosis of a set of conditions. By introducing greater participation in this process (Chambers 1992), the appraisal can be strengthened further, in preparation for a more robust later engagement. The same is the case for this PRA-UCR framework.

The PRA-UCR incorporates components of other tools to provide a matrix of climate risk for a small or intermediate city. The same tool could be used for all cities, but here the emphasis is on a tool that is based on low cost and limited knowledge. Examples of the appropriations from other tools include the Leopold Matrix, used extensively in Environmental Impact Assessments, and the pressure–state–impact–response (PSIR) framework of the UNEP. Table 15.1 reveals the use of the SIR stages of the PSIR, combined with climate change as the pressure. It also shows the stages of the appraisal and how they relate to specific dimensions for data collection. To facilitate prioritization and communication, the use of a traffic light system provides simplified information and clearly indicates the critical elements. These critical elements are generated from the Leopold Matrix, which equates the frequency of an event with its magnitude. A decision is therefore required whether preparation is more important in the case of an event that is relatively low impact but

Table 15.1 State–impact–response (SIR) model

SIR model	Dimension	Questions	Stage	Tool
State	Threat	What is...?	2	Graphics and matrix
	Sensitivity	Who is...?	6	Maps
	Exposure	Why is it...?		
Impact	Impact	Which are...?	4	Matrix
Response	Adaptive capacity	How are...?	1	Actor map
			3	Spatial Planning Instruments matrix
			5	Matrix
			6	Map

Source: Authors

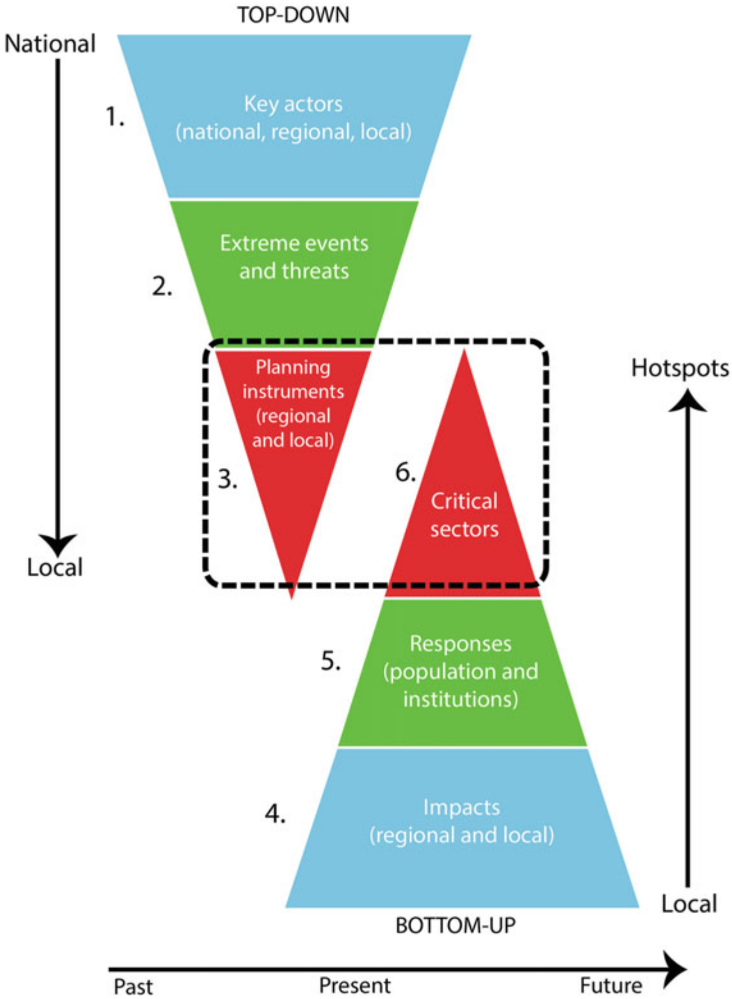

Fig. 15.4 Schematic view of the steps in the appraisal. (Source: Authors, based on IPCC 2012)

frequent, or for a high-impact event that may not occur more than once every 30 years (Fig. 15.4).

The goal of the appraisal is to generate preliminary information that can be based on existing data and observation, organized according to a specific format. Documents that should be assessed include climate records, census data, development plans, spatial plans, photographs, physical plans, disaster records, risk management systems, land use, hydrology, vegetation and biodiversity, geomorphology, areas with and without basic services, etc. This information is collated according to the framework, with additional information being generated from field visits and direct observations. At the heart of the process is the widest possible engagement within the different departments of the local government. The "State" of the UCR is the current situation in terms of the socio-ecological and socioeconomic conditions and the physical dimensions of the town or city. This includes the quantity and quality of resources and services. The "Impact" refers to the effects produced by the environmental conditions and infrastructure on the urban socio-ecological system, on the inhabitants, and on their activities in particular. Finally, the "Response" refers to the "soft" (e.g., education, consciousness-raising, cultural practices) or "hard" (construction of barriers, physical design modifications) measures that can be employed to increase resilience in the face of these impacts.

The objective of the appraisal is to identify "hotspots" where actions can make a relatively high positive contribution compared with more generic interventions (Krellenberg and Hansjuergens 2014; Krellenberg et al. 2014, 2017). This assumes that there is a low level of financial and human resources available for implementation. It is the organization of information according to the Leopold Matrix that enables the selection of hotspots to take place. The following sections provide evidence for the stage-by-stage approach based on the case study of Florencia. As the objective is to create a universal tool that has utility beyond a small number of towns and cities, the application in one case is merely an exercise to test the tool (Fig. 15.5, Table 15.2).

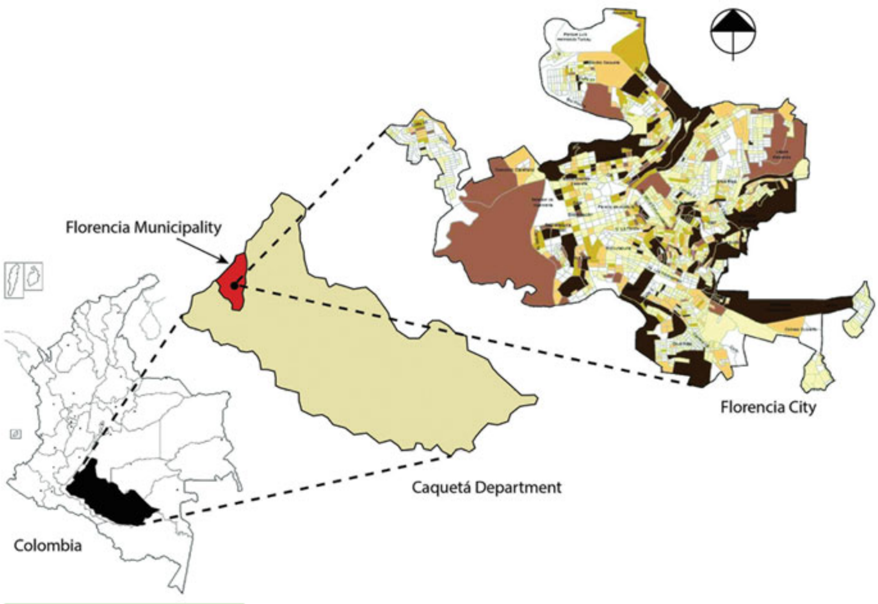

Fig. 15.5 Florencia, Colombia. (Source: Authors, based on DANE image for the urban center)

Table 15.2 Urban context

General information	Florencia
Urban population[a]	141,804 (1)
Urban area[a]	14.56 km^2
Urban density	9,739.3 hab/km^2
Average maximum temperature (°C)	30,7
Average minimum temperature (°C)	21.5
Annual precipitation (mm)	3,840
Annual relative humidity (%)	86.1
Altitude (m)	242
Climate	Warm humid
Principal economic activities	Livestock and agriculture

Source: Authors, based on DANE 2002 and population projections 2012
[a]Within the urban area of according to the Land Use Plan (POT)

15.4 The Actor Mapping Exercise

The purpose of actor mapping is to focus on the agents of change and other stakeholders in the local setting. Rather than a physical process of creating barriers and "climate-proofing" an area with defense systems, which is highly costly and potentially a "high regrets" option (where significant investment may ultimately fail, given the intensity of an event), there is widespread recognition that adaptation and resilience-building are inherently social processes. Almost all adaptation systems have the agents at their center, as the processes of adaptation are social learning processes; these processes may include an infrastructure component, but should not be dominated by this exclusively "hard" approach.

Figure 15.6 provides an introduction to the wide range of local and extra-local actors who have a bearing on climate adaptation. Although it is important to have local actors in the center of the figure, as they are ultimately responsible for the success or failure in building resilience, they do not operate in a vacuum. Building networks across public and civil society actors, and with regional, national, and international agencies, is critical for effective planning as it is through these partnerships that the critical capacity for transversal, mainstreamed adaptation can take place. Rather than climate risk planning falling within the remit of climate change specialists at the national, regional, and local levels, it should be viewed as a common element for all policy-making and decisions on plans and expenditure. By mapping these actors, it should be possible to begin the process of building partnerships and alliances (see CLOPAD 2011), and exploring best practice experiences and co-financing options. Climate change planning is a multi-scalar challenge, from the work of the IPCC to the neighborhood committee; therefore, the creation of networks of actors who will be directly and indirectly involved in planning and implementation should be regarded as a first step in the process.

Fig. 15.6 Relevant actors for climate risk planning. (Source: Authors)

15.5 Identification of Extreme Events and Threats

Climate change scenarios are complex and provide a wide range of possible outcomes that increase in uncertainty as they are downscaled, given the assumptions used in the models. Nevertheless, with the relative absence of more regional or local downscaling in Latin America, only the broader national trends at regional levels can be used. This in turn can be compared with recent trends and a register of extreme events and associated losses (see Henríquez et al. 2016). The recent trends in temperature and precipitation in Florencia are shown below, revealing the gradual increase in average temperatures (in line with national and international modeling) and evidence for the great variability in terms of rainfall events (Figs. 15.7 and 15.8).

Given that flooding is one of the principal climate risks, it is important to establish the connections between these intense events and the damage caused, and also a register of measures taken by communities and authorities given the frequency of these episodes. The immediacy of data compiled from local experiences is important in making the connection between the global debate on climate change and the influence of climate change on local events. The realization, in a post-normal climate, that flooding events are now shaped by climate change is critical in terms of changing the local discourse around risk and disaster (Table 15.3).

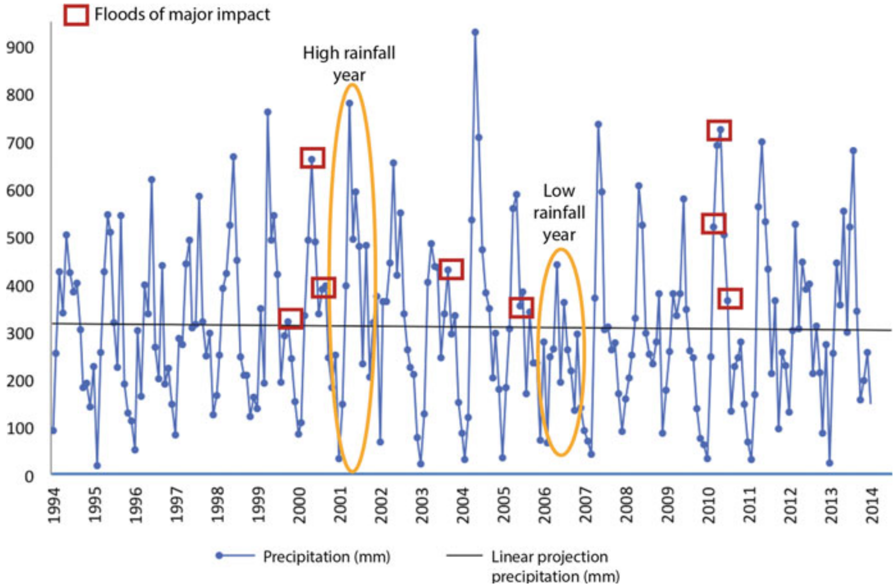

Fig. 15.7 Precipitation (mm) in Florencia. (Source: Authors, based on IDEAM)

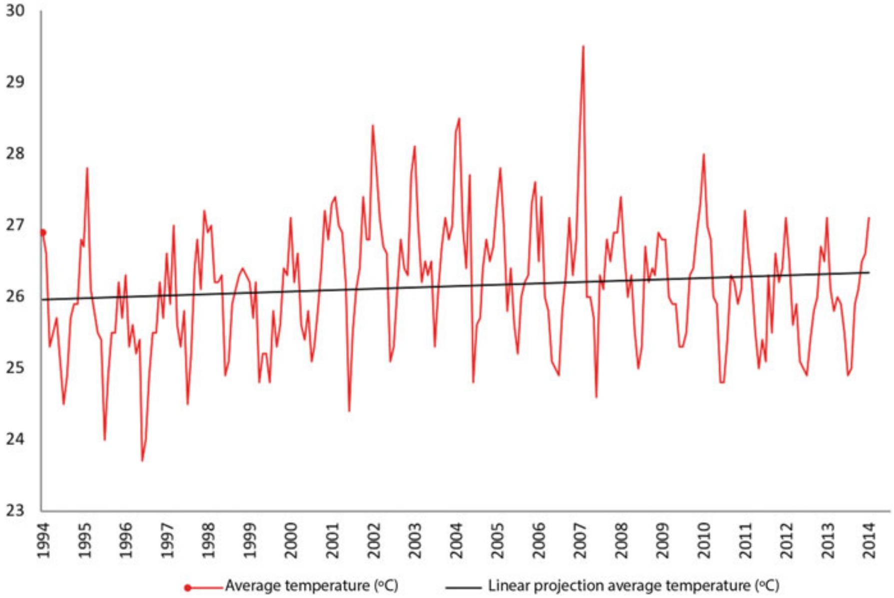

Fig. 15.8 Average temperature (°C) in Florencia. (Source: Authors, based on IDEAM)

Table 15.3 Experiences of climatic risk in Florencia

Date	Disaster	Affected neighborhoods	Dead/ disappeared	Victims	Other damage
18-08-1962	Landslide and flooding	La Vega, La Bocana, and the cemetery	40 deaths and more than 100 missing	3,000 affected	400 houses affected, left the entire city without electricity and water. The force of the water damaged the power plant and water pipes. Impacts along 20 km of the river
08-09-1991	Flooding	Raicero, Juan XXII and Villa Mónica	–	–	–
02-02-1993	Flooding and landslide	Flooded: Brisas Bajas, Consolata. Landslide: Cunduy and Tovar	–	–	–
19-05-1993	Flooding	–	–	–	Peak flow duration was 21 h, registering a maximum flow rate of 218 m^3/s.
03-06-1995	Flooding	–	–	–	Peak flow duration was 9 h, registering a maximum flow rate of 168 m^3/s.
04-10-1999	Flooding in La Yuca, La Perdiz, La Sardina Creeks, and Hacha River	25 neighborhoods	17 deaths	12,500 affected	110 mm/2 h
28-04-2000	Flooding	10 neighborhoods	–	–	–
24-05-2000	Flooding	11 neighborhoods	–	250 families affected	35 mm/24 h
27-09-2000	Flooding and landslide	8 neighborhoods flooded and landslide in Las Malvinas	–	–	–
14-06-2003	Flooding of La Perdiz Creek and Hacha River	20 neighborhoods	1 dead	1,500 affected	Road network and aqueduct damaged. Water provision suspended for 10 days in some neighborhoods

(continued)

Table 15.3 (continued)

Date	Disaster	Affected neighborhoods	Dead/ disappeared	Victims	Other damage
02-2004	Forest fire	_	_	_	60 hectares affected
10-06-2005	Flooding of La Perdiz Creek and Hacha River	San Judas, Raicero, Floresta, Guamal, Juan XXIII, Idema, San Luis, Esmeralda, Atalaya, Amazonia, Brisas del Hacha	_	1,442 families affected	_
04-09-2009	Flooding	_		132 families affected	_
10-03-2010	Flooding of La Perdiz Creek. Avalanche in La Yuca Creek	Flooded neighborhoods Guamal, Floresta and Juan XXIII. Landslides in 8 areas	_	_	_
22-05-2010	Flooding of La Perdiz Creek and Hacha River	27 neighborhoods	2 deaths, 5 missing	1,000 affected	60 homes damaged
09-06-2010	Flooding of La Perdiz, La Sardina Creeks and Hacha River	25 neighborhoods	2 deaths	5,000 affected	Reached 3 m on the level of the aqueduct and affected sewerage
04-04-2011	Flooding of La Perdiz, La Sardina Creeks and Hacha River	Guamal, La Floresta, Juan XXIII Bajo, Comuneros, San Luis, Ricardo Acosta, Triunfo, and Idema	_	_	_
04-07-2011	Flooding and landslide	Flooding: Floresta, Guamal, Juan XXIII, Isla 20 de Julio, Ricardo Acosta, Triunfo, Raicero, San Luis, Idema, San Judas, Nueva Colombia. Landslide: Alameda, Corazones, Rodrigo Turbay.	_	_	_
05-2014	Flooding in rural zones	Santo Domingo, El Caraño, Venecia, San Pedro, Roncesvalles, La Paz and Independencia	_	1,600 affected	_

Source: Authors, based on a review of news and municipal and departmental documents of risk management

Fig. 15.9 Flooding in June 2010, Florencia. (Source: Favio Sánchez archive)

Fig. 15.10 The flood of 9 June 2010. (Source: File Departmental Government Office)

Using an adapted Leopold Matrix, the process of prioritization can be initiated based on Fig. 15.9. The range of possible climate impacts is noted along the horizontal axis, with the impacted sectors along the vertical axis, from the physical environment to community health and education. Although many of these sectors are inter-related, the goal is to highlight the impacts that can be expected and those sectors most affected by them. This exercise should take place with as wide a participation as possible from local actors, as identified in the actor mapping stage. Rather than a purely technical, external process (for which relatively little verifiable information is readily available), this should include a wide range of perceptions. As more robust data are generated in later stages, this can be integrated into an iterative process of gradual improvements. However, the plan should not be dependent on these data, as in most localities it is unlikely to emerge in the short or medium term given resource constraints. The priorities in Florencia are most clearly associated with flooding and landslides associated with high rainfall events. Other concerns are drought and the risk of forest fires. These have an impact upon housing, transport and energy systems, infrastructure, and different land uses. To face these challenges, the role of planning instruments is crucial (Figs. 15.10, 15.11, and 15.12).

Fig. 15.11 Housing, La Floresta. (Source: Ayesha Salas archive, Florencia, July 2014)

CLIMATE THREATS / ELEMENTS (RECEPTORS)

Medium	Component	Parameters	Frequency / Magnitude	a Precipitation increase	b Precipitation decrease	c Temperature increase	d Temperature decrease	e Rising sea level	f Sea temperature increase	g Glaciers and permafrost reduction	h Cold nights and days	i Warm nights and days	j Flooding	k Coastal flooding	l Drought	m Storms	n Rainfall	o Hurricane / Cyclone	p Hailstorms	q Electric storms	r Cold waves	s Heat waves	t Forest fires	u Landslides	v Avalanche	w Mudslides	x Strong winds	y High tides and waves	EVALUATION
Terrestrial	Air	Air quality	F			1																							2
			M			1																							2
	Water	Surface water quality	F										3											3					6
			M										3											3					6
		Groundwater quality	F																										1
			M																										1
		Water deficit	F			1																							2
			M			1																							2
	Soil	Land use	F			1							5										3	5					17
			M			1							5										3	5					17
		Soil quality	F			1							3										3	3					10
			M			1							3										3	3					10
	Fauna	Ecological corridors	F			3																	3						9
			M			3																	3						9
		Endangered species	F			1																							3
			M			1																							3
	Flora	Ecological corridors	F			3																	3						9
			M			3																	3						9
		Endangered species	F			1																							3
			M			1																							3
Coastal	Water	Water quality	F																										0
			M																										0
		Temperature	F																										0
			M																										0
	Beach	Beach uses	F																										0
			M																										0
		Quality of the beach	F																										0
			M																										0
	Ecosystems	Habitat alteration	F																										0
			M																										0
		Endangered species	F																										0
			M																										0

System of indicators

F = Frequency

High = 5	Threats occurring between 0 and 5 years
Medium = 3	Threats occurring between 5 and 15 years
Low = 1	Threats occurring between 15 or more years
	Does not apply

M = Magnitude

High = 5	Deaths or large number of wounded and injured; serious impact on natural resources and infrastructure; considerable economic losses; and/or activities suspended for more than two days. Considerable physical changes.
Medium = 3	No deceased but wounded and injured; moderate impact on natural resources and infrastructure; moderate economic losses; activities and/or services suspended for hours up to two days. Moderate physical changes.
Low = 1	No deceased, only a few people affected; minor impacts on natural resources and infrastructure; light economic losses; activities and/or services are not suspended. Unsubstantial physical changes.
	Does not apply

Fig. 15.12 Characterization of threats. (Source: Authors)

MATRIX CHARACTERIZATION OF THREATS

CLIMATE THREATS / ELEMENTS (RECEPTORS)			Frequency / Magnitude	Precipitation increase	Precipitation decrease	Temperature increase	Temperature decrease	Rising sea level	Sea temperature increase	Glaciers and permafrost reduction	Cold nights and days	Warm nights and days	Flooding	Coastal flooding	Drought	Storms	Rainfall	Hurricane / Cyclone	Hailstorms	Electric storms	Cold waves	Heat waves	Forest fires	Landslides	Avalanche	Mudslides	Strong winds	High tides and waves	EVALUATION
Medium	Component	Parameters		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	
Socio-economic	Economy	Livestock	F			1							3		1								1	1					7
			M			1							3		1								1	1					7
		Agriculture	F			3							3		1									1					8
			M			3							3		1									1					8
		Fishing	F										1																1
			M										1																1
		Forestry	F			3																							3
			M			3																							3
		Mining	F																										0
			M																										0
		Commercial area	F										1																1
			M										1																1
		Industrial area	F										1																1
			M										1																1
		Tourism	F																										0
			M																										0
	Infrastructure	Communications	F										3											3				3	9
			M										5											5				1	11
		Building	F										3										1	3	1			3	11
			M										5										1	5	1			1	13
		Public space and recreation	F										3											3					6
			M										5											1					6
		Transportation (land or sea)	F										3											3	1				7
			M										5											5	3				13
		Energy	F			3							3		1									3	1			1	12
			M			3							5		1									5	3			1	18
	Population	Health	F			1							3											3	1				8
			M			1							3											3	1				8
		Education	F																										0
			M																										0
		Employment	F																										0
			M																										0
		Cultural Heritage	F																										0
			M																										0
		Waste management	F										3																3
			M										5																5
EVALUATION			F	0	0	23	0	0	0	0	0	0	44	0	7	0	0	0	0	0	0	0	17	35	5	0	0	8	
			M	0	0	23	0	0	0	0	0	0	56	0	7	0	0	0	0	0	0	0	17	41	9	0	0	4	

Fig. 15.12 (continued)

15.6 Review of Spatial Planning Instruments

In Fig. 15.13, the overarching planning instruments associated with climate change, risks, and disasters are highlighted. Some of these pre-date the rising concern with climate change, but most have been influential in shaping spatial planning decisions over the past 20 years. They also reveal that, given the strength of risk and disaster planning before the emphasis on climate change, there is a long tradition that reinforces the assumptions on integrated risk climate change development planning present in the IPCC special report on extreme events (2012).

The particular challenge is in localizing these national policy and strategy documents in local planning and practice (see Concejo Municipal de Florencia 2000; CMGRD 2012; Alcaldía de Florencia 2012, 2014; Gobernación de Caquetá 2012). The table below reveals these local instruments and how they are able to

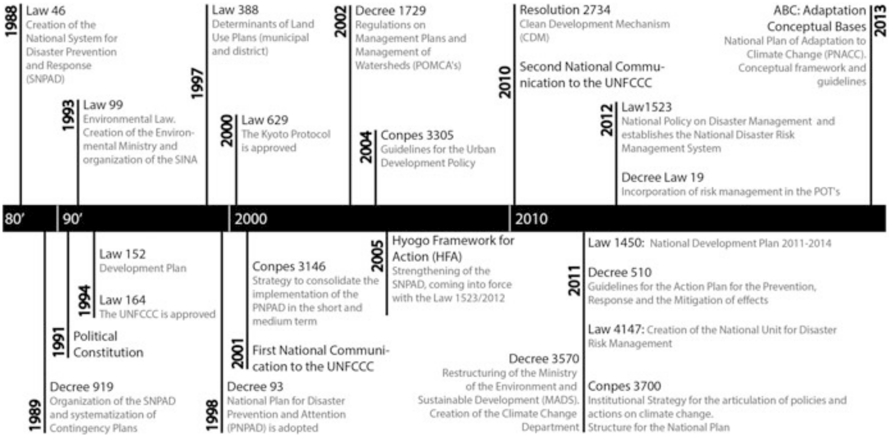

Fig. 15.13 The Colombian legal and institutional framework in relation to climate risk in planning instruments. (Source: Authors)

respond to the impacts that are identified. This process of connecting the instruments responsible for reducing climate risk with the specific threats is important as it may be necessary to revise the instruments and their implementation to ascertain how efficacious they are. The identification of "not coherent" weaknesses in these instruments, and thus their ability to combat the threats, provides an opportunity to change the instruments themselves to ensure that they remain relevant, in addition to reviewing procedures and assessing implementation. This should ensure that existing instruments are maximized in climate change planning, in a mainstream fashion, rather than a preference given for a specific, sectoral climate change plan that may be disconnected from most local policies, programs, plans, and investments generated across the board (Fig. 15.14).

15.7 Characterization of Impacts

As part of the process of focusing and prioritizing, there is a need to establish the nature of the impacts and their gravity. In Fig. 15.15, the matrix connects the climate change impacts with specific local impacts. This translation of broadly defined impacts into specific local impacts is useful in moving beyond more generic references and to focus on a local setting for the climate risks that are experienced. When this is also targeted geographically, through hotspots, there is increased clarity in what to do, and where, which is precisely what local decision-makers are looking for. As noted previously, the nature of the impacts replicates what is noted in the section above on climate impacts and the sectors affected. The additional contribution here is that the type of local impact is highlighted, for example, in flooding, the specific effects on agricultural productivity and potential later migration, the costs of infrastructure maintenance, or the rise in the incidence of yellow fever and dengue.

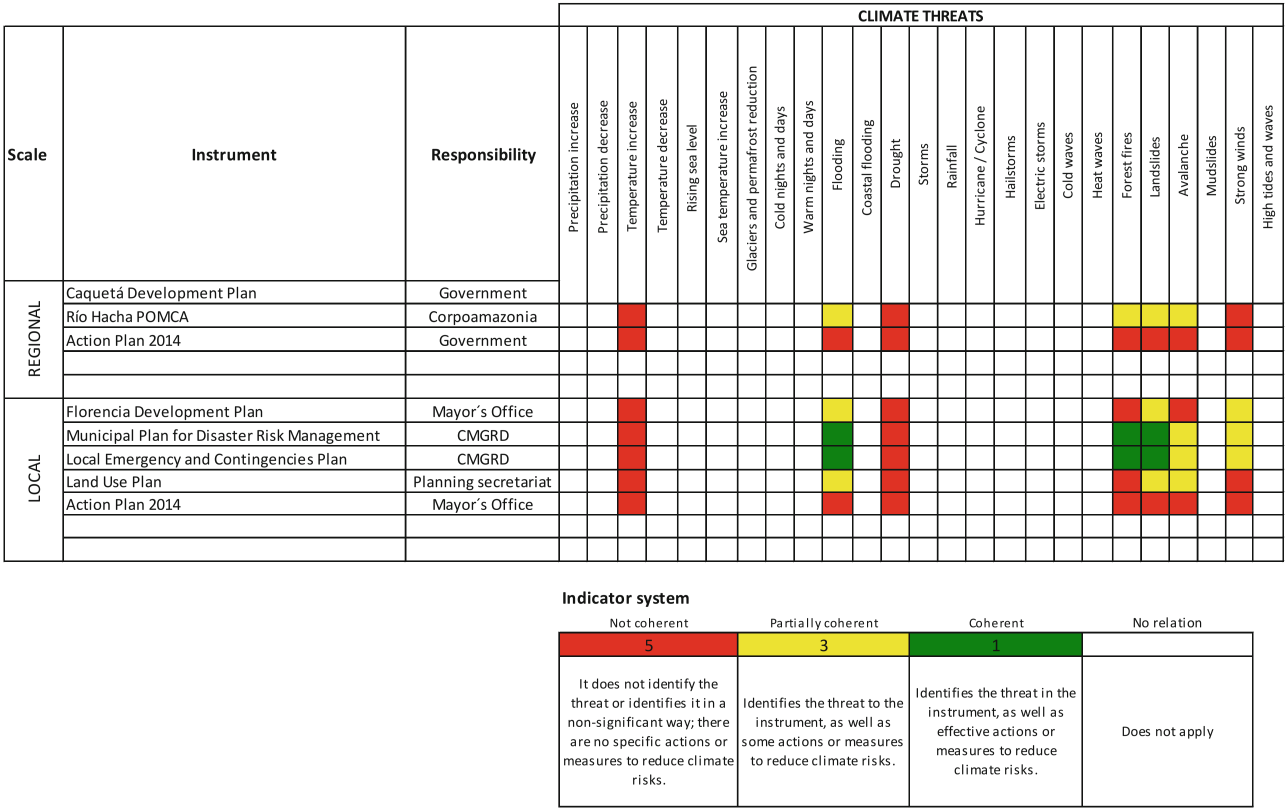

Fig. 15.14 Planning instruments. (Source: Authors)

CLIMATE THREATS

Sector	Impacts	a Precipitation increase	b Precipitation decrease	c Temperature increase	d Temperature decrease	e Rising sea level	f Sea temperature increase	g Glaciers and permafrost reduction	h Cold nights and days	i Warm nights and days	j Flooding	k Coastal flooding	l Drought	m Storms	n Rainfall	o Hurricane / Cyclone	p Hailstorms	q Electric storms	r Cold waves	s Heat waves	t Forest fires	u Landslides	v Avalanche	w Mudslides	x Strong winds	y High tides and waves	Total Sensitivity
Water	Water security			-1																							-1
	Salinization of aquifers																										0
	Recharge of aquifers			-1																							-1
	Acidification of oceans																										0
	Sedimentation																										0
Biodiversity	Extinction of species			-1																							-1
	Diseases and pests			-1							-3																-4
	Displacement of species			-1																							-1
	Eutrophication																										0
	Soil alkalization																										0
	Desertification																										0
	Salinization																										0
	Eolic erosion																				-1						-1
	Water erosion																					-3					-3
	Coastal erosion																										0
	Ecosystem changes			-1																	-3	-3					-7
Silvo-agricultural	Irrigation demand			-1																							-1
	Performance in primary sector			-1							-3											-1					-5
	Food security			-1																							-1
Health	Declining air quality																				-1						-1
	Respiratory diseases																				-1						-1
	Infectious deseases			-1							-3																-4
	Psychological illnesses			-1																							-1
	Mortality			-1							-3											-3	-1				-8
	Morbidity																										0
	Thermal comfort			-3																							-3
	Violence and conflicts			-1							-3											-1					-5
	Migration			-1							-3										-3	-3	-3				-13
Energy	Hydropower production			-1																							-1
	Refrigeration demand			-1																							-1
	Heating demand																										0
Infrastructure	Protection costs										-3											-3					-6
	Insurance costs			-1							-1											-1			-1		-4
	Maintenance costs			-1							-3											-3			-1		-8
	Risk areas										-3											-3	-1				-7
	Heat island			-3																							-3
	Collapsed drainage systems										-3																-3
	Relocation of land uses										-3										-1	-3	-1				-8
Fishing and aquiculture	Species modification																										0
	Growth rates																										0
	Mortality rates																										0
	Productivity																										0
	Displacement of species																										0
Driving force		0	0	-24	0	0	0	0	0	0	-34	0	0	0	0	0	0	0	0	0	-10	-27	-6	0	-2	0	

System of indicators

Highly probably negative	Probably negative	Probably positive	Highly probably positive	Unlikely
-3	-1	1	3	
Relevant negative change in the socio-ecological system. Generates greater losses and disadvantages	Negative change in the socio-ecological system. Generates minor losses and disadvantages.	Positive change in the socio-ecological system. Generates opportunities and benefits.	Relevant positive change in the socio-ecological system. Generates greater opportunities and benefits.	Unlikely or unrelated changes.

Fig. 15.15 Characterization of impacts. (Source: Authors)

15.8 Identification of Responses

Although diagnostics are vital, the connection with responses is critical. Figure 15.16 takes the local impacts and considerations from the previous stage and indicates the actions required, and the efficacy of existing actions. This is important, as it should not be assumed that no action is taking place in the face of climate change because there is a long history of risk, disaster, and responses, from hard to soft, developed over time. The points highlighted in Fig. 15.16 include the weaknesses in current interventions in the field of watershed management and protection of biodiversity in the watershed, to reduce the intensity of flood events, in addition to the lack of basic vulnerability studies of the local area.

Having highlighted existing weaknesses, and areas of opportunity that are not being worked on at present, such as community organization and preparedness at the local level, the next step is to look at the specific localities that are most at risk and where resource allocation can be most effective. The micro-geographies of climate risk determine that the identification of responses should be dove-tailed with the identification of hotspots. In the short term, these hotspots are where most losses are expected to take place; however, the focus on hotspots should not, in the long term, reduce attention from more widespread processes of adaptation and resilience-building across the urban settlement in question; the use of the term 'hotspots' equates to Allen et al. (2017) term "urban risk traps" to identify the complexity of localized risk and the importance of reframing risk mitigation investments.

15.9 Mapping and Identification of Hotspots

The following maps reveal the localities that should be prioritized in a climate risk planning process in Florencia. At this stage, four maps have been generated: the first is the mapping of the exposure, the second is the mapping of the sensitivity, and the third is the mapping of the capacity for adaptation. These three maps represent the dimensions of vulnerability. The fourth map is the juxtaposition of the previous three maps, in which the urban hotspots are identified. According to Martine and Schensul (2013), these are the sectors with exposure to natural hazards, with a history of some kind of disaster and the existence of a sectoral vulnerability (agricultural, social, ecosystems, etc.), a lack of suitability of territorial planning instruments, a low-quality urban infrastructure, a high population density, and a lack of response to disasters.

The final map is a synthesis map that should be regarded as a final outcome of the preliminary appraisal process. This map should not only be co-developed by local government officers and other urban stakeholders, but should also be subsequently used by them to inform their decisions and to disseminate more widely to

CLIMATE THREATS / Institutional practices, cultural, technological, educational, etc

Sector	Measure	Precipitation increase	Precipitation decrease	Temperature increase	Temperature decrease	Rising sea level	Sea temperature increase	Glaciers and permafrost reduction	Cold nights and days	Warm nights and days	Flooding	Coastal flooding	Drought	Storms	Rainfall	Hurricane / Cyclone	Hailstorms	Electric storms	Cold waves	Heat waves	Forest fires	Landslides	Avalanche	Mudslides	Strong winds	High tides and waves	TOTAL
		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	
Water	Control and protection of surface water			-5																							-5
	Control and protection of groundwater																										0
	Management of rainwater and runoff										-5																-5
	Generation of rainwater reservoirs																										0
	Protection of wetlands										-5																-5
	Reduction in water demand																					-5					-5
Biodiversity	Reforestation of the basin			-5							-5										-5	-5					-20
	Protection of soil quality																										0
	Protection of soil and slopes																					-5	-5				-10
	Protection of native species																										0
	Protection / restoration of urban ecosystems																										0
	Biological control																										0
	Protection of forests and ecosystems			-5																	-5	-5					-15
Silvo-agricultural	Control of the forest resource										-5										-5						-10
	Innovation/technology in the primary sector																										0
	Urban gardens																										0
	Composting and vermiculture programs																										0
	Control of pets																										0
Health	Control and monitoring of air quality																										0
	Management of mining and industrial waste																										0
	Improvement of the health system										-3											-3					-6
	Coverage of basic services										-3											-3					-6
Energy	Diversification of energy sources																										0
	Reduction of consumption programs																										0
	Innovation in infrastructure and buildings																										0
	Reuse or recycling of waste																										0
Infrastructure	Coastal protection																										0
	Relocation of land uses										-3											-3					-6
	Planning of land uses										-3											-3					-6
	Settlement in safe places										-5											-5					-10
	Relocation of affected population										-5											-5					-10
	Planned and resistant buildings																										0
	Improvement of vulnerable sectors										-3											-3					-6
	Investment in defensive infrastructure										-3											-3					-6
	Maritime infrastructure investment																										0
	Domestic solid waste management																										0
	Domestic wastewater management										-3											-3					-6
	Management and creation of green areas																										0
	Generation of network of urban cycleways																										0
Fishing and aquiculture	Research in new technologies																										0
	Condition of resources																										0
	Technological innovation																										0
Population and institutionality	Employment																										0
	Introduction of CC in local and regional plans			-3							-3										-3	-3	-3		-3		-18
	Monitoring and evaluation of local plans																										0
	Monitoring system and early warning																										0
	Community organization										3										-3	-3	-3				-6
	Institutional organization for emergencies										3										3	3	3		3		15
	Environmental education and community risk			-5							-3										-3	-3	-3		-3		-20
	Development of local plans			-5							-3										-3	-3	-3				-17
	Strengthening of local institutions																										0
	Participation of the community in planning																										0
	Implementation of microcredits																										0
	Economic assistance to vulnerable communities										-3										-3	-3	-3				-12
	Strengthening regulatory frameworks																										0
	New economic activities																										0
	CC vulnerability studies			-5							-5										-5	-5	-5		-5		-30
	Climate risk studies			-5							-5										-5	-5	-5		-5		-30
	Mining control										-3											-3					-6
	Strengthening partnerships with institutions																										0
	Sustainable urban development																										0
	Strengthening social capital			-5							-3										-3	-3	-3		-3		-20
	Training public officials in CC																										0
	Investment in research										-5											-5					-10

Indicator system

Poor or not undertaken	Insufficient	Appropriately undertaken	No relation
-5	-3	3	

Fig. 15.16 Capacity to respond. (Source: Authors)

the remaining private sector and civil society actors to encourage their future involvement in the climate risk planning process (if this has not been possible in the initial phase).

What is evident in the synthesis map, and what is common to small and intermediate towns and cities in general, is that climate risk compounds existing problems of low-income settlements located in areas that are exposed to flooding and landslides. For this same reason, the importance of generating and implementing adequate responses cannot be disconnected from housing, sanitation, health, education, and employment interventions in these same communities. Climate change is yet another of the many factors that combine to reveal their existing vulnerability, and increase their susceptibility to being affected by the longer-term processes and episodic events associated with climate change phenomena (Figs. 15.17, 15.18, 15.19, and 15.20).

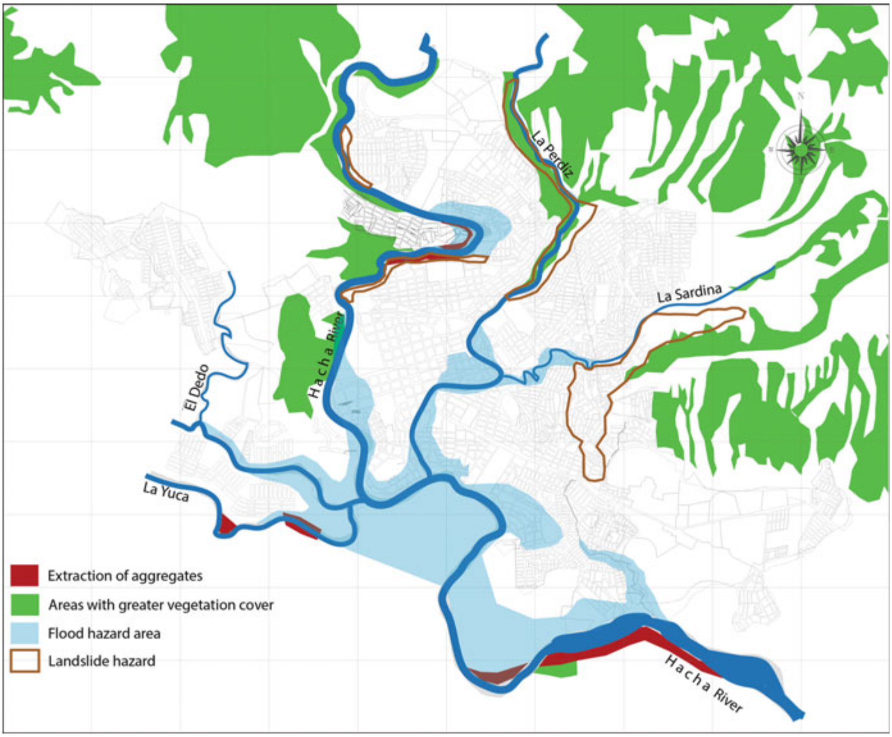

Fig. 15.17 Exposure mapping in Florencia. (Source: Authors)

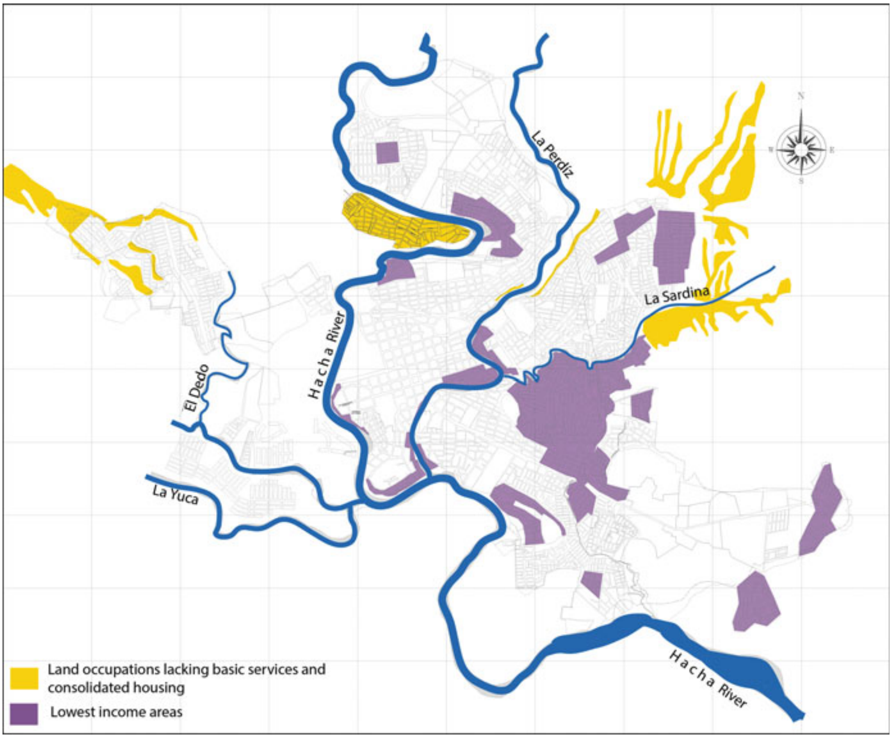

Fig. 15.18 Sensitivity mapping in Florencia. (Source: Authors)

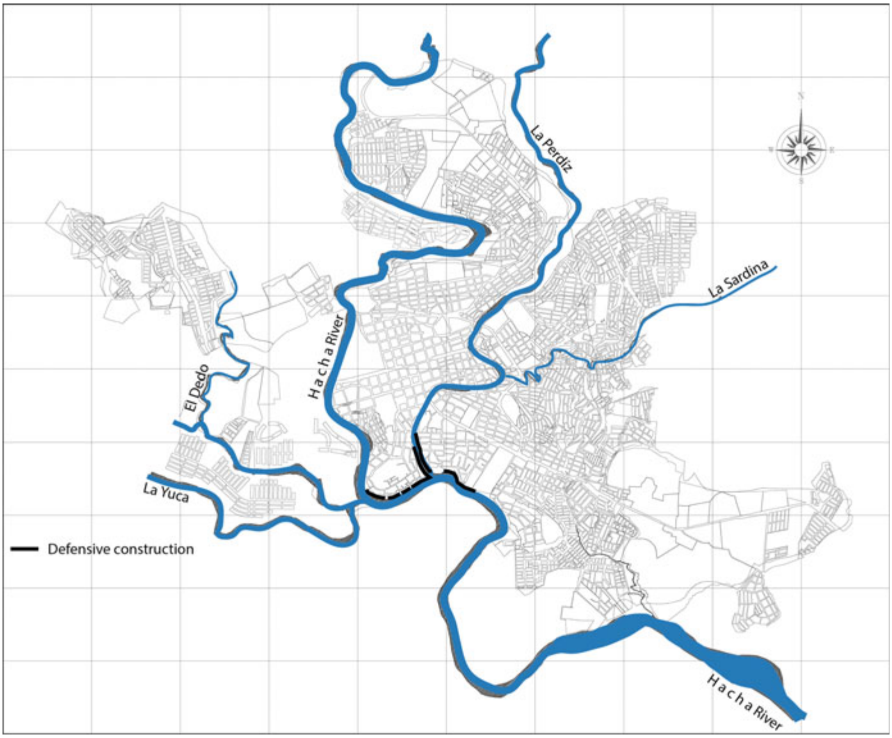

Fig. 15.19 Adaptive capacity mapping in Florencia. (Source: Authors)

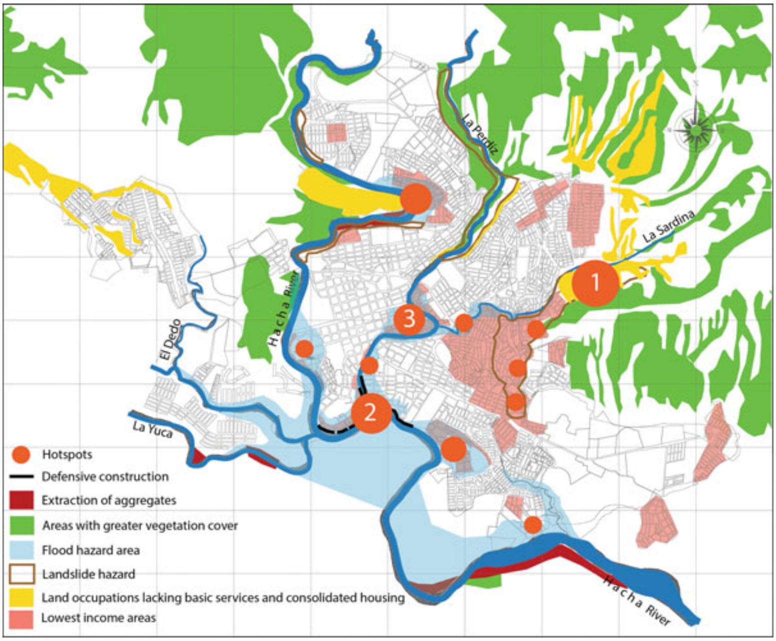

Fig. 15.20 Hotspots mapping in Florencia. (Source: Authors)

15.10 Conclusions

Climate risk planning, particularly for adaptation and increased resilience in urban areas, is a sine qua non in the twenty-first century. Climate risk is part and parcel of all development options as it provides a meteorological context in which choices have to be made. IPCC scenarios for the current century reveal the overarching trends in temperature and precipitation around the world, in addition to the changing patterns of extreme events (IPCC 2014a, b). These options include decisions regarding mortality and morbidity in the face of extreme events, to changing economic production options regarding agricultural production and processing, shifting geographies of disease risk, and ensuring potable water supply, among others.

Despite the relative lack of models that downscale these global trends and the uncertainty across the multiple scenarios on offer, the notion that authorities can sit back and wait for climate change to unfold is evidently unsatisfactory, or even irresponsible. This is particularly the case at the local level where impacts are experienced directly and responses, whether pre-event or post-event, are required. Given the persistent rise in urban dwelling around the world, it is here that much of the work to adapt to climate change will take place (and through mitigation, the long-term reduction of the threats themselves). Although many large metropolitan areas have introduced sectoral or mainstream climate change planning, most urban settlements have not. For this reason, they are more vulnerable. Consequently, it is here that preliminary inroads must be made. Instead of waiting for more resources or some fictitious idea of certainty of impacts from climate change, an initial appraisal should be carried out. The PRA-UCR is a framework for doing this.

The PRA-UCR should not be understood as a definitive tool for defining an urban climate adaptation plan. It is, instead, the precursor to subsequent steps that lead to increased awareness among decision-makers, technical staff and other urban stakeholders, and prioritization of objectives, resources implementation, and management. The application in the case of Florencia reveals the broad-based nature of the process, in addition to the ability to highlight specific risks and define hotspots for initial actions. There are other adaptation tools that currently exist; however, the most effective tool for a preliminary appraisal is that which requires the least expenditure and the lowest level of previous knowledge. This should be the initial rung of the ladder. It is only with all settlement authorities becoming aware of climate risk and integrating this into their decision-making across all sectors that it will be possible to increase awareness and participation, encourage adaptation measures and resilience-building, and ultimately reduce losses from the impacts of climate change.

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