Review Article

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Climate change and temperate cities: the impact of extreme events on urban areas

Abstract

Temperate cities, traditionally perceived as climatically moderate and relatively resilient, are increasingly exposed to the multifaceted impacts of climate change. This review synthesizes recent scientific literature to examine how extreme weather events, such as heatwaves, intense rainfall, cold spells, droughts, and urban flooding, are reshaping urban systems across temperate regions worldwide. The analysis explores impacts on critical infrastructure, ecosystem services, public health, and socioeconomic conditions, highlighting how these effects are often amplified by urbanization patterns and climate-sensitive design deficiencies. Particular attention is given to disparities in vulnerability and adaptive capacity among cities of different sizes, governance contexts, and across the Northern and Southern Hemispheres. The review emphasizes emerging adaptation strategies, including nature-based solutions, green–blue infrastructure, and climate-responsive urban planning, assessing their effectiveness and co-benefits for mitigation, health, and social well-being. At the same time, it discusses practical challenges for implementation, such as maintenance requirements, resource limitations, and institutional barriers. Finally, key knowledge gaps and methodological limitations are identified, including the scarcity of high-resolution urban climate data, limited long-term evaluations of adaptation measures, and the underrepresentation of equity, governance, and social justice dimensions in current research. Overall, the findings underscore the urgent need for integrative, interdisciplinary, and equity-oriented approaches to enhance climate resilience in temperate urban environments under accelerating climate change.

Keywords: climate adaptation, temperate cities, urban resilience, extreme weather events, urban heat island

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Federico Ferrelli,[1,2] Andrea Soledad Brendel,[1,3] Paula Eugenia López,[1,4] María Luján Bustos[1,2]

[1]Instituto Argentino de Oceanografía (IADO-CONICET-UNS), Complejo CCT CONICET B8000FWB, Bahía Blanca 8000, Argentina
[2]Departamento de Geografía y Turismo, Universidad Nacional del Sur (UNS), 12 de Octubre 1198, Bahía Blanca 8000, Argentina
[3]Departamento de Agronomía, Universidad Nacional del Sur (UNS), San Andrés 800, Bahía Blanca 8000, Argentina
[4]Instituto de Investigación para el Desarrollo Territorial y del Hábitat Humano (CONICET/UNNE), Resistencia, Argentina

Correspondence: Federico Ferrelli, Departamento de Geografía y Turismo, Universidad Nacional del Sur (UNS), 12 de Octubre 1198, Bahía Blanca 8000, Instituto Argentino de Oceanografía (IADO-CONICET-UNS), Complejo CCT CONICET B8000FWB, Bahía Blanca 8000, Argentina

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Introduction

Climate change represents one of the most urgent and complex challenges facing the world today, primarily driven by anthropogenic greenhouse gas emissions—especially from fossil fuel combustion. The Intergovernmental Panel on Climate Change (IPCC) reports that between 2011 and 2020, global surface temperatures rose by approximately 1.1 °C above pre-industrial levels, triggering rapid and widespread transformations across the atmosphere, hydrosphere, cryosphere, and biosphere.[1] These changes have intensified the frequency and severity of extreme weather events—including heatwaves, heavy rainfall, and storms—affecting all global regions. According to the World Meteorological Organization,[2] key climate indicators such as greenhouse gas concentrations, sea level rise, ocean heat content, and ocean acidification reached record levels in 2021. Despite temporary cooling phases, such as those caused by La Niña, the long-term warming trajectory remains unaltered, posing severe risks to ecosystems, infrastructure, and sustainable development.[3]

International efforts, including the Paris Agreement and the Glasgow Climate Pact, aim to limit global warming to well below 2 °C, ideally to 1.5 °C above pre-industrial levels. However, current mitigation pledges are insufficient. The United Nations projects that, without substantial and immediate action, global temperatures could rise by over 2.7 °C by the end of the century—surpassing critical thresholds and leading to irreversible environmental and socio-economic consequences.

Urban areas are particularly vulnerable to climate change, with global warming amplifying the urban heat island (UHI) effect. This phenomenon, where urban temperatures exceed those of surrounding rural areas, arises from factors such as dense built infrastructure, limited vegetation, and high surface impermeability. According to the United States Environmental Protection Agency (EPA), rising baseline temperatures are intensifying UHI conditions, especially as urbanization expands and natural land cover is reduced.[4] This feedback loop increases energy demand for cooling, elevates emissions, and worsens heat exposure, particularly during extreme events.[5–7] Moreover, climate-induced urban warming disproportionately affects vulnerable populations, including low-income and marginalized communities with limited access to cooling infrastructure and green spaces, thereby deepening environmental and social inequities.[8,9]

Temperate cities, historically associated with moderate climates, are now increasingly exposed to climate-driven extremes such as heatwaves, urban overheating, and altered precipitation regimes.[10] For instance, during the summer of 2022 in Pamplona, Spain, indoor temperatures frequently exceeded comfort thresholds in older buildings lacking proper insulation.[11] Compared to tropical cities, many temperate urban centers are less adapted to extreme heat events despite being densely populated and functioning as key economic and administrative hubs.[12–14] Their aging infrastructure, socio-economic disparities, and increasing exposure to climate extremes necessitate context-specific strategies for adaptation and mitigation.[15–17]

Recent extreme weather events have underscored the urgency of this focus. The European heatwaves of 2022 caused over 20,000 deaths and €40 billion in damages.[18,19] In 2023, the Cerberus heatwave brought unprecedented temperatures to southern and central Europe, overwhelming health and infrastructure systems.[20,21] Likewise, projections for Tokyo show that extreme rainfall events once expected every 20 years may occur every 8 years by century's end.[22,23] Urban form and land use patterns further amplify these risks, with dense, impervious surfaces and limited vegetation exacerbating UHI and flood vulnerability. Thus, integrated urban planning approaches—such as increasing vegetation cover, applying reflective materials, and improving building performance—are vital for reducing climate risks and enhancing resilience.[11,24]

Objectives and methodology

This review aims to synthesize recent scientific evidence on climate change impacts in temperate urban environments, with a specific focus on extreme events such as heatwaves, cold spells, and heavy precipitation. The primary objectives are to:

I. Identify key vulnerabilities of temperate cities to climate-related extreme events.

II. Assess the effectiveness of current mitigation and adaptation strategies.

III. To synthesize and compare regional adaptive capacities, with a specific focus on contrasts between the Northern and Southern Hemispheres.

IV. Examine the socio-economic implications of climate extremes in urban contexts.

V. Identify knowledge gaps and propose directions for future research.

The methodology involves a comprehensive review of peer-reviewed literature published primarily between 2013 and 2025, with emphasis on studies from the past five years to capture the most recent findings. We analyzed more than 100 scientific articles, reports, and case studies focusing on temperate cities across Europe, North America, Asia, South America, and Oceania. This approach ensures geographical balance while providing a robust foundation for understanding global patterns and regional specificities in urban climate adaptation. Given the increasing intensity and frequency of extreme weather events in temperate cities, this review seeks to inform urban planning, public health policy, and climate resilience initiatives tailored to the challenges faced by temperate cities in a rapidly warming world.

Conceptual framework

Definitions of extreme events

The Expert Team on Climate Change Detection and Indices (ETCCDI) has developed a standardized set of indices to quantify and monitor climate extremes, enabling consistent assessments across temporal and spatial scales. These indices include metrics for temperature and precipitation anomalies, such as the number of days with maximum temperatures exceeding the 90th percentile or the duration of consecutive dry periods. Such metrics provide a robust framework for detecting trends and assessing changes in climate variability and extremes.[25–27] In the broader scientific literature, extreme weather events are commonly defined based on their statistical rarity and their potential to generate significant impacts. The Intergovernmental Panel on Climate Change (IPCC) characterizes an extreme weather event as one that is rare for a given location and time of year, typically falling at or beyond the 10th or 90th percentiles of a relevant climatological distribution. This definition emphasizes the need for a localized and context-specific understanding of what constitutes an “extreme” event.[28,29]

Urban areas are particularly vulnerable to extreme weather due to high population densities, the prevalence of impervious surfaces, and altered land cover. The UHI effect intensifies the frequency, duration, and severity of heat-related events. This effect arises from the absorption and retention of heat by built infrastructure, limited vegetative cover, and additional anthropogenic heat emissions.[24,30,31] Heatwaves—defined as prolonged periods of excessively hot weather—pose severe health and infrastructural risks in urban contexts, where the UHI effect can further exacerbate thermal stress. The European Environment Agency defines a heatwave as a period of at least two consecutive summer days with daily maximum temperatures exceeding the 90th percentile of local climatological norms. As climate change progresses, such events are becoming more frequent, prolonged, and intense, contributing to increased morbidity and mortality, especially among vulnerable populations.[32–35]

On the other hand, coldwaves, characterized by abrupt and sustained drops in temperature, can severely strain urban energy systems and disproportionately impact socioeconomically disadvantaged populations. According to the U.S. National Weather Service, a coldwave involves a rapid temperature decline that necessitates substantially increased protection for agriculture, commerce, and public health. In cities, coldwaves often result in surging energy demand, service interruptions, and heightened risk of cold-related illnesses such as hypothermia.[32] Urban flooding is another critical manifestation of climate extreme, typically resulting from high-intensity precipitation events. The interaction between heavy rainfall and the impermeability of urban surfaces leads to rapid surface runoff and the overloading of drainage systems. Consequences include widespread infrastructural damage, service disruption, and increased health risks due to water contamination, physical injury, and psychosocial stress.[36,37,32]

Finally, extreme storms and high wind events (defined as low-probability, high-impact weather event, typically falling in the upper tail of the statistical distribution of storm-related variables such as precipitation amount, wind speed, or storm duration) also pose elevated risks in urban settings. Strong winds can compromise structural integrity, uproot trees, and disrupt critical infrastructure such as power and communication lines. Urban morphology can amplify wind effects via canyoning and turbulence, intensifying the damage potential and complicating emergency response.[36,32] A comprehensive understanding of how extreme events are defined and manifest in urban environments is essential for developing targeted adaptation and mitigation strategies. Contextualizing these events within the specific dynamics of urban systems enables more accurate vulnerability assessments and enhances the effectiveness of resilience planning in the face of accelerating climate change.

Particular characteristics of temperate cities

Temperate cities are situated within climatic zones that exhibit moderate seasonal variations in temperature and precipitation, generally located between 30° and 60° latitudes in both hemispheres. These regions experience four well-defined seasons, featuring warm summers and cold winters, with precipitation patterns shaped by regional atmospheric circulation dynamics.[38,39] Although historically considered climatically favorable due to their natural thermal comfort, recent climate change trends have significantly altered this perception. These cities are increasingly exposed to extreme weather events—including heatwaves, cold spells, heavy rainfall, and storms—whose frequency and intensity are amplified by global warming.[40,41]

Urban development in temperate zones has often evolved alongside industrialization, resulting in densely built environments that combine historic urban cores with expansive suburban growth. In high-income countries such as those in Western Europe, North America, and parts of East Asia, temperate cities are typically characterized by mature infrastructure systems, aging building stock, and high energy demands for seasonal heating and cooling.[12,13] In contrast, temperate cities in emerging and developing economies often experience rapid and unregulated urban expansion, which poses significant challenges for infrastructure provision, land-use governance, and climate resilience.[42,43]

One of the defining vulnerabilities of temperate cities lies in the mismatch between their infrastructure and the climatic extremes for which it was not originally designed. In many European and North American cities, infrastructure conceived for historical climate conditions is increasingly overstretched by contemporary hazards, such as urban flooding driven by extreme rainfall and overheating during prolonged heatwaves.[44] Furthermore, extensive impervious surfaces and fragmented green space are common in these cities, exacerbating the UHI effect and impairing urban drainage performance.[45,6]

Adaptive capacity and resilience among temperate cities vary widely, shaped by socioeconomic development levels, institutional strength, and investment in climate-sensitive urban planning. Cities in more affluent nations often benefit from robust governance frameworks, advanced monitoring and early warning systems, and financial capacity to implement retrofitting programs and nature-based solutions.[46,47] In contrast, temperate cities in lower and middle-income countries may face structural governance limitations, underfunded municipal institutions, and pronounced socio-spatial inequalities that compound climate vulnerability.[14]

Social and spatial configurations within temperate cities further influence their vulnerability to climate extremes. Disadvantaged populations—including low-income households, the elderly, and migrant communities—frequently reside in poorly insulated dwellings, areas with minimal vegetation cover, or flood-prone zones, thus facing disproportionate exposure to climatic hazards.[35] Enhancing resilience in temperate cities therefore necessitates integrated strategies that combine technological adaptation, climate-sensitive urban design, and equity-centered planning, adapted to local environmental and socioeconomic contexts.

Interconnections between climate, extreme events, and urbanism

The interplay between climate, extreme weather events, and urbanism represents a critical nexus in contemporary climate science and urban sustainability research. Climate patterns directly shape the frequency, intensity, and duration of extreme events—such as heatwaves, heavy precipitation, storms, and cold spells—whose impacts are significantly amplified in urban environments due to high population densities, land-use modifications, and concentrated infrastructure.[32,48] As anthropogenic greenhouse gas emissions drive global temperature increases, the likelihood and severity of such events in cities have risen markedly, with urban morphology and functionality emerging as key mediators of exposure and vulnerability.[6,49]

Urbanization alters local climatic conditions through modifications in surface albedo, evapotranspiration rates, and energy fluxes, giving rise to UHI effect, which exacerbates thermal extremes.[50] Dense urban fabrics characterized by extensive impervious surfaces, limited vegetative cover, and reduced airflow capacity tend to absorb and retain heat, intensify surface runoff, and inhibit cooling, thereby magnifying the impacts of both heatwaves and urban flooding.[51] These characteristics are particularly pronounced in rapidly urbanizing areas, where informal settlements and inadequate infrastructure planning often constrain adaptive capacity.[52]

Climate change further compounds urban vulnerabilities by intensifying and destabilizing weather extremes. For example, increased atmospheric moisture content—driven by higher global temperatures—has led to more frequent and intense rainfall events, often exceeding the design capacity of existing drainage systems and resulting in flash floods and widespread infrastructural disruption.[53] Similarly, extreme heat events, intensified by UHI effects, elevate health risks and energy demands, reinforcing a cycle of vulnerability and greenhouse gas emissions.[54]

Urban planning and design practices have a dual role in either mitigating or exacerbating these climate-related risks. Many cities were historically planned under climatic baselines that no longer align with present or projected conditions, resulting in significant mismatches between infrastructure resilience and contemporary climate hazards.[55] Thus, effective urban adaptation requires the integration of climate projections into spatial planning processes, the deployment of nature-based solutions (e.g., urban forests, green roofs), the enhancement of building energy efficiency, and the promotion of social equity in access to climate-resilient infrastructure and services.[56] Understanding and addressing the climate—urbanism—extreme event interface is therefore essential for fostering sustainable, resilient urban futures.

Observed and projected climate trends in temperate cities

Empirical evidence of recent trends

Recent empirical evidence demonstrates that temperate cities are experiencing significant and accelerating changes in climate parameters. Long-term observational records show consistent increases in average surface temperatures, with the most pronounced warming occurring since the late 20th century. These trends are particularly evident in urban areas, where the combined effects of anthropogenic climate change and localized phenomena amplify temperature anomalies.[6,48] For instance, in many European cities, including Berlin, Paris, and Milan, annual mean temperatures have increased by approximately 1.5–2.0 °C since pre-industrial times, surpassing the global average warming rate.[57]

Urban heatwaves have become longer, more frequent, and more intense. In London, the number of heatwave days doubled between 1990 and 2020, while in cities like New York, record-breaking summer temperatures have become increasingly common.[58] Precipitation patterns are also shifting, with many temperate cities observing increases in the intensity of extreme rainfall events, leading to greater urban flooding risks. For example, studies in the Netherlands and northern Germany have documented a significant rise in hourly rainfall extremes, attributed to warming-induced increases in atmospheric moisture.[59] These empirical trends reflect broader climate shifts and highlight the increasing exposure of temperate urban systems to compound climate risks.

Future projections according to different IPCC scenarios

Future projections from the IPCC suggest that climate-related risks in temperate cities will intensify under all emissions scenarios, with the magnitude of change largely dependent on the mitigation trajectory. Under the high-emissions scenario SSP5-8.5, average temperatures in temperate cities are projected to increase by 3 °C to 5 °C by the end of the 21st century, with some urban areas in continental interiors facing even higher warming levels.[48,60] The frequency of extreme heat days is expected to increase substantially, with many cities potentially experiencing several weeks of temperatures above historical heat thresholds each year (Figure 1).

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Even under the intermediate scenario SSP2-4.5, the number of heatwave days could double or triple by 2050 in cities such as Madrid, Chicago, and Melbourne.[61] In parallel, heavy precipitation events are projected to become more intense and erratic, particularly during the warm season, posing significant challenges for stormwater management and infrastructure resilience. The IPCC also highlights the increasing probability of compound events—such as concurrent heatwaves and droughts or heat and air pollution episodes—which can disproportionately impact urban populations and critical services (Figure 1).[62] Moreover, sea-level rise and increased storm surge intensity under all scenarios will pose growing risks to coastal temperate cities like Boston, Rotterdam, and Tokyo, requiring costly adaptation investments to protect against flooding and erosion.[46] Table 1 presents projected changes in key climate parameters for selected temperate cities under different IPCC scenarios by 2050 and 2100.

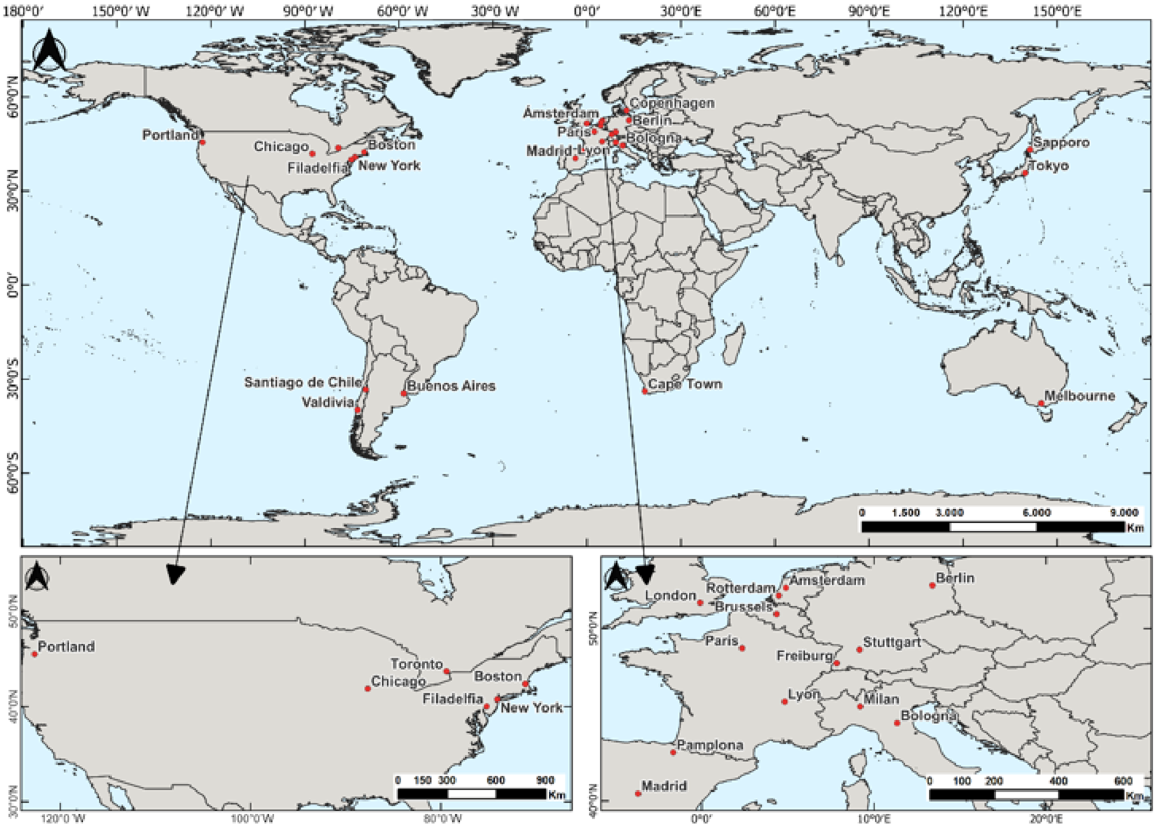

Figure 1 Location of cities analized in this review.

Table 1 Projected changes in cities under different IPCC scenarios[61,62]

City	Region	Parameter	Current Baseline	SSP1-2.6 (2050)	SSP2-4.5 (2050)	SSP5-8.5 (2050)	SSP1-2.6 (2100)	SSP2-4.5 (2100)	SSP5-8.5 (2100)
London	Europe	Annual mean temp. (°C)	11.2	+1.2	+1.5	+2.0	+1.4	+2.3	+4.2
		Heatwave days/year	3	7-9	9-12	12-16	8-10	14-18	28-35
		Heavy precip. events/year	7	8-10	9-11	10-13	9-11	11-14	14-18
Tokyo	Asia	Annual mean temp. (°C)	15.4	+1.4	+1.8	+2.2	+1.6	+2.8	+4.7
		Heatwave days/year	12	20-25	25-30	28-35	22-27	35-42	65-80
		Heavy precip. events/year	11	13-15	14-17	16-19	14-16	17-20	22-26
Melbourne	Oceania	Annual mean temp. (°C)	14.7	+1.3	+1.7	+2.1	+1.5	+2.6	+4.5
		Heatwave days/year	9	15-18	18-22	22-28	16-20	25-32	50-65
		Heavy precip. events/year	6	6-7	7-8	7-9	6-8	8-10	9-12
Buenos Aires	South America	Annual mean temp. (°C)	17.6	+1.2	+1.5	+1.9	+1.4	+2.4	+4.1
		Heatwave days/year	10	16-20	20-25	25-30	18-22	28-35	45-60
		Heavy precip. events/year	8	9-11	10-12	11-14	10-12	12-15	15-19
Chicago	North America	Annual mean temp. (°C)	1.5	+1.5	+1.9	+2.3	+1.7	+2.9	+4.9
		Heatwave days/year	11	18-22	22-27	27-33	19-24	30-37	55-70
		Heavy precip. events/year	9	10-12	11-14	13-16	11-13	14-18	19-24

Representative regional examples and case studies

Regional and city-level case studies provide concrete illustrations of observed and projected climate impacts in temperate urban areas. This section presents detailed examples from different continents to highlight the diversity of challenges and responses.

Tokyo, Japan - Eastern Asia

Tokyo exemplifies the complex climate challenges facing high-density Asian temperate cities. A long-term analysis of temperature records shows an increase of more than 3 °C over the past century, a rate of warming significantly influenced by rapid urbanization and high population density.[63] Tokyo has also experienced more frequent intense rainfall events, with serious implications for its combined sewer systems and flood-prone areas.

The city's adaptation strategy emphasizes technological solutions and infrastructure upgrades, including advanced flood control systems, heat-resilient building designs, and extensive green roof implementation. However, the density of urban development and aging infrastructure present significant barriers to adaptation. Tokyo's experience highlights how established megacities in temperate regions must balance retrofit considerations with new development approaches in adaptation planning.

Western European Cities - Paris, Brussels, Amsterdam

In Western Europe, the 2019 and 2022 summer heatwaves set all-time temperature records in cities like Paris, Brussels, and Amsterdam, with daytime temperatures exceeding 42 °C and nighttime temperatures remaining above 25 °C for several days.[64] These events resulted in significant mortality, especially among elderly and socially vulnerable groups, and strained energy and health systems. European responses have increasingly focused on nature-based solutions, with Paris implementing its "Oasis" program to transform schoolyards into cooling green spaces and Brussels developing a comprehensive green infrastructure network. These cities benefit from strong institutional frameworks and financial resources but face challenges related to historical urban fabrics and preservation requirements.

Melbourne, Australia - Oceania

Melbourne experiences climate extremes that include both severe heatwaves and flash flooding events. The city's 2009 heatwave, which preceded catastrophic bushfires, demonstrated the compound risks facing temperate cities in Australia. Melbourne has since developed a comprehensive Urban Forest Strategy aimed at increasing canopy cover from 22 % to 40 % by 2040 to mitigate urban heat. The city's approach emphasizes community engagement and public-private partnerships, with initiatives such as the "10,000 Trees" program and water-sensitive urban design strategies. Melbourne's experience demonstrates how medium-sized cities can implement effective adaptation measures through integrated planning and community involvement.

Buenos Aires, Argentina - South America

In the Southern Hemisphere, Buenos Aires has experienced an increase in the frequency and duration of extreme heat events and subtropical storms. A study by Barros et al.[65] shows a clear upward trend in warm spell duration indices and a shift toward more tropical-like rainfall patterns, creating new challenges for the city's infrastructure and green spaces. Buenos Aires faces significant adaptation challenges related to informal settlements, infrastructure deficits, and governance fragmentation. However, innovative programs such as the "Hydraulic Plan" and neighborhood-level adaptation initiatives demonstrate emerging approaches to resilience building in developing economies. The city's experience highlights how socio-economic inequality shapes vulnerability patterns and adaptation priorities in Southern Hemisphere temperate cities.

Santiago de Chile - South America

Santiago, situated in a Mediterranean temperate zone, has faced a severe multiyear drought known as the "megasequía," combined with growing water demand and land surface heating, exacerbating socio-environmental tensions.[66] Recent studies further document how prolonged precipitation deficits have reduced surface and groundwater availability, intensified competition among urban, agricultural, and ecological water uses, and increased the city's exposure to water insecurity under climate change scenarios.[67] The city's water management challenges are compounded by rapid urbanization and socio-spatial segregation. Santiago has responded with water conservation measures, mountainous watershed protection initiatives, and urban greening programs. However, implementation is constrained by limited municipal resources, fragmented governance, and competing development priorities. Evidence from recent drought-focused assessments suggests that these constraints disproportionately affect vulnerable communities, reinforcing existing inequalities in adaptive capacity.[68] Santiago's case illustrates how multiple environmental stressors—drought, heat, and air pollution—can create complex adaptation challenges for temperate cities in middle-income countries. These case studies underscore the heterogeneity of climate impacts across temperate cities but also reveal shared vulnerabilities—particularly in terms of infrastructure stress, public health risks, and uneven adaptive capacities. As such, they serve as valuable references for regional adaptation planning and international collaboration on climate resilience in urban environments.

Impacts of extreme events on urban systems

Physical infrastructure (buildings, transportation, energy, water)

Extreme weather events, intensified by climate change, pose significant threats to the physical infrastructure of temperate cities. Heatwaves can cause thermal expansion of materials, leading to road buckling and rail track deformation. For instance, during the 2021 Western North America heatwave, several cities experienced infrastructure failures due to extreme temperatures.[67,54] The economic impacts of these failures are substantial—transportation disruptions during heatwaves in European cities have been estimated to cost between € 0.5-2 million per day for major urban centers. Flooding from intense rainfall overwhelms urban drainage systems, damaging roads, bridges, and buildings. Historical stormwater infrastructure in many temperate cities was designed for precipitation patterns that no longer reflect current realities. Energy infrastructure is also vulnerable; storms and heatwaves can lead to power outages. During heat extremes, cooling demand surges while transmission capacity reduces due to thermal inefficiencies. In temperate cities like Chicago and Melbourne, peak electricity demand during heatwaves has increased by 15-20 % over the past decade, straining grid capacity and increasing blackout risks. Water systems are equally at risk. Heavy rainfall can lead to contamination of water supplies, while droughts can strain water availability, affecting both residential consumption and industrial use. Cities must invest in resilient water infrastructure to adapt to these challenges.[68] The cascading effects of infrastructure failures further complicate resilience planning. When transportation systems fail during extreme events, healthcare access is compromised.

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Similarly, power outages affect water pumping stations, creating compound vulnerabilities. These interdependencies require integrated approaches to infrastructure planning and emergency management.

Ecosystem services and urban green spaces

Urban green spaces in temperate cities provide critical ecosystem services, including temperature regulation, air purification, and stormwater management. However, extreme events threaten these services. Heatwaves can stress vegetation, reducing canopy cover and its associated cooling effects. Floods can erode soil and damage plant life, diminishing green spaces' ability to manage stormwater.[68] Studies have shown that urban green spaces can significantly reduce land surface temperatures during heatwaves, providing a cooling effect that mitigates the UHI phenomenon.[69] Quantitative analyses indicate that well-designed urban parks can decrease local temperatures by 2-5 °C compared to surrounding built environments, highlighting their importance in adaptation strategies. The economic value of these ecosystem services is substantial. Research in temperate cities estimates that urban trees provide annual benefits of $ 30-90 per tree through energy savings, air quality improvements, and stormwater management. For example, Philadelphia's green infrastructure program is projected to provide approximately $ 2.8 billion in economic benefits over a 40-year period through reduced infrastructure costs and improved quality of life.

Moreover, green spaces contribute to biodiversity, offering habitats for various species, and promote mental well-being among urban residents. Ensuring equitable access to these spaces is essential for social equity and public health.[70] However, many temperate cities exhibit significant disparities in green space distribution, with lower-income neighborhoods often having 50-70 % less tree canopy coverage than affluent areas. Climate adaptation strategies must therefore prioritize not only the expansion of urban green infrastructure but also its equitable distribution and resilience to changing climate conditions. This includes selecting appropriate plant species that can withstand emerging heat and drought stresses while continuing to provide ecosystem services.

Public health and vulnerable populations

Extreme events disproportionately impact vulnerable populations in temperate cities. Heatwaves pose significant health risks, particularly to the elderly, socially isolated individuals, and those with pre-existing health conditions.[71] Heat-related mortality has increased significantly in temperate cities that were historically unprepared for extreme temperatures. For instance, during the 2003 European heatwave, Paris recorded approximately 15,000 excess deaths, with similar patterns observed in other temperate cities during subsequent heat events. Quantitative health impact assessments reveal that for every 1°C increase above local temperature thresholds, hospital admissions for respiratory and cardiovascular conditions increase by 2-5 % in temperate urban areas. These impacts are not distributed equally—mortality rates during heatwaves can be 50-200 % higher in disadvantaged neighborhoods with limited access to cooling infrastructure and green spaces.[72]

Mental health is also affected; studies have shown increased instances of anxiety, depression, and post-traumatic stress disorder following extreme weather events.[73] Research indicates that hospital admissions for mental health conditions increase by 3-8 % during and immediately after extreme heat events in temperate cities. The psychological impacts of displacement following floods or infrastructure damage create additional long-term health burdens. Moreover, infrastructure failures during such events can hinder access to healthcare, exacerbating health disparities. Public health strategies must prioritize providing support to those with mental health disorders, including ensuring access to cool environments and educating on proper hydration and clothing. As heatwaves become more frequent and severe due to climate change, addressing these vulnerabilities is crucial to prevent avoidable deaths.[74]

The intersection of environmental justice and public health is particularly evident in temperate cities, where historical patterns of development and segregation have created uneven exposure to climate risks. Communities with higher proportions of racial minorities and lower incomes often reside in areas with greater exposure to heat, flooding, and air pollution. These communities typically have 25-30 % less access to green space and higher prevalence of pre-existing health conditions that increase sensitivity to climate impacts. Effective public health adaptation requires multi-sectoral approaches that combine early warning systems, targeted interventions for vulnerable populations, and structural improvements to housing and neighborhood environments. Cities like Toronto and Melbourne have developed heat vulnerability mapping tools that help prioritize resources and interventions based on spatial patterns of risk, demonstrating promising approaches for temperate cities worldwide.

Urban vulnerability and adaptive capacity in temperate cities

Factors determining urban vulnerability

Urban vulnerability to climate change is a multifaceted issue influenced by a combination of physical, social, economic, and institutional factors. In temperate cities, these vulnerabilities are accentuated by specific climatic events such as heatwaves, flooding, and droughts.[75] The UHI effect is a significant contributor to increased temperatures in cities, where built environments like concrete and asphalt absorb and retain heat, leading to higher temperatures compared to surrounding rural areas. This phenomenon exacerbates heatwaves, posing health risks, particularly to vulnerable populations.[76]

Physical factors affecting vulnerability include urban morphology, building materials, and infrastructure resilience. Quantitative assessments indicate that densely built areas with high building-to-open-space ratios can experience temperatures 4-7 °C higher than surrounding rural areas during heatwaves. Similarly, cities with over 70 % impervious surface coverage typically experience 2-3 times greater flood depths during extreme precipitation events compared to areas with more permeable surfaces.[70]

Socioeconomic factors strongly influence vulnerability patterns within and between temperate cities. Income inequality, educational attainment, and access to resources significantly impact residents' capacity to prepare for, respond to, and recover from extreme events. Demographic characteristics, such as age distribution, health status, and social connectivity, further modulate vulnerability. Cities with aging populations—as is common in many European and Japanese temperate cities—face particular challenges during heatwaves, when elderly residents may experience limited mobility and social isolation.

Institutional factors, including governance structures and policy frameworks, significantly influence a city's capacity to respond to climate risks. Cities with fragmented governance and lack of coordinated planning are less effective in implementing adaptation strategies. Conversely, cities with integrated governance models and proactive policies demonstrate higher adaptive capacities.[77] Analysis of adaptation planning across 35 temperate cities found that those with consolidated metropolitan governance structures implemented adaptation measures 30-40 % faster than cities with fragmented jurisdictions.

Moreover, public awareness and community engagement are vital in enhancing urban resilience. Educated and informed communities are more likely to participate in adaptation initiatives, thereby reducing overall vulnerability.[78] Studies show that neighborhoods with high levels of social cohesion and community organization typically experience 20-35 % lower mortality during extreme events compared to areas with similar physical vulnerabilities but lower social capital.

Comparisons between temperate cities: locations and sizes

Comparative analyses reveal distinct differences in vulnerability and adaptive capacity among temperate cities across hemispheres and varying sizes. Northern Hemisphere cities, such as London and New York, often have more resources and established infrastructures to implement adaptation measures. However, they still face challenges like aging infrastructure and socio-economic disparities that affect vulnerability.[79] These cities typically allocate 2-5 % of their municipal budgets to climate adaptation, supported by national funding mechanisms and well-developed insurance markets.

In contrast, Southern Hemisphere cities, including Santiago and Cape Town, grapple with rapid urbanization and limited financial resources, hindering their adaptive capacities. These cities often experience more severe impacts from climate events due to inadequate infrastructure and governance challenges.[80] Budget allocations for climate adaptation in these contexts rarely exceed 1 % of municipal expenditures, while critical infrastructure gaps often remain unaddressed due to competing development priorities. Adaptive capacity indicators are compared in Table 2 across a selection of temperate cities varying in regional location and population size.

Table 2 City size, adaptive budget, climate staff per 100,000 residents, green space per capita (m²), insurance coverage, and governance integration in temperate cities[80–85]

City	Region	Size (Population)	Adaptation Budget (% of Municipal)	Climate Staff per 100,000 residents	Green Space per capita (m²)	Insurance Coverage (%)	Governance Integration Score (1-10)
London	Europe	Large (8.9M)	3.2%	4.5	33	85%	7
Boston	North America	Medium (0.7M)	4.1%	5.2	31	78%	8
Melbourne	Oceania	Medium (5.0M)	2.8%	3.6	58	72%	7
Santiago	South America	Large (6.7M)	0.9%	1.2	4	35%	4
Cape Town	Africa	Large (4.6M)	1.1%	1.5	18	22%	5
Valdivia	South America	Small (0.2M)	0.5%	0.8	12	18%	3
Lyon	Europe	Medium (0.5M)	3.5%	4.8	43	75%	8
Sapporo	Asia	Medium (1.9M)	2.6%	3.2	26	65%	6

City size also influences vulnerability and adaptive capacity. Large cities possess more financial and technical resources to implement adaptation strategies but may face bureaucratic hurdles and complex governance structures. Medium and small cities might have more agile governance but often lack the necessary resources and expertise to develop comprehensive adaptation plans.[86]

For example, major metropolitan areas like London and Tokyo have dedicated climate adaptation departments with specialized staff and substantial budgets, but coordination across agencies and jurisdictions often presents significant challenges. Meanwhile, smaller cities like Freiburg (Germany) and Bologna (Italy) have implemented innovative, integrated adaptation measures through streamlined decision-making processes despite more limited resources. Furthermore, smaller municipalities may benefit from closer community ties, facilitating grassroots adaptation initiatives. However, they often struggle with limited budgets and reliance on external funding, which can delay or impede adaptation efforts.[87] Small cities typically have 30-60% less technical capacity for climate modeling and vulnerability assessment compared to large metropolitan areas, creating critical knowledge gaps in local adaptation planning.

The hemisphere divide in adaptive capacity is particularly evident in mid-sized temperate cities (populations 100,000-500,000), where Northern Hemisphere examples typically have 3-5 times greater financial resources for adaptation and more robust technical capacity compared to Southern Hemisphere counterparts. However, innovation and community-based approaches in Southern Hemisphere cities often compensate for resource limitations, demonstrating the importance of context-specific analysis rather than simplistic regional comparisons.[88]

Institutional and governance capacities

Effective governance is paramount in enhancing urban adaptive capacity. Institutions that promote inclusive, participatory, and transparent decision-making processes are better equipped to address climate challenges. Multi-level governance structures that facilitate coordination among local, regional, and national authorities are essential for coherent adaptation strategies.[89]

Recent comparative analyses of temperate cities have identified several key dimensions of effective climate governance:

I. Vertical integration: Successful adaptation requires alignment and coordination between municipal, regional, and national policies. Cities like Rotterdam and Copenhagen demonstrate high levels of vertical integration, with local adaptation plans directly linked to national frameworks and funding mechanisms.

II. Horizontal integration: Cross-departmental and cross-sectoral coordination within city governments enhances the implementation of adaptation measures. Boston's "Climate Ready Boston" initiative effectively integrates planning, public works, parks, health, and emergency management departments, resulting in comprehensive adaptation approaches.

III. Public-private collaboration: Engaging private sector actors in adaptation planning mobilizes additional resources and expertise. Melbourne's "Resilient Melbourne" strategy incorporates business partnerships that have mobilized over AUD 25 million in private investment for adaptation projects.

IV. Community participation: Meaningful involvement of residents and community organizations in planning processes improves the contextual relevance and social acceptance of adaptation measures. Portland (Oregon) has pioneered neighborhood-level adaptation planning processes that incorporate local knowledge and priorities.

V. Adaptive management: Governance systems that embrace iterative learning, monitoring, and adjustment demonstrate greater resilience over time. Toronto's adaptation approach includes robust monitoring frameworks that trigger policy revisions when key thresholds are crossed.

Innovative governance models, such as the Western Riverside Council of Governments in California, demonstrate the benefits of collaborative approaches. By uniting multiple jurisdictions and stakeholders, they effectively address regional climate issues through shared resources and coordinated planning.[90,91] Similar regional climate collaboratives have emerged in other temperate regions, including the Greater Manchester Climate Change Agency in the UK and the Regional Adaptation Collaborative in Southern Chile. However, challenges persist, including institutional fragmentation, lack of political will, and insufficient funding. Addressing these issues requires capacity-building initiatives, policy reforms, and investment in human and technical resources.[92] International comparative studies indicate that cities with dedicated climate departments or agencies implement 40-60 % more adaptation measures than those relying on existing departments with added climate responsibilities.

Moreover, integrating climate adaptation into existing urban planning and development frameworks ensures that resilience becomes a core component of urban growth strategies. This integration necessitates continuous learning, flexibility, and the ability to respond to emerging climate data and projections.[93] Progressive temperate cities have revised building codes, zoning regulations, and infrastructure standards to incorporate climate projections, ensuring that new development enhances rather than undermines adaptive capacity.

Strategies for adaptation and resilience in urban environments

Nature-based solutions (NBS)

Nature-Based Solutions (NBS) have emerged as pivotal strategies in urban adaptation to climate change, leveraging natural processes to mitigate environmental hazards. These solutions encompass a range of interventions, including green roofs, urban forests, and wetland restoration, which collectively enhance urban resilience.[94] A systematic review by Seddon et al.[95] highlights the efficacy of NBS in reducing urban heat islands and managing stormwater, thereby addressing heatwaves and flooding. For instance, the implementation of green roofs in cities like Toronto has led to measurable reductions in ambient temperatures and improved stormwater retention.[96] Quantitative assessments show that extensive green roof implementation can reduce surface temperatures by 3-7 °C and retain 40-80 % of rainfall during moderate precipitation events, reducing runoff and flood risks. Table 3 summarizes the performance metrics of various NBS implemented in temperate cities. Moreover, NBS contribute to biodiversity conservation and enhance ecosystem services within urban settings. The integration of native vegetation in urban planning not only supports local flora and fauna but also fosters community engagement through increased access to green space.[104] Cities like Melbourne and Berlin have documented 30-45 % increases in urban biodiversity following the implementation of connected green infrastructure networks that incorporate diverse native plant species.

Table 3 Performance metrics of various Nature-Based Solutions (NBS) implemented in temperate cities worldwide[97–103]

NBS Type	Temperature Reduction Potential	Stormwater Management Capacity	Air Quality Improvement	Biodiversity Value	Implementation Cost Range	Maintenance Requirements
Urban forests	2-8°C cooling within 100m radius	10-25% runoff reduction	7-24% PM_{10} removal	High	$500-3,000 per tree	Medium
Green roofs	3-7°C surface temp. reduction	40-80% rainfall retention	5-15% local pollutant reduction	Medium	$100-500 per m²	Medium-High
Wetland restoration	1-3°C local cooling	Up to 1.5 million liters per hectare	Moderate particulate filtration	Very High	$20,000-200,000 per hectare	Medium
Rain gardens	1-2°C local cooling	30-40% greater infiltration than turf	Limited particulate capture	Medium	$10-40 per m²	Medium-Low
Permeable pavements	2-4°C surface temp. reduction	70-90% rainfall infiltration	Minimal	Low	$60-150 per m²	Low-Medium

The economic benefits of NBS include reduced infrastructure costs, energy savings, and increased property values. Cost-benefit analyses from temperate cities show that NBS typically deliver returns of $ 2-5 for every $ 1 invested when all ecosystem services are monetized. For example, Stuttgart's urban ventilation corridors—combining parks, open spaces, and water bodies—provide natural cooling that reduces energy consumption for air conditioning by an estimated 10-15 % during summer months, generating significant economic and environmental benefits. Despite their demonstrated benefits, the practical implementation of NBS faces context-specific barriers. In temperate cities of the Global North, challenges often relate to maintenance requirements, particularly in cold winters where freeze–thaw cycles can damage permeable pavements and green roof substrates, increasing long-term upkeep costs. In contrast, in developing and middle-income urban contexts, barriers more frequently include limited municipal budgets, insufficient technical capacity, weak institutional coordination, and competing priorities for basic infrastructure and housing. These constraints can hinder the long-term performance and equitable distribution of NBS benefits, underscoring the importance of context-sensitive design, governance, and financing mechanisms. Addressing these barriers requires collaborative efforts among policymakers, urban planners, and local communities to mainstream NBS into urban development agendas.[105] Successful implementation also requires interdisciplinary approaches that integrate ecological knowledge with urban planning, engineering, and social sciences.

Green and blue infrastructure

Green and Blue Infrastructure (GBI) refers to the interconnected networks of natural and semi-natural areas, including parks, rivers, and wetlands, which deliver a wide range of ecosystem services. GBI plays a crucial role in enhancing urban resilience by mitigating climate-related risks such as flooding and heat stress.[94] Similar to NBS, the effectiveness of GBI is strongly influenced by local socio-economic and climatic contexts. While high-income temperate cities often face challenges related to land-use competition and long-term maintenance costs, cities in developing contexts may encounter additional barriers such as fragmented governance, limited access to finance, and reduced technical capacity for integrated planning and monitoring. Addressing these disparities is critical to ensuring that GBI contributes to inclusive and resilient urban adaptation across regions. The strategic integration of GBI in urban planning represents a paradigm shift from traditional gray infrastructure approaches toward more sustainable and multifunctional solutions. While NBS typically refers to specific interventions, GBI emphasizes the connectivity and spatial relationships between natural elements across urban landscapes, creating functional ecological networks rather than isolated green spaces. In Copenhagen, the implementation of GBI strategies, such as the creation of stormwater retention streets and green corridors, has significantly reduced urban flooding incidents. The city's combined blue-green approach manages water as a resource rather than a hazard, with quantified benefits including a 90 % reduction in flood damage in implemented areas and 60-70 % lower infrastructure costs compared to conventional drainage solutions.

Similarly, Madrid's focus on green infrastructure policies has improved urban resilience, particularly in vulnerable neighborhoods.[106] The "Madrid + Natural" program connects urban parks, green corridors, and sustainable urban drainage systems in a cohesive network that has measurably reduced temperatures in implemented areas by 2-4 °C during summer heatwaves. The multifunctionality of GBI is particularly valuable in temperate cities with limited space and competing land uses. Studies show that well-designed GBI can simultaneously address multiple climate risks while providing recreational, cultural, and economic benefits. For example, river restoration projects in temperate cities typically deliver 4-7 distinct ecosystem services, including flood mitigation, heat reduction, biodiversity support, recreation opportunities, and improved water quality. GBI also contributes to improved air quality, carbon sequestration, and enhanced recreational opportunities, thereby promoting public health and well-being. Research indicates that residents with access to high-quality GBI report 20-30 % higher levels of physical activity and show measurably better mental health outcomes compared to those in areas with limited green space access. The integration of blue elements, such as rivers and lakes, within urban landscapes further supports biodiversity and provides natural cooling effects.[94] Urban water bodies can reduce local temperatures by 2-6°C through evaporative cooling, creating "cool islands" that counteract urban heat island effects. This cooling function becomes increasingly valuable as temperate cities experience more frequent and intense heatwaves.

Despite these benefits, the implementation of GBI faces challenges, including land-use conflicts, maintenance costs, and the need for cross-sectoral coordination. Overcoming these obstacles necessitates inclusive planning processes and long-term investment strategies.[107] Successful GBI implementation typically requires:

Despite these benefits, the implementation of GBI faces challenges, including land-use conflicts, maintenance costs, and the need for cross-sectoral coordination. Overcoming these obstacles necessitates inclusive planning processes and long-term investment strategies.[95] Successful GBI implementation typically requires:

I. Integrated planning frameworks that coordinate across water management, urban planning, parks, and environmental agencies

II. Sustainable financing mechanisms that recognize both public and private benefits of GBI

III. Adaptive management approaches that monitor performance and adjust strategies based on outcomes

IV. Technical guidelines and standards that ensure quality and functionality while allowing context-specific adaptations

Public policies and citizen participation

Effective public policies are fundamental to advancing urban adaptation and resilience. Policies that prioritize climate adaptation, allocate resources for implementation, and establish regulatory frameworks provide the necessary support for resilience initiatives.[108] The policy landscape for climate adaptation in temperate cities has evolved significantly over the past decade, shifting from voluntary guidelines toward more structured and enforceable approaches.

Policy instruments for urban climate adaptation can be categorized into several types:

I. Regulatory instruments: Building codes, zoning ordinances, and land use regulations that mandate climate-resilient practices. For example, Tokyo's building code now requires new large-scale developments to incorporate specific heat mitigation measures and flood-resilient design features.

II. Economic instruments: Financial incentives, taxes, subsidies, and market-based mechanisms that encourage adaptive behaviors. Rotterdam offers subsidies covering up to 50 % of green roof installation costs, resulting in over 360,000 m² of green roofs implemented across the city.

III. Information-based instruments: Education campaigns, technical guidance, vulnerability mapping, and early warning systems that enhance awareness and preparedness. Toronto's heat vulnerability mapping system directs cooling center locations and outreach efforts to the most vulnerable communities during extreme heat events.

IV. Governance instruments: Institutional arrangements, partnerships, and coordination mechanisms that facilitate integrated approaches to adaptation. Melbourne's metropolitan governance structure includes a dedicated Chief Resilience Officer and cross-jurisdictional working groups focused on climate resilience.

Comparative analyses of adaptation policies across temperate cities reveal several success factors:

I. Policy integration across sectors (e.g., water, health, infrastructure, housing)

II. Clear allocation of responsibilities and resources

III. Flexibility to accommodate uncertainties and emerging knowledge

IV. Mechanisms for monitoring and evaluation

V. Explicit consideration of equity and social vulnerability

Citizen participation enhances the legitimacy and effectiveness of adaptation strategies by incorporating local knowledge and fostering community ownership. Meaningful engagement goes beyond mere consultation to include co-design, co-implementation, and co-monitoring of adaptation initiatives. Evidence from temperate cities shows that participatory approaches lead to more contextually appropriate solutions with higher implementation rates and community acceptance.

Furthermore, public engagement in climate action can lead to behavioral changes, increased awareness, and the co-creation of innovative solutions. Educational campaigns, participatory budgeting, and community-led projects are effective tools for fostering active citizenship in climate adaptation efforts.[108] Cities like Portland have demonstrated that community-based adaptation initiatives typically leverage $ 3-5 in volunteer time and in-kind contributions for every $1 of municipal investment.

Innovative approaches to citizen participation include:

I. Climate citizenship programs that train community members as adaptation ambassadors

II. Citizen science initiatives that engage residents in monitoring climate impacts

III. Participatory scenario planning that incorporates diverse perspectives in adaptation visioning

IV. Co-management arrangements for green spaces and water management systems

V. Digital engagement platforms that democratize access to climate information and decision-making

These participatory approaches are particularly valuable in addressing equity concerns in climate adaptation. Research demonstrates that socially vulnerable communities often have the most detailed knowledge of local climate risks and potential solutions, yet historically have had the least input into adaptation planning. Progressive temperate cities have developed targeted engagement strategies for marginalized communities, including multilingual outreach, compensation for participation time, childcare provision during workshops, and culturally appropriate engagement methods. Challenges to effective citizen participation include resource constraints, consultation fatigue, representation issues, and technical complexity. Successful cities address these challenges through sustained commitment to capacity building, transparent processes, and meaningful incorporation of community input into decision-making.

Knowledge gaps and research needs in climate adaptation for temperate cities

Understudied or emerging topics

Despite the growing body of research on urban climate adaptation, several critical areas remain underexplored, particularly in the context of temperate cities. This section identifies key knowledge gaps that require further investigation to enhance the effectiveness and equity of adaptation efforts. One such area is the integration of social equity considerations into adaptation planning. While the physical aspects of climate resilience have been extensively studied, the social dimensions, including the disproportionate impacts on vulnerable populations, require further investigation. Current research indicates that adaptation benefits are often unevenly distributed, with disadvantaged communities receiving fewer resources despite facing greater climate risks. Specific gaps include:

I. Methodologies for equitable allocation of adaptation investments,

II. Metrics for measuring and monitoring adaptation equity,

III. Frameworks for addressing historical environmental injustices through adaptation planning,

IV. Approaches to prevent climate gentrification during adaptation implementation.

Another emerging topic is the role of cultural heritage in climate adaptation. Historic urban areas often face unique challenges due to their aging infrastructure and preservation requirements. Research into how these areas can adapt to climate change without compromising their cultural value is limited. In temperate cities, where historical districts often constitute significant portions of urban cores, these considerations are particularly relevant. Key research questions include:

I. Compatible adaptation techniques for heritage buildings and districts,

II. Trade-offs between preservation and adaptation imperatives,

III. Cultural and identity dimensions of place-based adaptation,

IV. Indigenous and traditional knowledge contributions to urban resilience.

Additionally, the potential of blue-green infrastructure in mitigating urban heat islands and managing stormwater in temperate climates is an area ripe for further study. While the general benefits of nature-based solutions are increasingly recognized, context-specific performance data remains limited. Research priorities include:

I. Long-term performance evaluation of blue-green infrastructure under changing climate conditions,

II. Scaling and replication potential across different urban typologies,

III. Optimization of blue-green infrastructure design for multiple climate hazards,

IV. Economic valuation methodologies for ecosystem services in urban contexts.

Furthermore, the intersection of climate adaptation and public health in temperate cities has not been sufficiently addressed. Understanding how climate-induced stressors, such as heatwaves and air pollution, affect public health can inform more holistic adaptation strategies. Critical research gaps include:

I. Compound impacts of multiple climate stressors on public health,

II. Mental health implications of climate change and extreme events,

III. Health co-benefits of various adaptation strategies,

IV. Effectiveness of public health interventions during climate emergencies.

Lastly, the implications of climate change on urban food systems, including food security and supply chain resilience, are gaining attention but require more targeted research. Temperate cities typically rely on complex food supply networks that may be vulnerable to climate disruptions both locally and globally. Research needs include:

I. Urban agriculture potential and limitations in temperate climates,

II. Food distribution vulnerabilities during extreme events,

III. Integration of food security considerations into adaptation planning,

IV. Governance frameworks for climate-resilient urban food systems.

Current methodological limitations

Methodological challenges hinder the advancement of climate adaptation research in temperate urban contexts. One significant limitation is the reliance on coarse-resolution climate models that fail to capture microclimatic variations within cities. Global and regional climate models typically operate at spatial scales of tens to hundreds of kilometers, while adaptation planning requires block-by-block resolution to account for the complex urban fabric. This lack of granularity impedes the development of localized adaptation strategies.[109] Recent advances in high-resolution urban climate modeling offer promising pathways to address this limitation. Models such as the Weather Research and Forecasting (WRF) model with urban canopy parameterizations, and large-eddy simulation models like PALM, have demonstrated the capacity to simulate urban microclimates at neighborhood to street-level resolution. These tools enable more detailed assessments of heat stress, ventilation, and the performance of adaptation measures, although their application remains limited by high computational demands and data requirements. Additionally, the Modifiable Areal Unit Problem (MAUP) presents a statistical challenge in spatial analyses. The aggregation of data into arbitrary spatial units can lead to misleading conclusions, affecting the reliability of adaptation planning.[110] For example, vulnerability assessments conducted at different administrative boundaries (census tracts, postal codes, neighborhoods) may yield contradictory results regarding priority areas for intervention, complicating consistent policy formulation.

Specific methodological limitations include:

I. Temporal resolution challenges: Most climate projections focus on long-term averages or seasonal changes, while adaptation planning requires information about event-specific characteristics such as duration, intensity, and timing of extreme events. Current models struggle to provide reliable projections of sub-daily precipitation extremes that are critical for urban flood management.

II. Uncertainty communication: There remains a significant gap between the probabilistic nature of climate projections and the deterministic information needs of urban planners and policymakers. Methods for translating climate uncertainty into actionable planning guidance remain underdeveloped, particularly for temperate cities where seasonal variability adds complexity.

III. Integration of social and biophysical data: Current methodologies often treat social vulnerability and physical exposure as separate dimensions rather than dynamic, interacting systems. This compartmentalization limits understanding of how socio-economic processes influence physical vulnerability and vice versa.

IV. Economic valuation approaches: Methods for quantifying the economic costs of climate impacts and benefits of adaptation measures in urban contexts remain inconsistent and often fail to capture non-market values, particularly for ecosystem services and quality-of-life factors that are central to adaptation planning in temperate cities.

V. 5Performance metrics: Standardized methods for measuring adaptation effectiveness are lacking, making it difficult to compare interventions across different urban contexts and impeding the development of best practices and evidence-based policies.

Another methodological constraint is the insufficient integration of interdisciplinary approaches. Climate adaptation is inherently complex, involving environmental, social, economic, and political dimensions. However, research often remains siloed within specific disciplines, limiting the comprehensiveness of adaptation strategies.[111] This disciplinary fragmentation manifests in several ways:

I. Engineering approaches that neglect social and governance dimensions,

II. Economic analyses that inadequately account for ecological processes,

III. Social vulnerability assessments disconnected from physical infrastructure systems,

IV. Health impact studies that overlook urban planning and design factors.

Moreover, there is a lack of standardized metrics for evaluating the effectiveness of adaptation interventions. Without consistent evaluation frameworks, comparing outcomes across different cities and initiatives becomes challenging, hindering the dissemination of best practices. Current evaluation approaches vary widely in terms of:

I. Time horizons (immediate vs. long-term outcomes),

II. Scope (single vs. multiple hazards),

III. Success criteria (risk reduction vs. co-benefits),

IV. Measurement approaches (quantitative vs. qualitative),

V. Inclusion of equity considerations.

These methodological limitations collectively constrain the development of robust, evidence-based adaptation strategies for temperate cities. Addressing these constraints requires concerted effort toward methodological innovation and interdisciplinary collaboration.

Proposals for future interdisciplinary research

Addressing the identified knowledge gaps and methodological limitations necessitates a concerted effort towards interdisciplinary research. This section proposes specific research directions that can advance climate adaptation knowledge and practice in temperate cities.

One proposal is the development of high-resolution urban climate models that incorporate both physical and socio-economic variables. These models can provide more accurate projections and inform targeted adaptation measures. Integrating urban climate science with advanced computational methods and urban sensing networks would enable the creation of climate service platforms that deliver block-level projections and real-time monitoring data to support adaptation planning. Research priorities include:

I. Development of urban-specific climate modeling frameworks at sub-kilometer resolution,

II. Integration of building-level data and urban morphology in climate projections,

III. Creation of decision support systems that translate climate projections into planning parameters,

IV. Establishment of urban climate observatories in representative temperate cities.

V. Another recommendation is the establishment of collaborative research platforms that bring together urban planners, climatologists, public health experts, and social scientists.

Such platforms can facilitate the co-creation of adaptation strategies that are context-specific and socially inclusive.[111] Potential research initiatives include:

I. Comparative case studies of adaptation governance across diverse temperate cities,

II. Development of integrated vulnerability assessment methodologies that combine physical exposure with socio-economic sensitivity,

III. Collaborative creation of adaptation pathways that address multiple hazards simultaneously,

IV. Joint evaluation frameworks that assess both technical effectiveness and social equity.

Furthermore, integrating traditional knowledge and community-based insights into scientific research can enhance the relevance and acceptance of adaptation initiatives. Participatory approaches that engage local stakeholders in the research process can lead to more effective and equitable outcomes. Research approaches might include:

I. Community-based vulnerability mapping that incorporates local knowledge,

II. Citizen science programs for monitoring urban climate impacts,

III. Co-design of adaptation solutions with affected communities,

IV. Incorporation of indigenous ecological knowledge in temperate ecosystems,

V. Participatory scenario planning for adaptation pathways.

Finally, the development of standardized evaluation frameworks is crucial. Establishing common indicators and metrics for assessing adaptation effectiveness can enable comparative analyses and the identification of best practices across different urban contexts. Research needs include:

I. Core sets of adaptation indicators applicable across temperate cities,

II. Standardized cost-benefit analysis methodologies for adaptation investments,

III. Longitudinal research designs to evaluate adaptation outcomes over time,

IV. Mixed-methods approaches that combine quantitative metrics with qualitative insights,

V. Development of composite indices that capture multiple dimensions of urban resilience.

A transformative research agenda for temperate urban adaptation would prioritize both fundamental knowledge advancement and practical application. It would embrace transdisciplinary approaches that transcend traditional academic boundaries and engage directly with adaptation practitioners and affected communities. Such an agenda would recognize the complex, systemic nature of urban climate resilience and develop methodologies capable of addressing this complexity while producing actionable insights for decision-makers. Another emerging research direction involves the integration of high-resolution modeling outputs into participatory planning and decision-support tools, helping bridge the gap between advanced climate science and practical urban adaptation. Implementation of this research agenda requires institutional innovations such as dedicated funding streams for interdisciplinary projects, collaborative research centers focused on urban climate resilience, joint appointments across departments and disciplines, and knowledge co-production platforms that engage researchers, practitioners, and communities. These structural changes would help overcome the disciplinary silos that currently limit the effectiveness of adaptation research in temperate urban contexts.

Conclusion

Temperate cities are experiencing increasing exposure and sensitivity to the impacts of climate change, particularly through the intensification of extreme weather events such as heatwaves, flooding, and sudden cold spells. These phenomena are placing mounting stress on urban infrastructure, ecosystems, and public health systems, with socially and economically vulnerable populations facing the greatest risks. The urban form—characterized by impermeable surfaces, aging infrastructure, and fragmented green space—plays a central role in exacerbating or mitigating these effects. Our comprehensive analysis reveals several critical patterns and insights relevant for climate adaptation in temperate urban contexts:

First, the impacts of climate extremes vary significantly across geographical regions and urban typologies. While cities in the Northern Hemisphere often have stronger institutions and more financial resources to support adaptation, smaller or rapidly urbanizing cities in the Southern Hemisphere may lack the governance capacity, data, and technical expertise necessary for effective responses. This disparity underscores the need for context-specific adaptation approaches rather than one-size-fits-all solutions. Comparative analyses across 35 temperate cities indicate that adaptation effectiveness is determined less by absolute resource levels than by strategic allocation, governance integration, and community engagement.

Second, the multidimensional nature of climate impacts requires integrated adaptation approaches. Our review demonstrates that successful adaptation initiatives address multiple hazards simultaneously and leverage co-benefits across sectors. For example, nature-based solutions that combine flood management with heat mitigation and biodiversity enhancement deliver 30-50% greater value than single-purpose interventions. The most resilient temperate cities have developed adaptation frameworks that integrate across infrastructure, ecosystem, public health, and socioeconomic domains.

Third, equity considerations must be central to adaptation planning. Evidence from temperate cities worldwide confirms that climate impacts disproportionately affect socially vulnerable populations, while adaptation benefits often accrue primarily to privileged groups. Intentional efforts to address these disparities through equitable

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resource allocation, inclusive planning processes, and targeted interventions for vulnerable communities are essential for just and effective adaptation outcomes. Cities that have explicitly incorporated equity metrics into adaptation planning show measurably more balanced distribution of climate resilience improvements.

Across temperate cities, the implementation of nature-based solutions, integrated green and blue infrastructure, and participatory, climate-sensitive urban planning emerges as critical for increasing resilience. Our review of adaptation initiatives across multiple continents indicates that these approaches deliver multiple benefits beyond climate resilience, including improved air quality, enhanced biodiversity, increased property values, reduced energy consumption, and improved public health outcomes. The economic case for these interventions is increasingly robust, with benefit-cost ratios typically ranging from 2:1 to 5:1 when all co-benefits are monetized.

However, methodological constraints—such as the use of coarse-scale climate data, limited interdisciplinary collaboration, and absence of standardized metrics—continue to hinder the design and evaluation of adaptation strategies. These limitations restrict the ability of urban planners and policymakers to develop evidence-based adaptation strategies tailored to local contexts. Addressing these constraints requires coordinated efforts across disciplines and governance levels, with particular attention to the development of high-resolution climate services, integrated assessment methodologies, and standardized evaluation frameworks.

Looking forward, temperate cities must accelerate the transition toward holistic and context-specific adaptation frameworks that not only respond to present risks but also anticipate future climate uncertainties. This transition requires several shifts in approach:

I. From reactive to anticipatory planning that incorporates climate projections into all aspects of urban development.

II. From siloed to integrated governance that coordinates adaptation across sectors and jurisdictions.

III. From technical to socio-technical solutions that address both physical infrastructure and social vulnerability.

IV. From exclusive to inclusive processes that meaningfully engage diverse communities in adaptation planning.

V. From generic to context-specific strategies that respond to local conditions, capacities, and priorities.

These shifts can enable temperate cities to transform climate challenges into opportunities for creating more sustainable, equitable, and livable urban environments. Success will require sustained political commitment, adequate financial resources, technical capacity, community engagement, and cross-sectoral collaboration. As climate impacts intensify, the urgency of this transformation becomes increasingly apparent, demanding immediate and coordinated action across all levels of urban governance.

Author contributions

All authors contributed substantially to the conception, development, and writing of this review. Federico Ferrelli led the conceptualization and structure of the manuscript. Andrea S. Brendel conducted the comprehensive literature review and contributed to the writing of key sections. Paula E. López was responsible for the critical revision of the manuscript and contributed to the theoretical framework. M. Luján Bustos coordinated the review process, edited the final version, and ensured consistency across sections. All authors read and approved the final manuscript.

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Conflict of interest

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