11 Built Environment, Urban Systems, and Cities

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11 Built Environment, Urban Systems, and Cities

Cleveland, Ohio

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

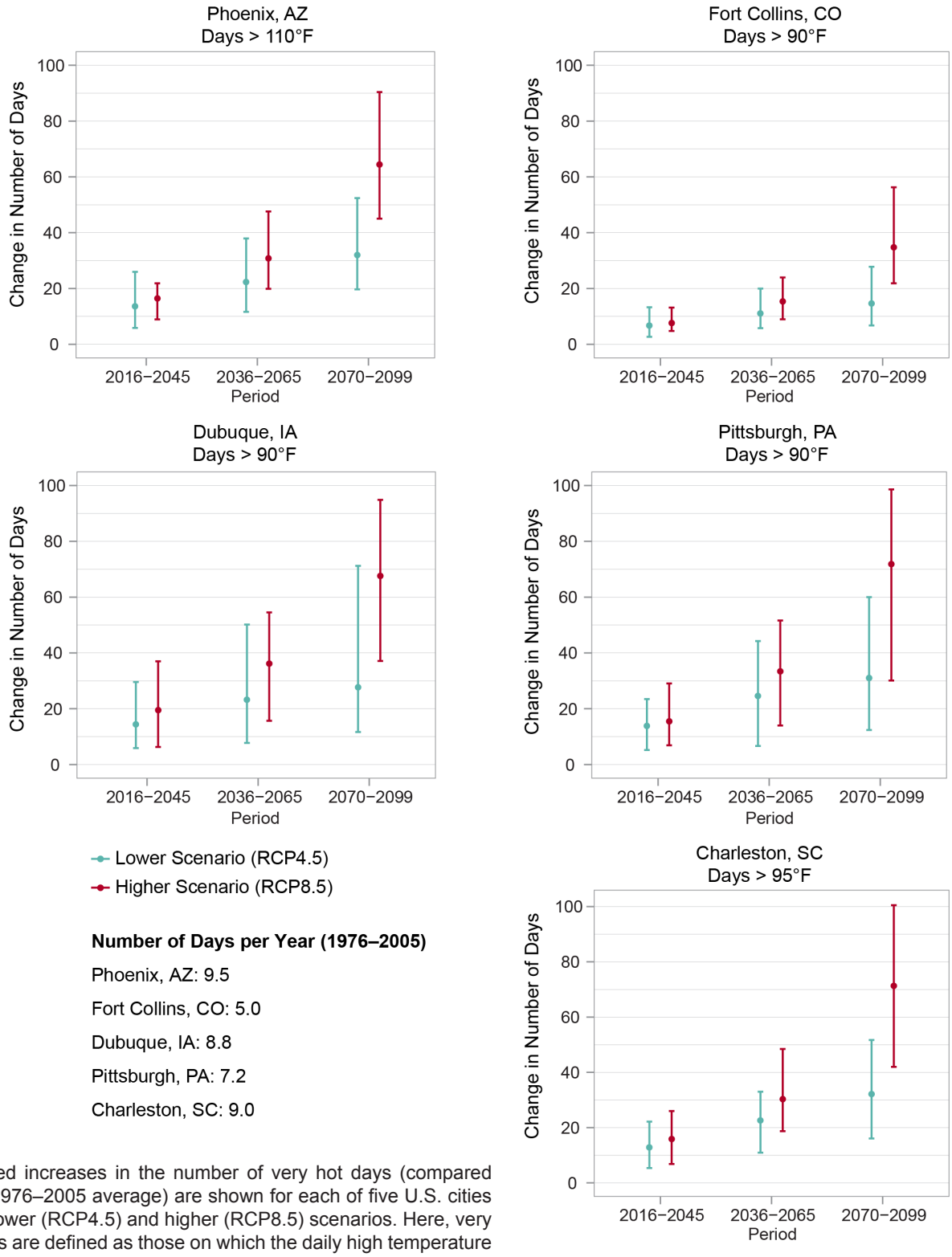
Executive Summary

Urban areas, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas are already experiencing the effects of climate change. Cities differ across regions in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics. Cities are already subject to higher surface temperatures because of the urban heat island effect, which is projected to get stronger. Recent extreme weather events reveal the vulnerability of the built environment (infrastructure such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work. Heat waves and heavy rainfalls are expected to increase in frequency and intensity. The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong. Infrastructure designed for historical climate trends is vulnerable to future weather extremes and climate change. Investing in forward-looking design can help ensure that infrastructure performs acceptably under changing climate conditions.

Urban areas are linked to local, regional, and global systems. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common. When climate stressors affect one sector, cascading effects on other sectors increase risks to residents' health and well-being. Cities across the Nation are taking action in response to climate change. U.S. cities are at the forefront of reducing greenhouse gas emissions and many have begun adaptation planning. These actions build urban resilience to climate change.

Projected Change in the Number of Very Hot Days



Number of Days per Year (1976–2005)

Phoenix, AZ: 9.5

Fort Collins, CO: 5.0

Dubuque, IA: 8.8

Pittsburgh, PA: 7.2

Charleston, SC: 9.0

Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. *From Figure 11.2 (Sources: NOAA NCEI, CICS-NC, and LMI)*.

Introduction

Recent extreme weather events reveal the vulnerability of the built environment (infrastructure, such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work in cities. This chapter builds on previous assessments of urban social vulnerability and climate change impacts on urban systems.[1,2,3] It discusses recent science on urban social and ecological systems underlying vulnerability, impacts on urban quality of life and well-being, and urban adaptation. It also reviews the increase in urban adaptation activities, including investment, design, and institutional practices to manage risk. Examples of climate impacts and responses from five cities (Charleston, South Carolina; Dubuque, Iowa; Fort Collins, Colorado; Phoenix, Arizona; and Pittsburgh, Pennsylvania) illustrate the diversity of American cities and the climate risks they face.

State of the Sector

Urban areas in the United States, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. In 2015, nearly 275 million people (about 85% of the total U.S. population) lived in metropolitan areas, and 27 million (about 8%) lived in smaller micropolitan areas.[4] Metropolitan areas accounted for approximately 91% of U.S. gross domestic product (GDP) in 2015, with over 23% coming from the five largest cities alone.[5] Urban land values are estimated at more than two times the 2006 national GDP.[6] Urbanization trends are expected to continue (Figure 11.1), and projections suggest that between 425 and 696 million people will live in metropolitan and micropolitan areas combined by 2100.[7] All of these factors affect how urban areas respond to climate change.

Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Urban social inequality is evident in disparities in per capita income, exposure to violence and environmental hazards, and access to food, services, transportation, outdoor space, and walkable neighborhoods.[9,10,11,12] Cities are connected by networks of infrastructure, much of which is in need of repair or replacement. Failing to address aging and deteriorating infrastructure is expected to cost the U.S. GDP as much as $3.9 trillion (in 2015 dollars) by 2025.[13] Current infrastructure and building design standards do not take future climate trends into account.[14] Urbanization affects air, water, and soil quality and increases impervious surface cover (such as cement and asphalt).[15,16,17] Urban forests, open space, and waterways provide multiple benefits, but many are under stress because of land-use change, invasive species, and pollution.[18] These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas, where the majority of the U.S. population lives and most consumption occurs, are the source of approximately 80% of North American human-caused greenhouse gas (GHG) emissions, despite only occupying 1%–5% of the land. Therefore, changes to urban activities can have a significant impact on national GHG emissions.[19] Land use and land-cover change contribute to radiative forcing, and infrastructure design can lock in fossil fuel dependency, so urban development patterns will continue to affect carbon sources and sinks in the future (Ch. 5: Land Changes).[19,20,21] Many cities in the United States are working to reduce their GHG emissions and can be key leverage points in mitigation efforts.

Current and Projected U.S. Population

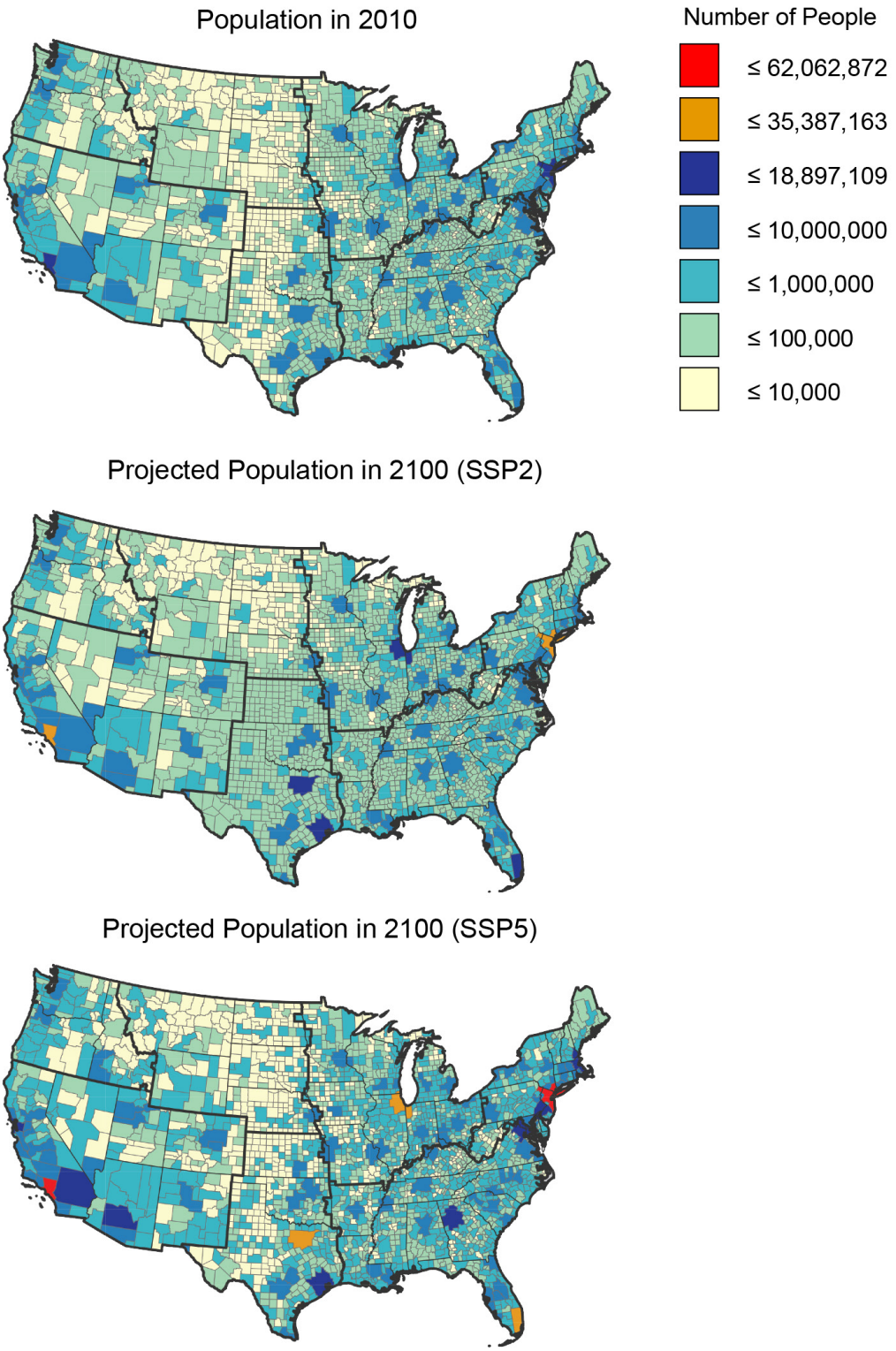


Figure 11.1: These maps show current population along with population projections by county for the year 2100. Projected populations are based on Shared Socioeconomic Pathways (SSPs)—a collection of plausible future pathways of socioeconomic development.[8] The middle map is based on demography consistent with the SSP2, which follows a middle-of-the-road path where trends do not shift markedly from historical patterns. The bottom map uses demography consistent with SSP5, which follows a more rapid technical progress and resource-intensive development path. Increasing urban populations pose challenges to planners and city managers as they seek to maintain and improve urban environments. Data are unavailable for the U.S. Caribbean, Alaska, and Hawai‘i & U.S.-Affiliated Pacific Islands regions. Source: EPA

Regional Summary

Urban areas in the United States are already experiencing the effects of climate change. Across regions, U.S. cities differ in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics.[1] In coastal areas, the built environment is subject to storm surge, high tide flooding, and saltwater intrusion (Ch. 8: Coastal, KM 1). Wildfires are on the rise in the West, lowering air quality and damaging property in cities near the wildland–urban interface (Ch. 6: Forests, KM 1; Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1; Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 2). In 2017, Los Angeles witnessed the largest wildfire in its history, with over 700 residents ordered to evacuate. The fire began during a heat wave and burned over 7,100 acres.[22] Key climate threats in the Northeast, on the other hand, are from precipitation and flooding: between 2007 and 2013, Pittsburgh experienced 11 significant flash flooding events[23,24] (Ch. 18: Northeast, KM 3). Heat waves (Figure 11.2) and heavy rainfalls (Figure 11.3) are expected to increase in frequency and intensity (Ch. 2: Climate KM 2 and 5).[25,26,27] The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong.[28]

In other parts of the country, drought conditions coupled with extreme heat increase wildfire risk, and rainfall after wildfires raises flood risks.[21] In 2012 and 2013, fires destroyed hundreds of homes in the Fort Collins area of the Northern Great Plains region. In those same years, floods washed out transportation infrastructure and caused $2 billion (in 2013 dollars) in total damages.[34,35]

Despite these differences, U.S. cities experience some climate impacts in similar ways. For example, prolonged periods of high heat affect urban areas around the country.[21] Cities are already subject to higher surface temperatures because of the urban heat island (UHI) effect, which can also affect regional climate.[29] The UHI is projected to get stronger with climate change.[29] Another commonality is that most cities are subject to more than one climate stressor. Exposure to multiple climate impacts at once affects multiple urban sectors, and the results can be devastating.[30] Over a four-day period in 2015, the coastal city of Charleston in the Southeast region experienced extreme rainfall, higher sea levels, and high tide flooding. These impacts combined to cause dam failures, bridge and road closures, power outages, damages to homes and businesses, and a near shutdown of the local economy (Ch. 19: Southeast, KM 2).[31,32,33] These kinds of incidents are expected to continue as climate change brings a higher number of intense hurricanes, high tide flooding, and accelerated sea level rise (Ch. 8: Coastal, KM 1).[21]

Projected Change in the Number of Very Hot Days

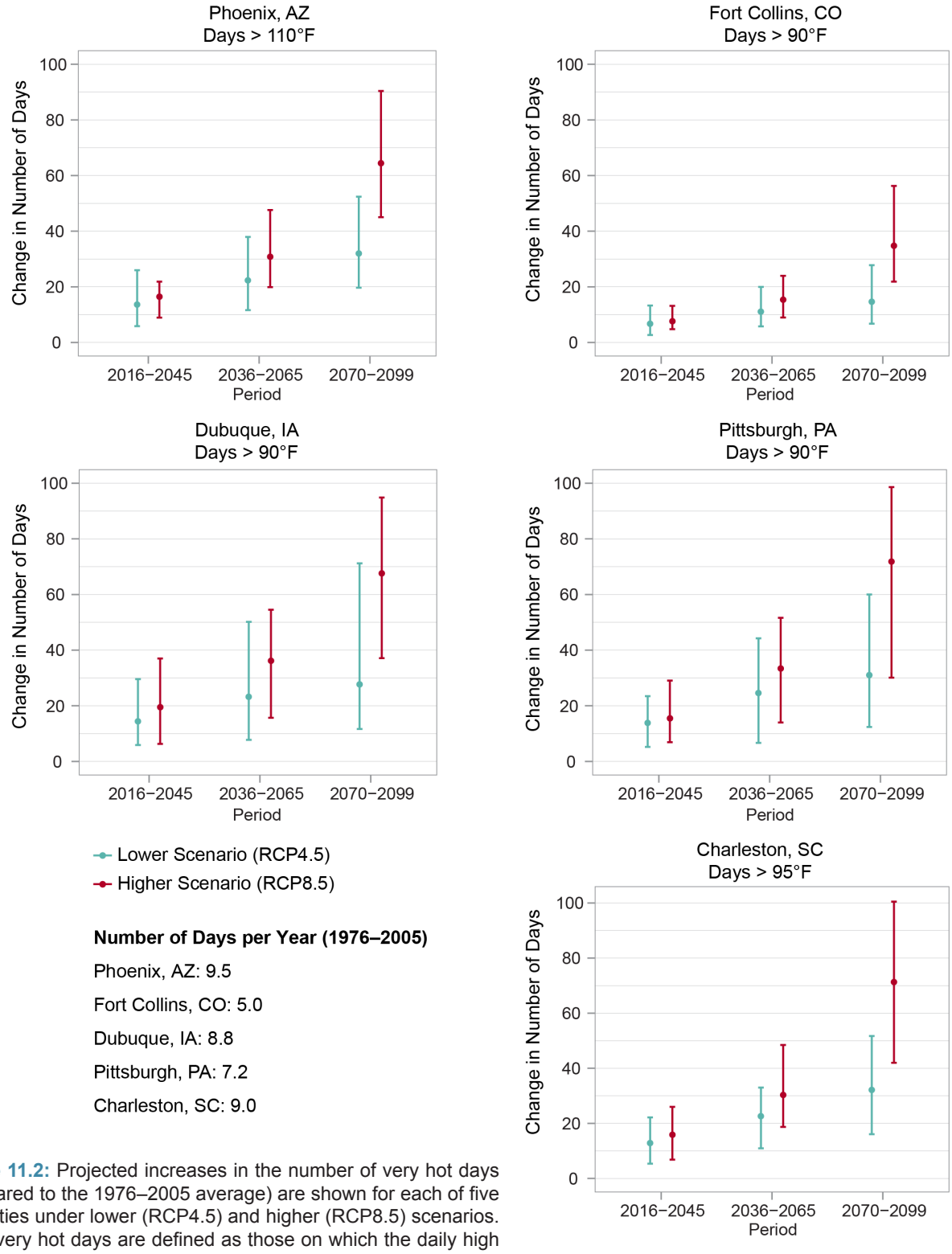
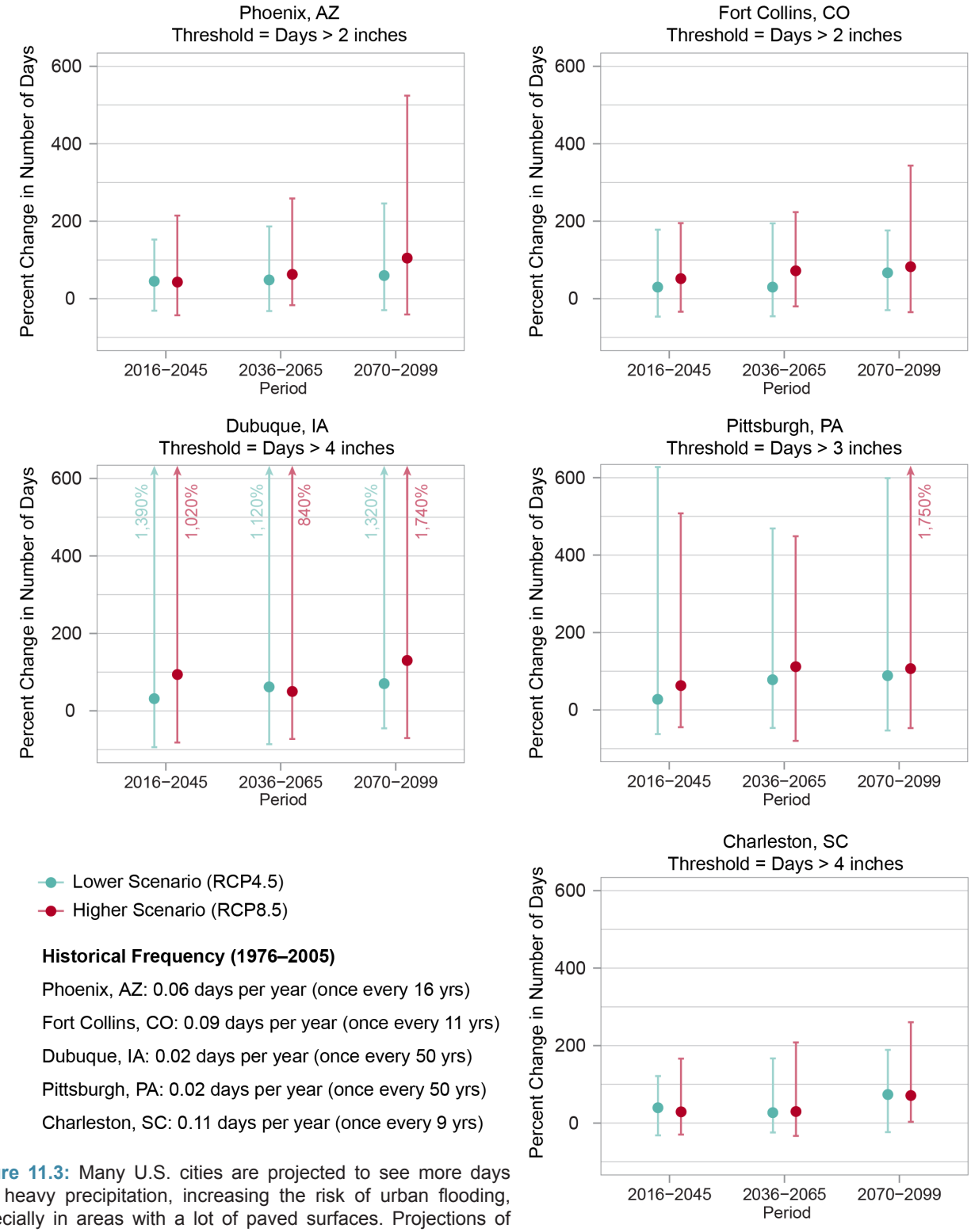


Figure 11.2: Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. Sources: NOAA NCEI, CICS-NC, and LMI.

Projected Change in the Number of Days with Heavy Precipitation



Historical Frequency (1976–2005)

Phoenix, AZ: 0.06 days per year (once every 16 yrs)

Fort Collins, CO: 0.09 days per year (once every 11 yrs)

Dubuque, IA: 0.02 days per year (once every 50 yrs)

Pittsburgh, PA: 0.02 days per year (once every 50 yrs)

Charleston, SC: 0.11 days per year (once every 9 yrs)

Figure 11.3: Many U.S. cities are projected to see more days with heavy precipitation, increasing the risk of urban flooding, especially in areas with a lot of paved surfaces. Projections of percent changes in the number of days with heavy precipitation (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, days with heavy precipitation are defined as those on which the amount of total precipitation exceeds a threshold value specific to each city. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same thresholds, for the period 1976–2005, in the lower left corner of the figure. Historical values are given in terms of frequency (days per year) and return period (average number of years between events). Sources: NOAA NCEI, CICS-NC, and LMI.

Another similarity cities share is that when climate stressors affect one city sector, cascading effects on other sectors increase risks to residents' health and well-being (Ch. 17: Complex Systems). Higher temperatures can increase energy loads, which in turn can lead to structural failures in energy infrastructure, raise energy bills, and increase the occurrence of power outages (Ch. 4: Energy, KM 1). These changes strain household budgets, increase people's exposure to heat, and limit the delivery of medical and social services. For all cities, the duration of exposure to a climate stressor determines the degree of impacts. In recent years in the Southwest region, California experienced exceptional drought conditions. Urban and rural areas saw forced water reallocations and mandatory water-use reductions. Utilities had to cut back on electricity production from hydropower because of insufficient surface water flows and water in surface reservoirs (Ch. 25: Southwest, KM 1 and 5).[36,37,38]

Urban areas are linked to local, regional, and global systems.[39,40,41] For example, changes in regional food production and global trade affect local food availability.[42] Likewise, urban electricity supply often relies on far-off reservoirs, generators, and grids. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common.[12,43,44]

Cities in all regions of the country are undertaking adaptation and mitigation actions. Several cities have climate action plans in place (see Bierbaum et al. 2013 for a review of U.S. urban adaptation plans[45]). Pittsburgh made commitments to reduce GHG emissions. Fort Collins initiated the Fort Collins ClimateWise Program. Phoenix is taking measures to reduce the UHI effect. These actions build urban resilience to climate change.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Cities are places where people learn, socialize, recreate, work, and live together. Quality of life for urban residents is associated with social and economic diversity, livelihood opportunities, and access to education, nature, recreation, healthcare, arts, and culture. Urban areas can foster economic prosperity and a sense of place. Yet, many cities in the United States face challenges to prosperity, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (Ch. 18: Northeast, KM 3).[13,18,46] These problems are intertwined. Climate change impacts exacerbate existing challenges to urban quality of life and adversely affect urban health and well-being.

Urban populations experiencing socioeconomic inequality or health problems have greater exposure and susceptibility to climate change.[12,47] Climate susceptibility varies by neighborhood, housing situation, age, occupation, and daily activities. People without access to housing with sufficient insulation and air conditioning (for example, renters and the homeless) have greater exposure to heat stress. Children playing outside, seniors living alone, construction workers, and athletes are also vulnerable to extreme heat (Figure 11.4).[12,48]

Threats from Extreme Heat

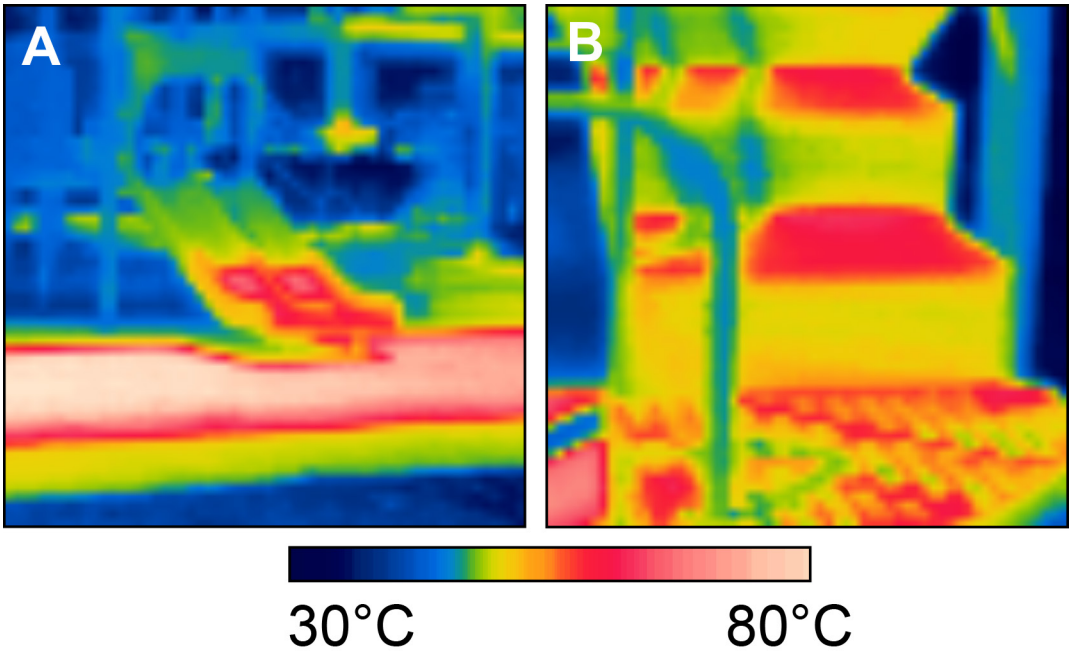


Figure 11.4: These images show surface temperatures of playground equipment in metropolitan Phoenix, Arizona. Children are particularly susceptible to high heat[12] and can be exposed through daily activities. (A) A slide and dark rubber surface in the sun (orange/red colors) are shown reaching temperatures of 71°C (160°F) and 82°C (180°F), respectively. The blue/green colors are under a shade sail. (B) Playground steps made of black powder-coated metal are shown reaching a temperature of 58°C (136°F) in the direct sunlight. Images use infrared thermography and were taken mid-day on September 15, 2014. Credit: Vanos et al. 2016.[49]

In addition to temperature extremes, climate change adversely affects urban population health through air and water quality and vector-borne diseases (Ch. 14: Human Health, KM 1). Urban residents feel economic impacts from food price volatility and the costs of insurance, energy, and water.[12,50] Climate change also threatens the integrity of personal property, ecosystems, historic landmarks, playgrounds, and cultural sites such as libraries and museums, all of which support an urban sense of place and quality of life (Ch. 24: Northwest, KM 2).[51,52,53] For example, historic landmarks in Charleston are at risk from sea level rise.[54] Urban ecosystems are further stressed by often unpredictable climate-related changes to tree species ranges, water cycles, and pest regimes.[55]

Coastal city flooding can result in forced evacuation, adversely affecting family and community stability, as well as mental and physical health (Ch. 14: Human Health, KM 1).[12] It also poses significant challenges to inland urban areas receiving these populations.[56,57] Many cities are undertaking creative problem solving to address climate change impacts and quality of life. They use approaches from urban design, sustainability, and climate justice.[58,59,60] For example, New York City's Trees for Public Health program targets street tree planting in neighborhoods of greatest need to improve the UHI effect, asthma rates, crime rates, and property values.[61]

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Urban infrastructure needs to perform reliably throughout its long service life. Infrastructure designed for historical climate trends is more vulnerable to future weather extremes and climate change. Impacts include changes in building enclosure vapor drive, energy performance, and corrosion of structures.[14,62] Above- and below-grade transportation systems are at increased risk from flooding and degradation that reduce expected service life (Ch. 12: Transportation, KM 1). Higher temperatures increase stress on cooling systems to perform as designed. High indoor temperatures reduce thermal comfort and office worker productivity, potentially requiring building closures. Over time, sea level rise and flooding are expected to destroy, or make unusable, properties and public infrastructure in many U.S. coastal cities (Ch. 8: Coastal, KM 1). Investor costs increase when infrastructure is degraded, damaged, or abandoned ahead of its anticipated useful life.[63,64]

Damages from extreme weather events demonstrate existing infrastructure vulnerabilities. Long-term, gradual risks such as sea level rise further exacerbate these vulnerabilities. Current levels of infrastructure investment in the United States are not enough to cover needed repairs and replacement.[13] Infrastructure age and disrepair make failure or interrupted service from extreme weather even more likely.[13] Heavy rainfall during Arizona's 2014 monsoon season shut down freeways and city streets in Phoenix because key pumping stations failed.[65] Climate change has already altered the likelihood and intensity of some extreme events, and there is emerging evidence that many types of extreme events will increase in intensity, duration, and frequency in the future.[27,66,67,68,69] Projecting specific changes in extreme events in particular places remains a challenge.

Costs are felt nationally as business operations, production inputs, and supply chains are affected.[70,71] Higher temperatures reduce labor productivity in construction and other outdoor industries.[12,44,72,73] Upgrades to buildings and the electrical grid are needed to handle higher temperatures.[74,75,76] Risk portfolios in the housing finance, municipal bond, and insurance industries may need to be adjusted.[44,72,77] Forward-looking design and risk management approaches support the achievement of design and investment performance goals.[78,79,80,81]

Incorporating climate projections into infrastructure design, investment and appraisal criteria, and model building codes is uncommon.[82,83,84,85,86,87,88,89] Standardized methodologies do not exist,[62,90,91,92] and the incorporation of climate projections is not required in the education or licensing of U.S. design, investment, or appraisal professionals.[80,93,94,95] Building codes and rating systems tend to be focused on current short-term, extreme weather. Investment and design standards, professional education and licensing, building codes, and zoning that use forward-looking design can protect urban assets and limit investor risk exposure.[83,96,97,98]

A handful of cities have begun to take a longer-term view toward planning.[99,100,101]

These cities have developed adaptation plans, resilience guidelines, and risk-informed frameworks. However, they do not yet have a portfolio of completed projects.[59,102] Adaptation planning is not always informed by technical analysis of changing hazards, climate vulnerability assessments, and monitoring and control systems.[79] U.S. cities can examine methods and learn from completed projects, such as those developed by Engineers Canada and UKCIP Design for Future Climate.[62,90] Managing climate risks promotes the integrity, efficiency, and safety of infrastructure to ensure reliable performance over the infrastructure's service life.[14,81]

Flash Flooding Impacts Urban Infrastructure and Well-Being

Figure 11.5: Flash flooding overwhelmed drainage systems and swamped roadways in Pittsburgh, Pennsylvania, in 2011. The flooding disrupted businesses and commutes, damaged homes, and caused four deaths. Photo credit: *Pittsburgh Post-Gazette*.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

The essential goods and services that form the backbone of urban life are increasingly vulnerable to climate change. Cities are hubs of production and consumption of goods, and they are enmeshed in regional-to-global supply chains. They rely on local services and interdependent networks for telecommunications, energy, water, healthcare, transportation, and more (Ch. 4: Energy, KM 1; Ch. 3: Water, KM 1; Ch. 14: Human Health, KM 2; Ch. 12: Transportation, KM 2; Ch. 17: Complex Systems, KM 1). Gradual and abrupt climate changes disrupt the flow of these goods and services.[44] For example, the 2012 High Park Fire in Colorado had wide-reaching impacts on air and water quality. The city of Fort Collins experienced air quality that was seven times worse than the daily average (Ch. 13: Air Quality, KM 2).[103] Storms washed ash and debris into the Cache la Poudre River, polluting the city's drinking water source for residents and industries.[104] In another example, two inches of rain fell in a single hour in Pittsburgh in August 2011. Four people died in the resulting flash flood. Impervious surfaces and combined sewer systems contribute to urban flash flooding risks (Figure 11.5).[105] For similar examples of cascading impacts, see Chapter 17: Complex Systems, Box 17.1 on Hurricane Harvey and Box 17.5 on the 2003 Northeast Blackout.

Cascading Consequences of Heavy Rainfall for Urban Systems

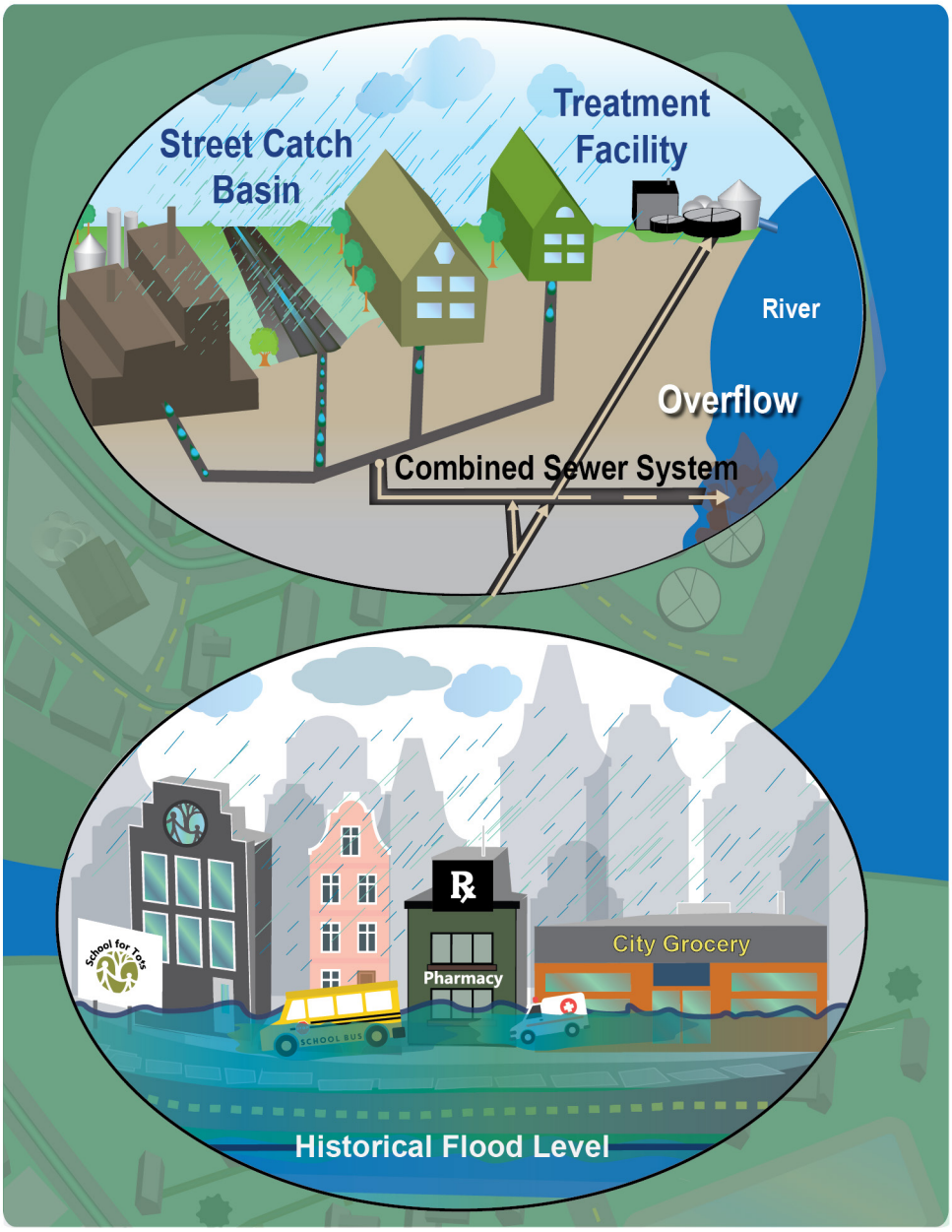


Figure 11.6: With heavy downpours increasing nationally, urban areas experience costly impacts. (top) In cities with combined sewer systems, storm water runoff flows into pipes containing sewage from homes and industrial wastewater. Intense rainfall can overwhelm the system so untreated wastewater overflows into rivers. Overflows are a water pollution concern and increase risk of exposure to waterborne diseases. (bottom) Intense rainfall can also result in localized flooding. Closed roads and disrupted mass transit prevent residents from going to work or school and first responders from reaching those in need. Home and commercial property owners may need to make costly repairs, and businesses may lose revenue. Source: EPA.

Figure 11.6 describes how heavy rainfalls, which are projected to increase with climate change, can disrupt the flow of goods and services to urban residents through increased runoff and localized flooding.

As interconnections among sectors increase, urban areas are more vulnerable to disruptions.[106] For example, energy and water systems are closely intertwined (Ch. 3: Water; Ch. 4: Energy; Ch.17: Complex Systems). Both higher water temperatures and extreme weather that causes power outages affect urban drinking

water treatment and distribution. Higher air temperatures increase urban energy demand for cooling and water demand for landscaping. Elevated water temperatures affect cooling for electricity production. Higher river temperatures during periods of low flow can require power plants to shut down or curtail power generation to stay within defined regulatory temperature limits. Higher energy loads raise the risk of power outages. Flooding can drown electrical substations. Disruptions to water and power supplies can result in problems—such as unsafe drinking water, limited access to money systems, no functioning gas stations, few available modes of transportation, no air conditioning or heating, and limited ability to communicate with others—that pose risks to urban dwellers.

Climate change also threatens food security in urban areas.[107,108] Loss of electricity from extreme weather leads to food spoilage. Transportation disruptions along the supply chain limit food mobility. Heat effects on agricultural labor impact product availability. Changes to the food supply generally lead to price volatility and food shortages, affecting household budgets and nutrition, cultural foodways, and food service profits. Urban populations who already experience food insecurity are likely to be affected the most.

Targeted coordination that addresses interconnected vulnerabilities can build urban resilience to climate change.[109,110,111] Coordination may involve municipal offices, public–private partnerships, or state and local agencies. The Charleston Resilience Network, for example, brought together public safety and health services, business organizations, and the state transportation department to discuss their performance during the region's October 2015 floods and to identify best practices to improve resilience.[112]

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

Cities across the United States are taking action in response to climate change for a number of reasons: recent extreme weather events, available financial resources, motivated leaders, and the goal of achieving co-benefits.[113,114,115,116] One strategy being used is to mainstream adaptation and mitigation into land-use, hazard mitigation, development, and capital investment planning.[45,115,117] Municipal departments from public works to transportation play roles, as do water and energy utilities, professional societies, school boards, libraries, businesses, emergency responders, museums, healthcare systems, philanthropies, faith-based organizations, nongovernmental organizations, and residents. City governments use a variety of policy mechanisms to achieve adaptation and mitigation goals. They adopt building codes, prioritize green purchasing, enact energy conservation measures, modify zoning, and buy out properties in floodplains. Nongovernmental stakeholders take action through voluntary protocols, rating systems, and public–private partnerships, among other strategies.

U.S. cities are at the forefront of reducing greenhouse gas (GHG) emissions (Ch. 29: Mitigation, KM 1). Urban mitigation actions include acquiring

high-performance vehicle fleets and constructing energy efficient buildings. A number of cities are conducting GHG inventories to inform decisions and make commitments to reduce their emissions. Comprehensive urban carbon management involves decisions at many levels of governance.[19]

Many U.S. cities have also begun adaptation planning. A common approach is to enhance physical protection of urban assets from extreme weather. For example, protection against sea level rise and flooding can involve engineering (such as seawalls and pumps) and ecological solutions (such as wetlands and mangroves) (Ch. 8: Coastal, KM 2).[118] Green infrastructure lowers flood risk by reducing impervious surfaces and improving storm water infiltration into the ground.[72,119] Green roofs use rooftop vegetation to absorb rainfall. Urban drainage systems can be upgraded to handle increased runoff.[72] Climate-resilient building and streetscape design reduces exposure to high temperatures through tree canopy cover and cool roofs with high albedo that reflect sunlight. Ensuring that critical urban infrastructure, such as drinking water systems, continues to provide services through floods or droughts involves a combination of technology, physical protection, and outreach (Ch. 3: Water, KM 3; Ch. 19: Southeast, KM 1).[120,121,122]

Social and institutional changes are central to urban responses to climate change (Figure 11.7).[59,114] Urban development patterns reflect social, economic, and political inequities. As such,

Urban Adaptation Strategies and Stakeholders

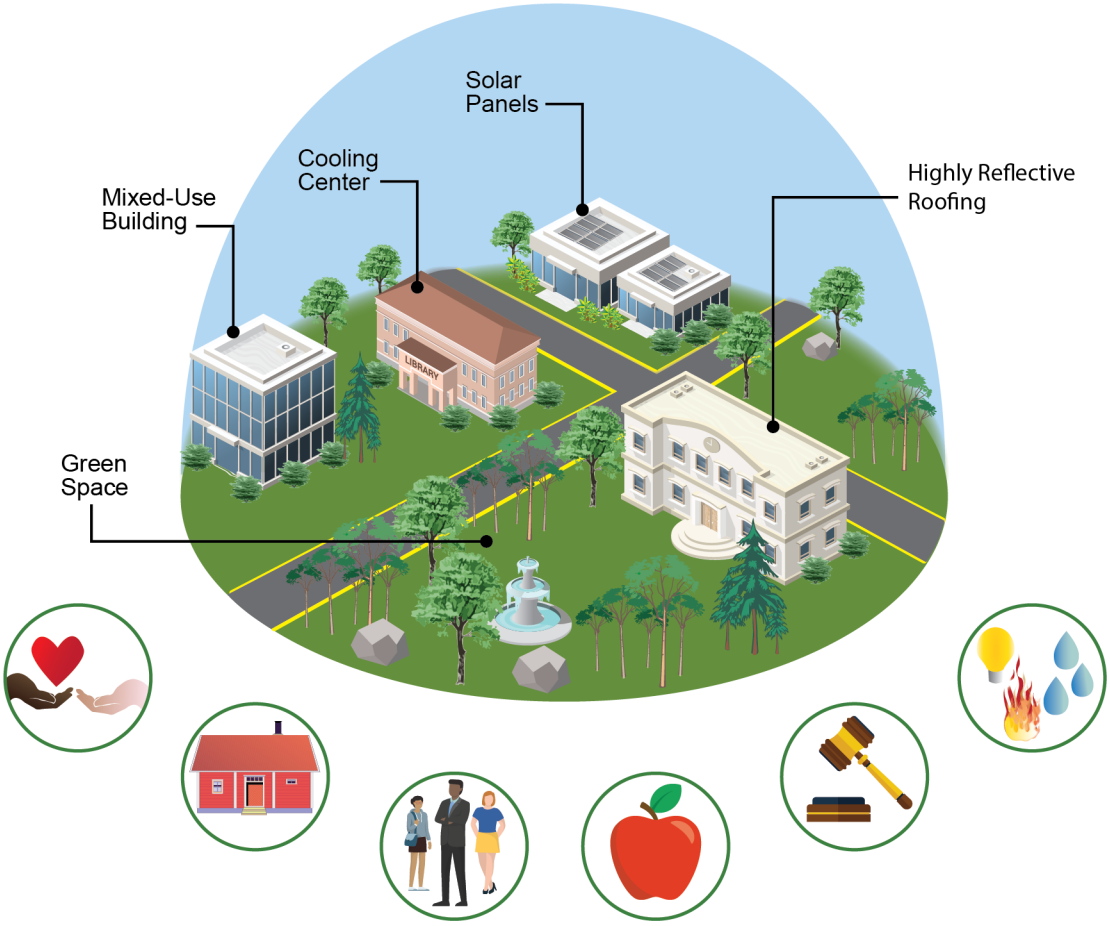


Figure 11.7: Protecting vulnerable people and places from the impacts of climate change involves infrastructure design (for example, green space and highly reflective roofing), along with social and institutional change (such as designating cooling centers). Social equity is supported by widespread participation in adaptation decision-making by non-profit organizations, local businesses, vulnerable populations, school districts, city governments, utility providers, and others. Source: EPA.

decisions about where to prioritize physical protections, install green infrastructure, locate cooling centers, or route public transportation have differential impacts on urban residents.[60,123,124,125] If urban responses do not address social inequities and listen to the voices of vulnerable populations, they can inadvertently harm low-income and minority residents.[60,123,124]

Urban actions can reduce climate change impacts on cities.[12,126,127,128,129,130] Urban adaptation plans often begin with small steps, such as improving emergency planning or requiring that development be set back from waterways (Ch. 28: Adaptation).[59,131] Not all plans address weightier concerns, tradeoffs, behaviors, and values. For example, coastal cities at risk from sea level rise may be constructing storm surge protections, but not discussing the possibility of eventual relocation or retreat (Ch. 8: Coastal, KM 3).[59,131] Increasing tree canopy and planting vegetation to manage storm water and provide cooling can increase water use, which may present difficulties for water-strapped cities.[132,133]

Urban adaptation and mitigation actions can provide near-term benefits to cities, including co-benefits to the local economy and quality of life (Ch. 29: Mitigation, KM 4).[3,19,113,134,135,136,137] Tree canopies and greenways increase thermal comfort and improve storm water management. They also enhance air quality, recreational opportunities, and property values (Figure 11.8). Wetlands serve to buffer flooding and are also a source of biodiversity and ecosystem regulation.

Urban climate change responses are often constrained by funding, technical resources,

Greenway in Dubuque, Iowa

Figure 11.8: In response to a history of flooding, Dubuque, Iowa, installed the Bee Branch Creek Greenway to control flooding and provide recreational space.[138] Photo credit: City of Dubuque, Iowa.

existing social inequities, authority, and competing priorities.[19,114,119,139,140,141] Coordinating among multiple jurisdictions and agencies is a challenge. Using scarce resources to address future risks is often a lower priority than tackling current problem areas. The absence of locally specific climate data and a standard methodology for estimating urban GHG emissions poses additional obstacles to urban responses.[19,72,114] Cities are dependent on state and national policies to modify statewide building codes, manage across landscapes and watersheds, incentivize energy efficiency, and discourage development that puts people and property in harm's way. Strong leadership and political will are central to addressing these challenges.[59,131,142] Many U.S. cities participate in networks such as the U.S. Conference of Mayors, ICLEI, the C40 Cities Climate Leadership Group (C40), and 100 Resilient Cities. Others participate in regional coalitions such as the Southeast Florida Regional Climate Change Compact. Multicity networks support development of urban climate policies and peer-to-peer learning (Ch. 28: Adaptation).[59,110,113,117,120,143] Effective urban planning to respond to climate change addresses social inequities and quality of life, uses participatory processes and risk management approaches, builds on local knowledge and values, encourages forward-looking investment, and coordinates across sectors and jurisdictions (Ch. 8: Coastal, KM 3).[59,60,115,120,124,140,142,144]

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Traceable Accounts

Process Description

Report authors developed this chapter through technical discussions of relevant evidence and expert deliberation and through regular teleconferences, meetings, and email exchanges. (For additional information on the overall report process, see App. 1: Process.) The author team evaluated scientific evidence from peer-reviewed literature, technical reports, and consultations with professional experts and the public via webinar and teleconferences. The scope of this chapter is urban climate change impacts, vulnerability, and response. It covers the built environment and infrastructure systems in the socioeconomic context of urban areas. This chapter updates findings from the Third National Climate Assessment and advances the understanding of previously identified urban impacts by including emerging literature on urban adaptation and emphasizing how urban social and ecological systems are related to the built environment and infrastructure. The five case-study cities were selected because they represent a geographic diversity of urban impacts from wildfire, sea level rise, heat, and inland flooding. The author team was selected based on their experiences and expertise in the urban sector. They bring a diversity of disciplinary perspectives and have a strong knowledge base for analyzing the complex ways that climate change affects the built environment, infrastructure, and urban systems.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there (*very high confidence*). Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (*high confidence*). Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts (*medium confidence*).

Description of evidence base

Urban areas provide resources and opportunities for residents' quality of life.[145,146] However, many cities face challenges to prosperity, including aging and deteriorating infrastructure,[13] social inequalities,[9,46] and lack of economic growth.[147,148] These challenges play out differently depending on a city's geographic location, economic history, urban development pattern, and governance. Studies link urban development with lower air,[15] water,[16] and soil[17] quality; altered microclimates (for example, urban heat islands);[149,150] increased risk of certain vector-borne diseases;[151] and adverse effects on biodiversity and ecosystem functioning.[152,153,154] Exposure to temperature extremes,[155] allergens,[156] and toxic substances[157] and limited access to healthy food[10,158,159] and green space[11,160,161] create environmental and social vulnerabilities for urban populations. Vulnerabilities are distributed unevenly within cities and reflect social inequalities related to differences in race, class, ethnicity, gender, health, and disability.[1] These populations of concern are at a greater risk of exposure to climate change and its impacts.[3,46,123]

Climate change combines with other trends to increase stress on the health and well-being of urban residents.[10,46,155,158] Research demonstrates that climate change can exacerbate many of the vulnerabilities described above. It raises temperatures, alters weather patterns, and increases the frequency and severity of extreme weather events, creating risks to urban ecosystems (such as urban tree cover),[162,163,164] infrastructure both above and below grade,[165,166,167] historic and cultural sites,[51,52,164,168,169,170] and residents' physical and mental health.[171,172,173,174] Coupled with climate change, urban expansion increases the risk of infectious disease[175,176] and air quality problems from wildfires.[55,177]

Metropolitan areas often have more resources than rural ones, as reflected in income per capita, employment rates, and workforce education.[178,179] Innovative urban problem solving that builds on these resources can take the form of policies and institutional collaborations,[58,180] technologies,[145,181] eco- and nature-based solutions,[182,183] public–private partnerships,[59] social network and climate justice initiatives,[60,184] "smart" cities,[106,145,181] or a combination of approaches. However, cities vary greatly in their capacity to innovate for reasons related to size, staffing, and existing resources.

Major uncertainties

It is difficult to predict future urban trends with certainty. Many factors influence the size and composition of urban populations, development patterns, social networks, cultural resources, and economic growth.[180] The degree to which climate change will exacerbate existing urban vulnerabilities depends in part on the frequency and intensity of extreme weather events,[145] which are projected with far less certainty than incremental changes in average conditions.[81] Moreover, projections are not often made at the city scale.[185] Climate change may accelerate urban tree growth, but overall effects on growing conditions depend on a variety of factors.[186] These uncertainties make it difficult to predict how climate change and other factors will intersect to affect urban quality of life. Furthermore, quality of life is difficult to measure, although some metrics are available.[187]

Urban climate vulnerability depends on local social, political, demographic, environmental, and economic characteristics.[59,110,145] Urban exposure to climate change depends on geographic factors (such as latitude, elevation, hydrology, distance from the coast).[145] Some places may be able to protect quality of life from minor climate stresses but not from extreme, though rare, events.[145] The speed and pace of innovative problem solving is difficult to predict, as is its effect on quality of life.[59]

Description of confidence and likelihood

There is *very high confidence* that the opportunities and resources available in a particular urban area influence the health and well-being of its residents. There is *high confidence* that climate change exacerbates challenges to aging and deteriorating infrastructure, degrading urban ecosystems, and urban residents' health and well-being. There is *medium confidence* that many cities are engaging in creative problem solving to address the challenges to quality of life posed by climate change. The effectiveness of this response depends on many factors (for example, intensity of extreme weather events, stakeholder collaboration, and internal and external resources available).

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities (*very high confidence*). With its long service life, urban infrastructure must be able to endure a future climate that is different from the past (*very high confidence*). Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks (*high confidence*).

Description of evidence base

There is wide agreement that architects, engineers, and city planners need to consider a range of future climate conditions in urban infrastructure design to guarantee that assets perform for the duration of their expected service lives.[14,62,80,81,188,189,190,191,192] Many researchers and professionals from various industries—engineering,[80,81,193,194] water resources,[195,196] architecture, construction and building science,[62,190,197,198,199,200,201,202] transportation,[203,204,205] energy,[206] and insurance[207,208]—are actively developing or have proposed strategies to integrate climate change science and infrastructure design. The Government Accountability Office, the State of California, and a variety of professional organizations have recognized the importance of incorporating forward-looking climate information (planning for or anticipating possible future events and conditions) in design standards, building codes, zoning requirements, and professional education and training programs to protect and adapt built systems and structures. This includes the need to develop and adopt design methodologies using risk management principles for uncertainty (see Ch. 28: Adaptation, KM 3 for more discussion)[90] and the integration of climate projections, nonstationarity, and extreme value analysis to inform designs that can adapt to a range of future conditions.[8,14,80,81,90,188,190,209,210,211,212,213,214,215] Similarly, there is support for incorporating climate change risk considerations into the preparation of financial disclosures.[44,96,191,216,217] Reports from multiple sectors highlight the need for licensed design professionals, property industry professionals, and decision-makers to be aware of emerging legal liabilities linked to climate change risks.[80,95,208,218,219,220]

Numerous studies document substantial economic damages in urban areas following extreme weather events and predict an increase in damages through time as these events occur with greater frequency and intensity.[14,165,166,167,205,221] Due to underinvestment in urban infrastructure[13,222] and well-documented urban vulnerabilities to the effects of climate change and extreme weather,[80,81,223] forward-looking design strategies are critical to the future reliability of urban infrastructure.[14,80]

Major uncertainties

There are gaps in our understanding of the performance capacity of existing structures exposed to climate change stressors and of the available resources and commitment (at the state, local, tribe, and federal level) to implement forward-looking designs in investments.[192,224] The scale and speed with which climate security design principles will be integrated into infrastructure design, investments, and funding sources are difficult to predict, as are the implications for municipal bonds, solvency, and investment transparency.[77,83,96,97,98,192] There is also uncertainty regarding how

the U.S. legal system will determine the limits of professional liability for climate-related risks for licensed design professionals, attorneys, and investors.[95,218,219,220,225]

The extent to which key climate stressors will change over the design life of urban systems and structures is uncertain. It depends on the rate of global climate change as well as regional and local factors.[150,185,192] Engineering and architectural design is largely concerned with weather extremes,[80,81,190,226] which are generally projected with far less certainty than changes in average conditions.[81] Action depends on how individual decision-makers weigh the costs and benefits of implementing designs that attempt to account for future climate change. The extent to which the U.S. market is able to innovate to provide these services to the global market is unknown.

Description of confidence and likelihood

There is *very high confidence* that the integrity of urban infrastructure is and will continue to be threatened by exposure to climate change stressors (for example, more frequent and extreme precipitation events, sea level rise, and heat) and that damages from weather events demonstrate infrastructure vulnerability. Many urban areas have endured high costs from such events, and many of those costs can be attributed to infrastructure failures or damages. There is *very high confidence* that urban infrastructure will need to endure a future climate that is different from the past in order to fulfill its long service life. There is *high confidence* that investment in forward-looking design provides a foundation for reliable infrastructure that can withstand ongoing and future climate risks. How much implementing forward-looking design will reduce risks is less clear, since much depends on other factors such as changes in urban population, social inequalities, the broader economy, and rates of climate change.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services (*very high confidence*). Damage to such networks from current weather extremes and future climate will adversely affect urban life (*medium confidence*). Coordinated local, state, and federal efforts can address these interconnected vulnerabilities (*medium confidence*).

Description of evidence base

Research focusing on urban areas shows that climate change has or is anticipated to have a net negative effect on transportation,[43,205,223,227] food,[44,107,108] housing,[228] the economy,[44,228,229,230,231] ecology,[3,152] public health,[2,3,12,44,231,232] energy,[43,44,233,234] water,[43,122,228,235] and sports and recreation.[2,235,236]

Researchers have modeled and documented how negative effects on one system that provides urban goods and services cascade into others that rely on it.[3,43,44,109,122,229,231,233,234] Several draw on the example of Superstorm Sandy. These effects scale up to the national economy and across to other sectors, creating longer-term hazards and vulnerabilities.[44,99,109,227] The energy–water nexus, defined as the reliance of energy and water systems on each other for functionality, is a good example of documented system interdependency.[43,234] Research indicates that direct or high-level

climate impacts on a variety of urban sectors (such as transportation, energy, drinking water, storm water) have cascading economic, socioeconomic, and public health consequences.[3,12,44,229,231]

The literature shows that coordinated resilience planning across sectors and jurisdictions to address interdependencies involves using models and plans,[3,43,108,111,227,237,238] finding effective intervention points,[109] creating system redundancy,[43,237] and motivating behavioral change. Recent reports discuss how interdependencies among energy, water, transportation, and communications services inform adaptation strategies that span sectors.[43,227]

Major uncertainties

Interconnections among urban systems have been studied less extensively than climate change effects on individual urban sectors, and there are still gaps to be filled.[239,240,241] The complexity of urban systems leads to uncertainty and modeling challenges. System models need to account for interconnections, feedback loops, and cascading effects from rural areas, among urban sectors, and within a sector. Creating a comprehensive framework to understand these connections is difficult.[239,242] There is a lack of forward-looking models of how projected climate changes will impact interdependent urban systems. Cities do not usually have the range of data needed to fully analyze system connections.[102,111] Mixed methods analysis, where professional experience and qualitative data supplement available datasets, may partially compensate for this problem.[241] Despite information gaps, urban stakeholders are beginning to address system interconnections in adaptation efforts.[59]

While it has been demonstrated that climate change affects urban systems, the extent to which climate change will affect a given urban system is difficult to predict. It depends on the unique strengths and vulnerabilities of that system as well as the regional and local climate conditions to which the system is exposed.[110,223,243] Modifying factors include spatial layout, age of infrastructure, available resources, and ongoing resilience efforts.[43,244] Similarly, critical points of intervention are unique to each urban area. Local-scale analysis of vulnerability and resilience has not been done for most U.S. cities.[102,241]

The severity of future climate impacts and cascading consequences for urban networks depends on the magnitude of global climate change.[223] Urban systems may be able to tolerate some levels of stress with only minor disruptions. Stresses of greater frequency, longer duration, or greater intensity may compromise a system's ability to function.[36,43,109,122,227] Models can reveal changes in the likelihood or frequency of occurrence for a particular type of extreme event (such as a 100-year flood), but they cannot predict when these events will occur or whether they will hit a particular city or town.[245]

Description of confidence and likelihood

There is *very high confidence* that urban areas rely on essential goods and services that are vulnerable to climate change because they are part of interdependent networks of infrastructure, ecosystems, and social systems. There is *high confidence* that extreme weather events have resulted in adverse cascading effects across urban sectors and systems, as there is documentation of a significant number of case studies of urban areas demonstrating these effects. It is projected with *medium confidence* that network damages from future climate change will disrupt many aspects of urban life, given that the complexity of urban life and the many factors affecting urban

resilience to climate change make future disruptions difficult to predict. Similarly, there is *medium confidence* that addressing interconnected vulnerabilities via coordinated efforts can build urban resilience to climate change.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change (*high confidence*). Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits (*medium confidence*). Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges (*high confidence*).

Description of evidence base

Multiple review studies have documented that cities in all parts of the United States are undertaking adaptation and mitigation actions.[45,115,246] Municipal departments, including public works, water systems, and transportation, along with public, private, and civic actors, work to assess vulnerability and reduce risk. Actions include land-use planning, protecting critical infrastructure and ecosystems, installing green infrastructure, and improving emergency preparedness and response.[45,114,115,117,247] Many cities are part of multicity networks (for example, the Great Lakes Climate Adaptation Network, ICLEI, and C40 Cities Climate Leadership Group) that provide opportunities for peer-to-peer learning, sharing best practices, and technical assistance.[59,114,117,120] Researchers have recognized the benefits of shared motivation and resource pooling across cities[59] and of incorporating local knowledge, priorities, and values into adaptation planning.[45,248] The private sector, utilities, nongovernmental organizations, libraries, museums, and civic organizations are involved with urban adaptation and mitigation.[2,45,59,115,196,249,250] Studies are beginning to analyze the social, economic, and political factors that shape whether and how cities carry out climate change response.[114,115,116,131,142]

Numerous studies have examined the ways in which adaptation actions reduce the impacts of weather extremes in urban areas. Documented benefits include reductions in urban heat risk[48,126,127,128,130,251] and flooding impacts.[118,252,253] These actions can provide additional public health and economic benefits.[59,254,255,256,257] Studies have also noted that low-regret and incremental urban adaptation are not likely to significantly reduce the impacts of projected climate change.[59,131,258] In addition, several studies discuss how urban adaptation can cause adverse consequences related to existing socioeconomic and spatial inequalities and the uneven distribution of urban climate risks.[60,123,124,125]

Major uncertainties

While urban adaptation actions can reduce the effects of extreme weather, there is uncertainty regarding the effectiveness of these actions against future climate change.[115,246] Much of this uncertainty arises from the difficulties inherent in predicting the future impacts of climate change. This uncertainty is compounded by a lack of regional and local data for many cities, by the

difficulty of evaluating the effects of climate change on local extremes,[150,251] and by the inability of knowing how climate changes intersect with other urban changes.[67,185] Moreover, there is a lack of forward-looking models and standardized monitoring strategies to test the costs, co-benefits, and effectiveness of urban response. Adaptation actions that focus solely on physical protection of urban assets are not likely to effectively address social vulnerability.[114,123] Urban adaptation effectiveness depends heavily on local characteristics. While cities do learn best practices through multicity networks, one city's strategy may not be as applicable to other cities.

Research on drivers of and challenges to urban response is in the incipient stage, with divergent results about social and political requirements for effective response.[114,116,142] Although cities are leading the way in adaptation and mitigation, many face significant barriers such as resource challenges, which will affect the rate of spread, extent, and duration of urban response.[45,145] There is little research on the effectiveness of different incentives for urban response or how to best support action in low-income communities.

Description of confidence and likelihood

There is *high confidence* that municipal governments and other institutions in many U.S. cities are planning and implementing climate change adaptation and mitigation actions. There is *high confidence* that urban adaptation and mitigation can provide additional near-term benefits, although the distribution of benefits and harms within cities is uneven. There is *medium confidence* in the effect these actions have and will have on current and future climate change impacts. If cities take only small actions, they are unlikely to fully protect urban residents from devastating impacts, particularly given projected levels of climate change. There is *high confidence* that cities face challenges in responding to climate change and that when cities build on local knowledge, use risk management approaches, explicitly address social vulnerability, and participate in multicity networks, their ability to respond to climate change is improved. The degree of improvement depends on other factors that affect urban response outcomes.

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