REVIEW DRAFT

U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues

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Technical Input to the
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1 Introduction

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1.1 Goals and Scope

The goal of this document is to assess the new knowledge and information about climate change and U.S. cities that has been produced since the most recent major national assessment conducted by the US Global Change Research Program during the latter part of the last decade (Karl et al., 2009). The urban theme played an important role in prior U.S. climate assessment activities. For example, as part of the initial National Climate Assessment in 2000 (See http://www.globalchange.gov/publications/reports/scientific-assessments/first-national-assessment for more information about the 2000 Assessment), Rosenzweig and Solecki led the development of the first major assessment of how a large city and its surrounding metropolitan region could be impacted by climate varaibility and change. The work focued on the New York Metropolitan Region. For the 2009 Assessment, climate change and cities issues were presented within several sections of the report. The results of 2009 assessment provided some updates of the findings from the 2000 asssesment effort with a focus on new climate models and associated impacts and vulneraiblities.

The audience for this current assessment report includes a wide variety of interested parties. The immediate audience is the National Climate Assessment Development and Advisory Committee (NCADAC). Other audiences include policymakers, academics – science and technical experts including other NCA technical report authors, as well as the general public. The research team assembled for this report focused on an assessment of the scholarly literature of climate change and U.S. cities, with an emphasis on research findings generated since the 2009 USGCRP Report was assembled. As a result, the focus of the new assessment is on that material produced since the latter part of the 2000s to present. The scope of the report is to create a foundational document on climate change and U.S. cities that assesses state-of-the-art knowledge and information across a broad set of topics. The assessment is designed to be policy relevant but not policy-prescriptive.

This report was developed in a several step process including a two-day scoping workshop held on the Columbia University campus in October 2011 of approximately 70 cities and climate change experts including representatives from academic, federal and municipal government, and non-governmental organizations. At the workshop the draft outline of the report was reviewed and vetted, and authorship teams were created. From that time through early February 2012, an iterative process of draft chapter development and review took place. Each of the chapters were subject to multiple rounds of internal and external review.

1.2 Urban Issues Results from previous U.S. National Climate Assessments

As part of the 2000 U.S. National Climate Assessment the *Climate Change and a Global City Report* was published (Rosenzweig and Solecki 2001). The most significant conclusions from that assessment illustrated the key potential impacts, vulnerabilities, opportunities and challenges across a set of set of urban sectors including water, energy, transportation, public health, and decision-making. The assessment documented that climate change already was having an impact on the region and that significant populations and assets were at risk. Because of the tightly coupled character of urban systems, integrative or cascading impacts from extreme climate events could occur in urban areas.

For the 2009 national climate assessment, further advancement was made with respect to understanding climate change in cities. Urban issues were embedded in several sections of the report including in the chapter entitled *Society,* small sections within two regional chapters (Northeast and Southwest), and occasional references to cities and high-density settlements in other chapters. Differential vulnerability of populations and infrastructure was highlighted in the report. It was stated that urban areas have unique vulnerabilities to climate change even that these areas are already stressed systems, have large at-risk populations and intense concentrations of critical infrastructure, and existing climate risks such as heat islands, and inland and coastal flooding. The 2009 report also provided additional insights into the actions that cities had begun to take to adapt to climate change, particularly with respect to protection of vulnerable infrastructure and populations during extreme climate events such as heat waves and storm surge events. Specific activities noted include heat early warning systems and the procurement of heat resistant materials, and initial discussions regarding the increasing vulnerability of near-shore locations.

1.3 Scientific Background

This 2012 assessment report takes an explicitly systems-level perspective to detail and understand the connections between climate change and cities. The report focuses on how the climate shifts influence changes in urban systems such as water and energy supply, transportation and public health, and what societal context conditions like economics, governance, legal regimes and insurance mediate and influence these connections.

To understand and illustrate the connections between climate change and cities at the sector and service level, the report focuses on how the climate change will shift the function, structure, or organization of a specific sectors or services and thereby reveal system level vulnerabilities and opportunities and challenges for adaptation strategies. How these impacts, vulnerabilities, and adaptation strategies are mediated by a set of cross-cutting factors such as economics, equity, and governance is another critical component of the assessment process.

1.4 Guiding Framework

The assessment utilizes several conceptual outlines to structure its analytical discussion of climate change and cities. The assessment utilizes an urban climate risk conceptual framework for its analysis of climate risk data and scenarios and urban growth data for cities. The urban climate risk framework utilized here incorporates several basic elements including existing and emerging climate risk, interactions with urban sectors and services which help illustrate a set of vulnerabilities, impacts, and adaptation strategies which in turn are mediated by a set of cross-cutting issues and urbanization context. The diagram below illustrates of some these basic relationships.

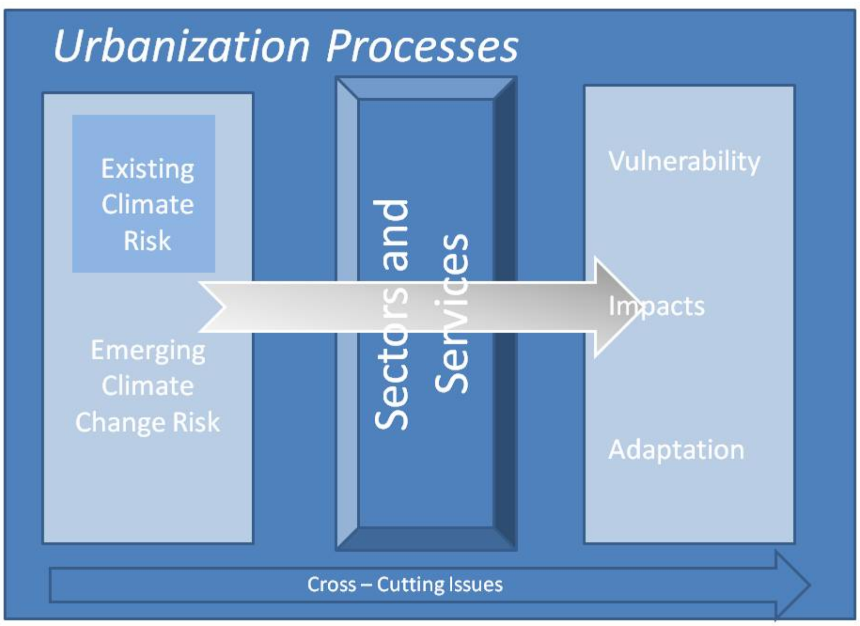


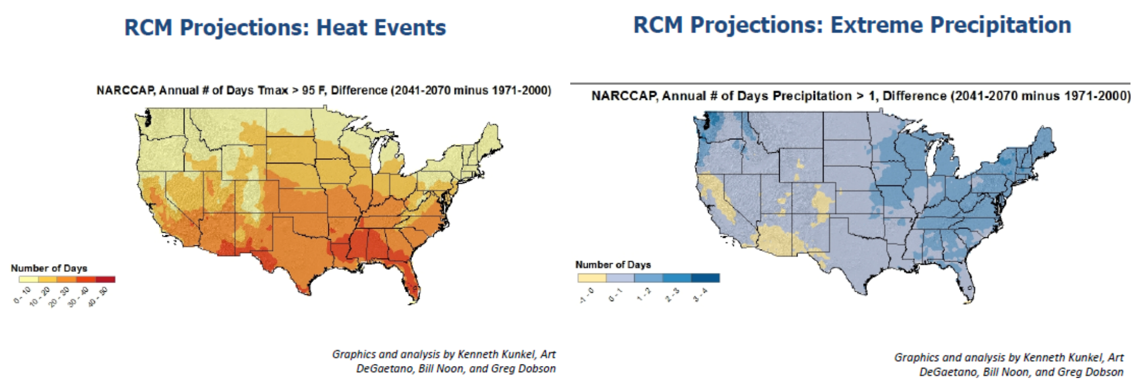
Figure 1.1. Urbanization Risk Assessment Framework (Source: authors)

The Assessment recognizes that there are several existing climate hazards present in U.S. cities. Key hazards include sea level rise and coastal storms, heatwaves, intense precipitation, drought, extreme wind events, urban heat islands, and secondary air pollutants, and cold air events including frozen precipitation. Current key climate risks on U.S. cities include the following:

- Populations vulnerable to river and coastal flooding;
- Major population centers on the nation's coasts have assets and populations exposed to flooding and associated equity issues;
- Economic loss potential much greater than insured loss; significant non-market value losses also a risk; and,

- Major coastal storm events (e.g., hurricane) could result in ~ hundreds of billions of USD economic losses.

Climate change in most cases will exacerbate these risks with the exception for the frequency of extreme cold events which will likely decrease over time. As an example of further detail, the nation will experience more days of extreme heat events particularly in the southern half of the U.S. (see Figures 1.2a and 1.2b). As highlighted in Chapter 2, these are areas of the county that also have experienced significant relative and absolute population growth in the most recent decade and are expected to rise more in the future. A new generation of climate change models is now being developing which will provide updated projections of future climate variations and extremes that might impact the cities. It is expected that these new models will illustrate a potential acceleration and increasing intensification of the climate change trends.



Figures 1.2a and 1.2b. RCM Projections for Heat Events and Extreme Precipitation (Source: K. Kunkel, A. DeGaetano, B. Noon, G. Dobson 2011)

1.4.1 Climate Change and Dynamic Urbanization

The process of climate change overlays an ever dynamic pattern of urbanization in the United States. The country's population continues to become more metropolitan focused as opposed to rural while the increase in per capita rate of land conversion drives ever more land use shifts from agricultural and rural to urban, suburban and extended exurban. In more detail, urban growth surged in the early 1990s but slowed slightly even as the number living in cities including core cities and suburban areas continued to grow (Figure 1.3). Currently approximately 80 percent of the U.S. population lives throughout the extended metropolitan regions. The spatial extent and population of urban areas continue to grow. As a percentage of growth, most of the nation's recent growth took place in the metropolitan areas of the American south and intermountain west and west coast.

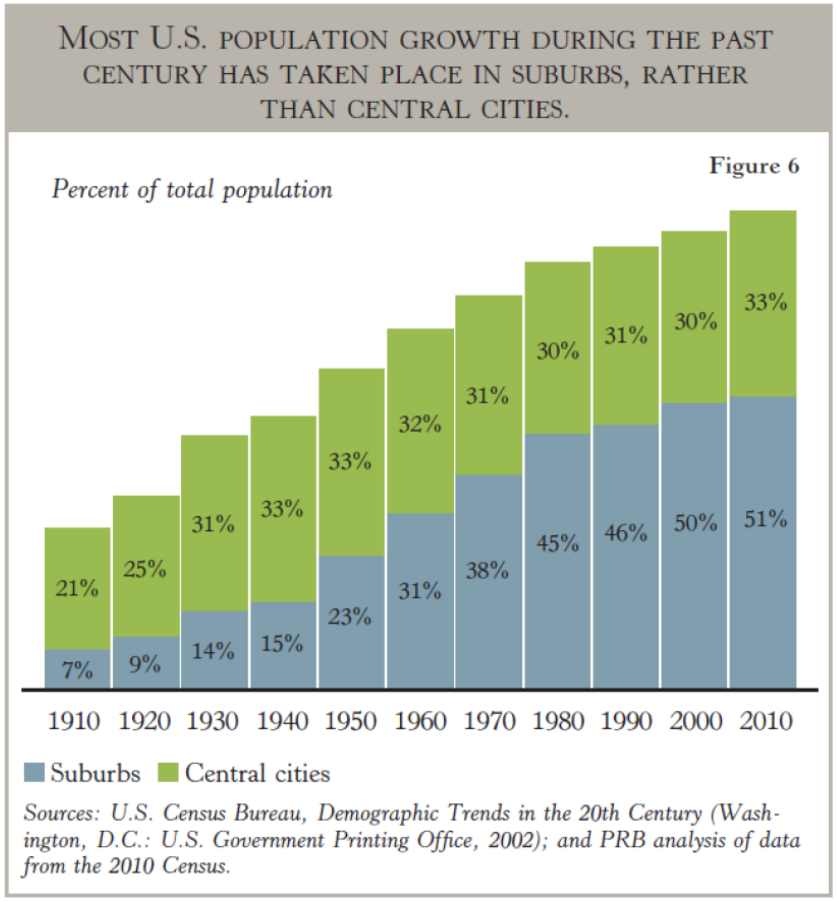


Figure 1.3. Population Growth in U.S. Central Cities and Suburbs (Source: U.S. Census Bureau and Population Reference Board)

Cities in the U.S. as a group are defined by a broad variety of densities, locations, and physical and social contexts ranging from older high density urban cores such as Manhattan, the Loop area of Chicago and parts of the San Francisco to much lower density (often by a factor 15 to 20 times) to new extended suburban and exurban locations around Las Vegas, Dallas, and Orlando. More than half of the total U.S. population now lives in suburban settings. The inherent variety of urban settings influences the relative impact of climate change and the vulnerability and adaptive capacity of urban systems.

1.5 Key Definitions

Several key definitions are used to frame the report and assessment process. These include the following including several for which the definition is derived from the IPCC AR4, Glossary materials.

- Adaptation - Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects. Various types of adaptation exist, e.g. *anticipatory* and *reactive*, *private* and *public*, and *autonomous* and *planned*.

Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

- Climate Change - Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or *external forcings*, or to persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*.

- Climate Impacts - Shifts that result from climate change including positive or negative impacts as measured by social, ecological and economic metrics. Impacts can abrupt and sudden, or emerge slowly over time; easy or difficult to discern; appear in the near future or distant future with continued and/or accelerated climate change.

- Risk – A metric to illustrate the relative severity of a hazard; include probability times the event consequence.

- Urban – Settlements patterns which are high to medium population density with interconnected infrastructure systems and commuting patterns and a high concentration of cultural, economic, and political institutions.

- Urban System - An integrated set of components and processes which define the flows and storage of materials and energy in an urban context which include feedback mechanisms and other regulatory controls and boundary conditions. Examples include urban water supply systems and energy supply systems which involve coupled natural and human components.

- Urbanization - The conversion of land from a natural state or managed natural state (such as agriculture) to cities; a process driven by net rural-to-urban migration through which an increasing percentage of the population in any nation or region come to live in settlements that are defined as *urban centres*, as well as the re-building of existing urban areas through processes of dis(investment) and migration.

- Vulnerability – Vulnerability is the degree to which a *system* is susceptible to, and unable to cope with, adverse effects of *climate change*, including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its *sensitivity*, and its *adaptive capacity*.

1.6 Report Outline Introduction

The report is divided into the following sections.

1. Introduction

2. Climate Change and Urban Systems

3. Urban Sectors and Services
4. Critical Dimensions of Adaptation Planning
5. Sustained Urban Climate Assessment
6. Conclusions – Summary and Recommendations

2 Urban Systems and Climate Change in Context

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2.1 The nature of cities and urban areas

Cities, urban areas, and/or metropolitan regions[i] are the centers of human activity and industry in the United States and house over 80 percent of its population. How cities will be affected by and respond to a changing climate are thus questions of primary importance to American society. But cities also are important *drivers* of environmental changes locally and sometimes at great distances (Rees and Wackernagle, 1996, Luck et al., 2001, McGranahan and Satterthwaite, 2003, Grimm et al., 2008a). Locally, urban activities create distinctive climates, including urban heat islands (UHI; Grimmond, 2011), which have impacts on urban populations that can be exacerbated by global climate change. Cities influence global-scale climate trends by contributing up to 70 per cent of annual greenhouse gas (GHG) emissions globally (UN Habitat, 2011), largely because they account for most of the world's population (indeed, on a per capita basis cities contribute less GHGs than non-urban areas; Dodman, 2009*a*).

Although in this report we are concerned primarily with the impacts of global climate change on cities and their infrastructure, we develop a conceptual framework that acknowledges the dual role played by cities as drivers of and responders to global climate change (Grimm et al., 2008a). The framework takes into account other unique urban characteristics: their inherent heterogeneity, the prevalence of built (human-constructed) components, the ways in which they are shaped by the environment in which they have developed, and the multiple scales that influence urban phenomena (Table 2.1). Before introducing this framework, we discuss fundamental characteristics of urban areas: their structure, organization, and dynamic functioning in the context of current theory.

2.1.1 Structure and organization of urban areas

What are the parts of a city and how are they assembled? The most obvious aspects of their structure are the human population and the built environment. Cities are made up of a population of residents, their housing, the institutions and infrastructure that support their activities, the geophysical template upon which they operate (including soils, water environment, topography, etc.), and the resident biotic populations (plants and animals, both deliberately imported and naturally occurring) (Figure 2.1.). From these building blocks, urban areas develop distinctive properties stemming from how these pieces are arranged and organized across the landscape (Table 2.1.). Urban areas are hierarchical, meaning that various levels of organization are nested, such as houses into blocks into neighborhoods, employees into companies into industries, and culverts into city blocks into sub basins. This nested hierarchy has a vertical and horizontal structure, and in total constitutes the scaffolding within which cities function (Figure 2.1; Wu and David, 2002).

Table 2.1. Features of cities that must be captured by a conceptual framework to understand the impacts and responses of cities to global climate change.

Feature	Explanation	Examples
Driver of and responder to environmental change	Urban areas both drive (due to human production and consumption activities) and respond to global environmental change	CO_2 production from urban transportation sector; exacerbation of urban heat island by regional climate change
Diverse component systems	Key elements of an urban socio-ecological system include a) biophysical features; b) engineered and built systems; and c) people and their institutions	a) Topographic features, trees, rivers; b) buildings, pavement, sewerage; c) neighborhoods, schools, values and mores, city government
Intrinsic character and internal heterogeneity	Within cities, interactions of these components lend a distinctive character, but there is variation in this character across the urban area; e.g., among neighborhoods, leading to variation in vulnerability	City size, shape, and housing density distribution; differential exposure to flood risk; neighborhoods with high proportion ethnic population; prevalence of parks
Characteristics arising from setting and context	There are differences *among* urban areas, which may be due to their historical, geographical, political, and social contexts, that may explain differences in vulnerability	Coastal vs. inland cities, cities in drylands vs. cities in humid environments, border or coastal cities vs. mid-continent cities, old vs. new cities
Influence by actors at multiple levels of organization and/or scales	Various actors modify vulnerability. These actors may be internal or external to the system, operating at scales ranging from highly local to global; cross-scale effects may also be important	National or international economic distress may limit response capacity; state regulations may constrain municipal adaptation strategies; cultural norms may dictate acceptable responses
Diversity of potential mitigation and/or adaptation strategies.	Because of all of the above factors, there is no “one-size-fits-all” solution or best strategy that will apply to all cities	Retaining stormwater may be better in water-limited, environments, while conveyance to fringing wetlands may be better in humid environments

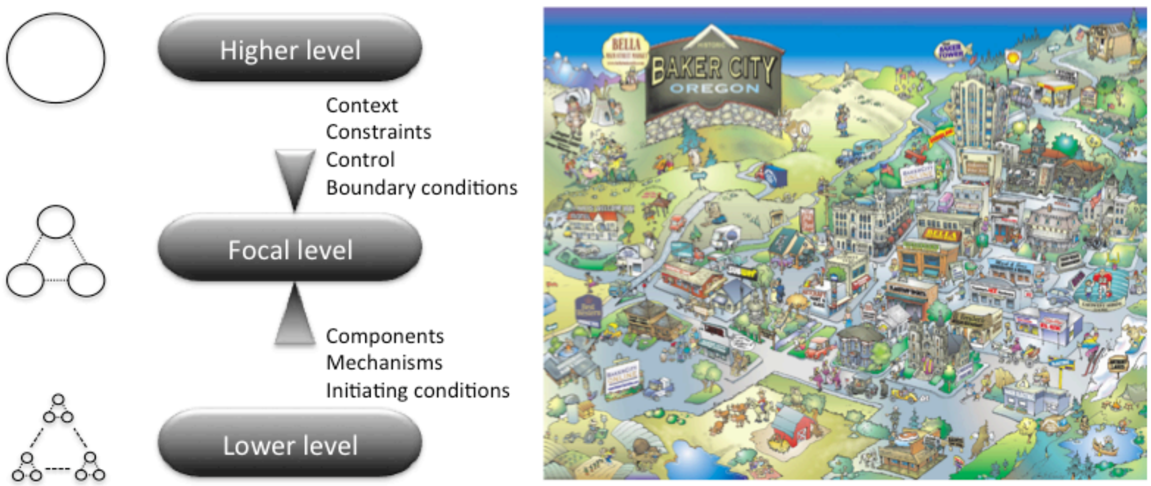


Figure 2.1. Schematic representations of a nested hierarchy (after Wu and David, 2002), and a cartoon depicting the complexity of real cities—with their nested neighborhoods, biotic, abiotic, and built components, and spatial structure—as exemplified by a map of Baker City, OR.

Cities are heterogeneous. For example, more than 90 percent of the soil in downtown areas may be covered by impervious surface but that proportion may be as low as 10 percent in outer suburbs (Schueler et al., 2009). Vegetation abundance, topography, and hydrology can vary tremendously within individual metropolitan areas (Grove, 2006; Hope et al., 2003) as can risk of inundation from rising sea level or overtopped levees (Kirshen et al., 2008; Frickel et al., 2009). These same features can differ among cities as well. Although we recognize any city as a city because of shared characteristics of relatively high population density and built infrastructure, its intrinsic character—its daily and seasonal rhythms, its skyline, its density, its building materials, and the age structure of its human population—can vary widely (e.g., Figure 2.2). Some of this variation is related to the age or geographical location of the city, among other contextual factors (Grimm et al., 2008b; McDonnell et al., 2009). However, urban areas are not just the physical units and their organization, they also comprise entities manifested from the *activity or functioning* within cities, including plant growth and soil decomposition (as in any ecosystem), but also markets, politics, social interaction, plant growth or crime, and culture.

Figure 2.1.2. Images showing some of the unique characteristics that define individual cities (clockwise from upper left: Boise, ID; Annapolis, MD; St Louis, MO, and Tucson, AZ).

2.1.2 Dynamic functioning of urban areas

Functioning has to do with what goes on in a city. Clearly, human activities dominate urban dynamics through economic activities, social and institutional organizations, political structures, and demographics. Human decisions and behaviors associated with these components directly drive changes in land use and the availability of resources such as clean air, water, and food. In addition to these human factors, ecological factors and natural disasters also play a key role in how these decisions initially play out and subsequently feed back (Alberti, 2009). Examples abound in post-Katrina New Orleans. For example, a resolution to deny building permits to developers who plan to build low-income housing with federal tax credits effectively perpetuates historical racial segregation (Gotham and Campanella, 2011).

In the past decade or so, a merger between scientific efforts in life, Earth, and social sciences has begun to better understand the complex dynamics of urban areas. Researchers in this new field hypothesize that urban areas cannot be fully understood by analyzing cities as human systems only, or as ecological systems only, but rather as a coupled socio-ecological system (SES; Alberti, 2009; Collins et al., 2000; Grimm et al., 2000; Ernstson et al., 2010; Walker et al., 2006). In a SES framework, interactions and feedbacks between components become very important in understanding the functioning of the whole. The most obvious intersection between the social and ecological spheres of a coupled system is expressed by the concept of ecosystem services (Daily, 1997): the benefits people derive from ecosystems (including provisioning of water, food, fiber, etc.; regulation of climate, water quality, extreme event magnitudes and so forth; and cultural benefits such as recreation and a sense of place; MEA, 2005; Collins et al., 2011). People extract services from local ecosystems, which may or may not affect the ability of these ecosystems to sustain that level of extraction. If extraction levels are unsustainable, the quality of life for urban inhabitants and/or public perceptions and policies related to those services may feed back to how they are managed.

2.1.3 A conceptual framework for cities and climate change

From this underlying structure, organization, and dynamic functioning, several fundamental properties can be derived that describe cities (Table 2.2). From these fundamental properties we can develop a conceptual framework. Cities have been described as complex, adaptive systems (CAS; Batty, 2008; Alberti, 2008). CAS theory has brought increased understanding of system change and non-linear dynamics, emerging in the past two decades within the fields of ecology and conservation biology (Allen and Holling, 2008; Hobbs et al., 2009; Levin, 1999). More recently, CAS theory has reached a wider diversity of fields including human health, finance, and resource management regimes (e.g., Grimm and Schneider, 2011; Preis et al., 2011; Biggs et al., 2009; Repetto, 2006; Sornette, 2002). The concepts have become particularly widely used to understand how natural systems or SESs respond to shocks (Carpenter and Scheffer, 2009; Gunderson and Pritchard, 2002; Hobbs et al., 2009; Allen and Holling, 2008).

Table 2.2.

Properties of complex, adaptive, urban systems (Alberti, 2008)
Hierarchical organization
Spatial heterogeneity
Emergent properties
Resilience
Multiple equilibria
Non-linearity
Discontinuity
Path dependency

Social, ecological, and built components of cities interact within and across scales of urban hierarchies in ways that are often difficult to predict and may generate emergent_properties (Gunderson, 2002, Liu et al., 2007, Walker et al., 2006). Emergent properties arise when rules or laws operating on individual interacting actors result in complex patterns or behaviors that are not predictable from the actors individually. For example, resilience and stability (see Section 2.2) are emergent properties of urban and natural systems, where resilience is defined as the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to retain the same essential function, structure, identity, and feedbacks (Walker et al. 2004 and 2006; see Box 2.1).

There is not just one urban form and function; thus, urban systems exist in a "stability landscape" where multiple configurations are possible (termed multiple equilibria). For example, urban areas can be compactly developed or spread out, socioeconomically depressed or not, highly dependent on local energy sources or widely distributed energy, each a possible state representing a city. Change can be non-linear and sometimes difficult to reverse; the city may then transform to a far different configuration, as the example of Detroit, Michigan shows today. Many phenomena in cities are discontinuous in space, time, and scale (Alberti, 2008). Examples of discontinuity include abrupt transitions exhibited in fragmented land on the urban fringe (Shrestha et al., 2012), or episodic disease outbreaks. Finally, prediction of urban outcomes in the face of stressors like climate change is not contingent only on current drivers, it also depends on historical and legacy factors (i.e., path dependency), as in the previous New Orleans example.

We have seen that cities are structured and function in ways that are distinct from many other systems affected by climate change. Climate-change impacts on urban areas may be compounded by the impacts on the far-flung supply chains of energy, water, materials, nutrients, and other inputs cities rely upon. For example, spread-out development arising in the post-war era may have been facilitated by geography and surrounding land use, but was enabled by federal policy and economic factors (Fishman, 1999). Witness the rapid, post-war expansion of the Phoenix metropolitan area across a flat, easily converted alluvial plain, with growth seemingly curtailed only by land ownership (Federal and Indian lands) and steep, undevelopable volcanic outcrops (Gober, 2006; Grimm and Redman, 2004; Shrestha et al., 2012). The resulting configuration may influence the city's capacity to cope with the potential impacts of climate change, in this case, drought conditions, anticipated by most climate change scenarios to increase in frequency and magnitude (Cayan et al., 2010), straining water provision to a geographically expansive population (see Gober and Kirkwood, 2010).

The variability among and within metropolitan regions suggests that solutions to the challenges of adapting to or mitigating the impacts of climate change will differ depending upon context and scale as well as the local culture and internal capacity. Multiple actors are constantly making decisions and behaving in ways that modulate both impacts and the responses. Decisions at one scale can have a strong effect on vulnerability at other scales (Gunderson, 2010, Gotham and Campanella, 2011). Thus, this additional layer of complexity also bears examination and inclusion in the conceptual framework for vulnerability and resilience of cities to climate change. Although some generic strategies may be relevant to all cities, the fundamental heterogeneity of cities and the differences among them are crucial to the choices made. We propose a resilience-based framework that contains the elements described in Table 2.1.1, embraces concepts embodied in SES and CAS approaches, and enables coherent assessment of the vulnerability of cities to climate change (Figure 2.3).

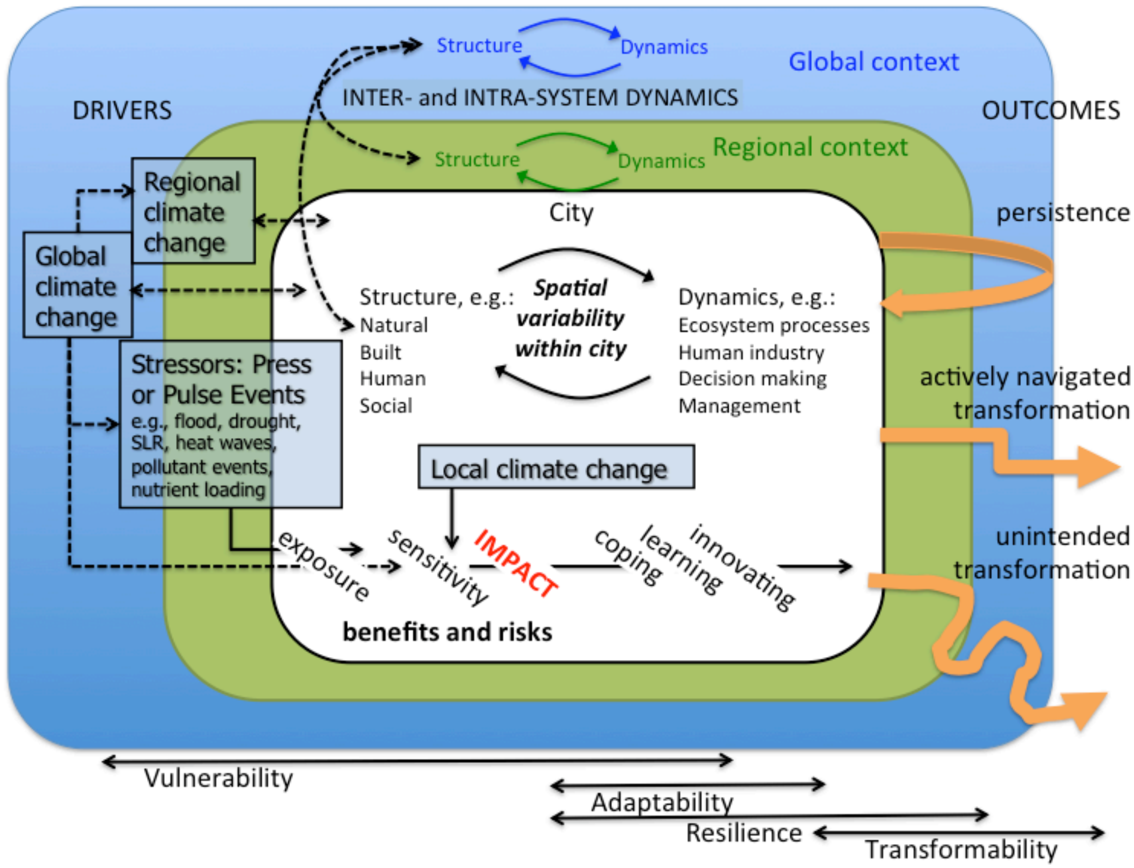


Figure 2.3. A conceptual framework for how cities may respond to climate change. The city is embedded within a region (green shading), which is surrounded by the global context (blue shading). Urban characteristics are context dependent and internally variable (see Table 2.1). Climate change modifies stressors, which result in impact depending upon exposure and sensitivity. In this framework, vulnerability, adaptability, resilience, and transformability all determine the outcomes of internal and cross-scale interactions under climate change. Adapted from Turner et al. (2003) and Chapin et al. (2009).

Climate change at global, regional, and local scales influences cities directly, but perhaps more importantly, through alteration in the suite of stressors impinging on the systems (Figure 2.3). These stressors can be identified as press (long-term, sustained) or pulse (episodic) events to which the system is exposed (Collins et al., 2011), and they include such things as extreme heat episodes, flooding or drought, and heavy precipitation. Presses and pulses also may be beneficial, such as periods of relatively benign temperatures in usually cold climates or storms that move polluting air masses away from cities. Cities and their component parts (i.e., infrastructure, neighborhoods, biota) are differentially exposed to these stressors, as well as overall climate change, and have different sensitivities, which reflect their vulnerability. The relative vulnerabilities are in part due to the dynamic interactions between different forms of capital and processes of the cities, such as decision-making, human industry, ecosystem processes, and so forth (Chapin et al., 2010). These interactions also give rise to adaptability and resilience, via coping, learning, innovating, and at an extreme, transformation (Figure 2.3).

Finally, although we might think of each city as being exposed to a unique constellation of stressors, threats, and risk, cities should not be considered in isolation. Cities are open systems, and both in a biophysical sense and a social and political sense (i.e., energy, materials, and information flow freely through individual cities and among regional, national, and global collections of cities). Indeed, some authors have called for a consideration of urban resilience that recognizes urban areas as nodes in systems of cities (Ernstson et al., 2010). This concept calls for explicit recognition of cross-scale influences in the vulnerability and resilience of cities to the impacts of climate and other environmental change.

2.2 Urban vulnerability, resilience, and transformation in the context of climate change

Resilience and vulnerability are related concepts with a long history in ecology, political science, and hazards/risk research, among other disciplines (Eakin and Luers 2006, Engle, 2011, Gallopin, 2006, Gunderson, 2002, Holling, 1973, Smit and Wandel, 2006, Turner et al., 2003, Turner, 2010). In general, both terms deal with a system's capacity to absorb stresses, whether press or pulse, and might seem to be opposites, but different characteristics are reflected in the two terms (Gallopin, 2006, Gotham and Campanella, 2011). The three components of vulnerability are exposure, sensitivity, and adaptive capacity (Polsky et al. 2007; Figure 2.3).

Each of the components of vulnerability is influenced by various social and cultural processes and legacies, resulting in differential vulnerability across urban areas. Resilience incorporates the capacity to absorb perturbations, but also the ability to recover, learn, adapt, and innovate (Walker et al., 2004, Figure 2.3). Resilient socio-ecological systems are able to maintain structure, function, identity, and feedbacks in the face of surprises and uncertainty (Folke, 2006), both of which are hallmarks of climate change. Here we recognize the utility of the resilience concept in dealing with non-linear dynamics of socio-ecological systems faced with rapid environmental change and, particularly, extreme events (Linnenluecke and Griffiths, 2010; see also Box 2.1).

Box 2.1. Transitions, tipping points, resilience and transformation

Concepts of tipping points and transitions are often best conceptualized using a "stability landscape," such as that shown in Figure 2.4. Walker et al. (2004) define resilience as the capacity to absorb disturbance and reorganize while undergoing change so as to still retain the same essential function, structure, identity, and feedbacks. In the stability landscape, the system (represented by the blue dot) is able to move around in a basin of attraction, bounded by the brown dashed line. The resilience of a system is a function of latitude (L; how much room there is to move), resistance (R; essentially how deep the basin is), precariousness (Pc), and panarchy (i.e., cross-scale interactions [not shown]; Gunderson, 2002). Its precariousness (Pc) is a function of how close it is to the boundary and how fast it is moving; a precarious system is one that is at high risk of crossing a threshold. When the system does cross a threshold, it has made a transition to a new basin of attraction. Thus, resilience is essentially the capacity to remain within the same basin of attraction (Walker et al. 2004). Drastic change can effect a transformation; in that case the system may not have moved at all, but the stability landscape itself has changed.

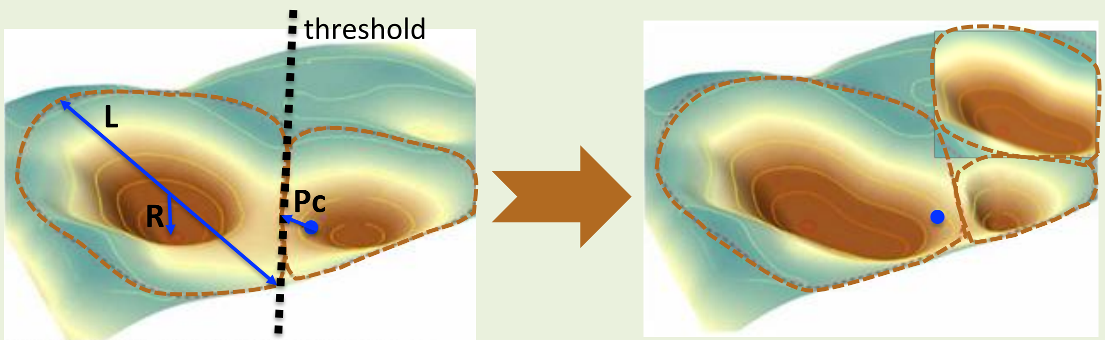
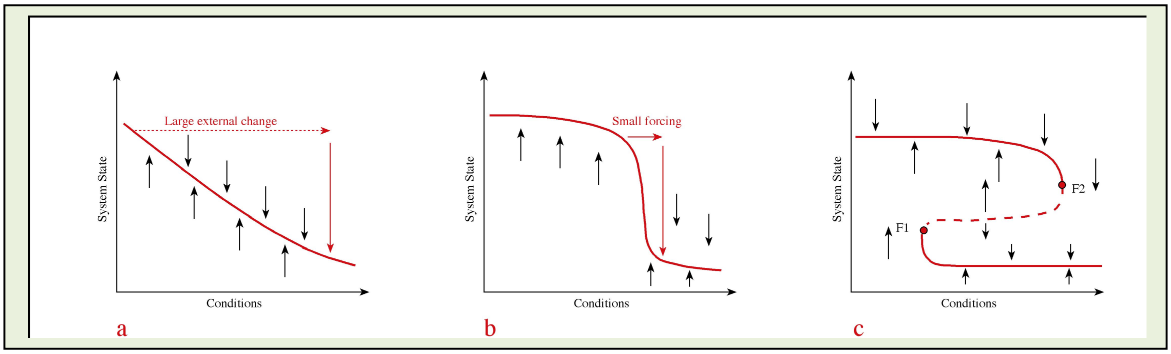


Figure 2.4. Schematic representation of stability landscapes before and after transformation, showing some resilience concepts discussed in the text. Adapted from Walker et al. (2004).

Three basic types of transitions have been defined, two of which include linear/non-critical transitions, indicating that there is a possibility of system recovery along a continuous equilibrium line (Figure 2.5). In the first case, transitions occur as a result of large-scale external change, such as environmental hazards causing a decline in the system state. The system can gradually recover over time. In the second case, a large transition could result from a smaller-scale perturbation that forces the system past a threshold, but again, there is high probability that the system could recover. The third type of transition is described as a critical transition, which includes a break in the system-equilibrium line, such that system recovery only occurs when the state recovers well beyond the original transition point. Critical transitions are defined as moments during which a system or sometimes a set of closely connected systems dramatically change. This change is seen as so profound that the system(s) enter into a phase change during which the function and quality of the system shift from one condition to another. Critical transition theory has been extensively applied to physical systems, and increasingly has been applied to socially organized and defined systems such as policy regimes and financial markets.



To define vulnerability or resilience operationally, we must answer the question, the vulnerability or resilience *of* what *to* what (Carpenter et al., 2001)? Related to climate change, this could be the vulnerability of water systems to increased storm magnitudes, of medical care systems to climate change-enhanced heat waves or more frequent episodes of acute air pollution, or of property rights to sea level rise. Determining exposure, sensitivity, and adaptive capacity is challenging, but forms the basis of vulnerability assessments, which are becoming central to planning for climate change in urban and non-urban systems (NRC, 2011). The vulnerability assessment was an organizing principle for the First Assessment Report of the Urban Climate Change Research Network (Rosenzweig et al., 2011), and is being incorporated into urban adaptation plans in cities including Boston, MA; Chicago, IL; Keene, NH; New York, NY; and San Francisco, CA.

How abrupt climate-dependent shifts take place within urban environmental systems is a required ingredient for understanding the connections between climate change and cities. Climate change will have significant impact on urban environmental systems (Rosenzweig et al., 2011) and will interact with existing stresses such as urbanization that threaten the structure and function of a system (e.g., NRC, 2011, Prashkievicz and Chang, 2011). Either independently or with other stresses, there is a high potential for climate change to cause increased dynamism and even transitions—the crossing of one or more thresholds—within urban environmental systems (see Box 2.1). Transitions can be understood as moments of rapid change from one state to another. Crucial issues within transition theory include the size and character of the driving force for change, the response of the system, and reasons behind the system response. The framework we present (Figure 2.1.3) allows for these kinds of transitions as "outcomes" of the interactions of the drivers, impacts, and responses to climate change.

2.3 History and status of urbanization in the United States

The United States underwent an urbanization transition in the 19th and 20th centuries, in which increasing proportions of the United States population came to live in urban areas. In 1900 the population of the United States was roughly 35 percent urban; from 1925-1950, the period encompassing the Great Depression and World War II, the percentage jumped from 40 percent to 65 percent urban (Weeks, 2008).[ii] By 2010 the United States population had become 84 percent urban, 60 percent of which is in suburban areas and 40 percent in central cities (Mather et al.,

2011) (Figure 2.6). The growth of lower-density settlements, popularly known as urban sprawl, has characterized most development in the last sixty years. Federal housing subsidies, availability of affordable automobiles, and marketing of the American Dream spurred the rise of low-density suburbs in the 1950s (Fishman, 1999); the 1980s and 1990s saw the rise of exurbs, newer rings of development beyond the older suburbs.

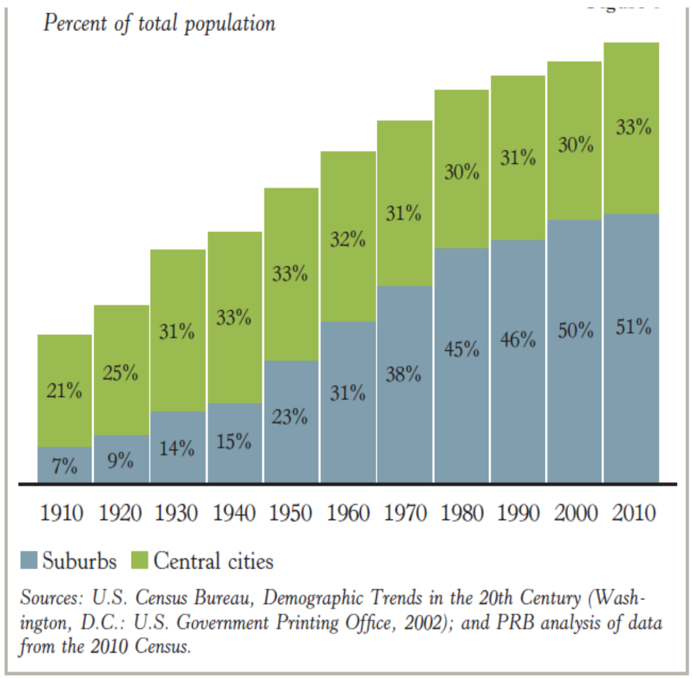


Figure 2.6. Urban population growth in the United States. Source: PRB, 2011

Beyond the increasing concentration of United States population in urban areas, there has been a progressive shift in the demographic balancing point of the continental United States (the so-called "population center," at which the United States population would be equal to the east and the west) from Louisville, KY in 1950 to Plato, Missouri (Census Bureau, 2011). This reflects a gradual shift in the United States population from the Northeast to the South and Southwest (the so-called "Sun Belt") during the same time period. Figure 2.7 shows the percentage change in United States population from 2000-2010. As the map depicts, the basic trend has continued, with growth concentrated in the Southwest, the Rocky Mountain region, the Mississippi Valley and Texas, and, on the East Coast, from Washington DC south to Florida. Urbanization trends are expected to continue through 2050, when the United States population is projected to be more than 90 percent urban (UN 2010).

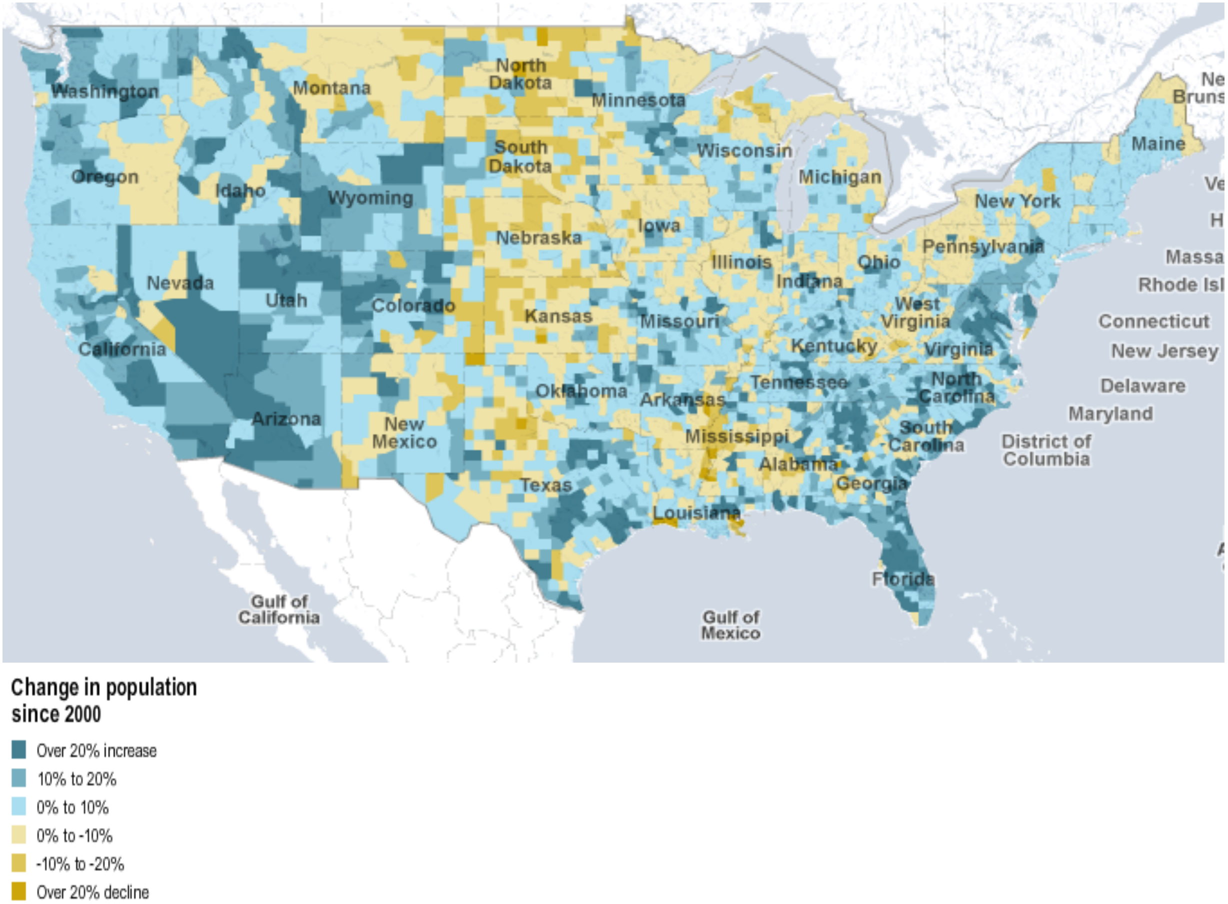


Figure 2.7. Population growth in the United States from 2000 to 2010. Source: http://projects.nytimes.com/census/2010.

Regional populations have distinctive demographic characteristics. For example, rural and more isolated counties tend to have higher percentages of elderly people (age 65 and older) (Figure 2.8), and coastal cities have high percentages of foreign born (Figure 2.9). The high degree of international immigration to the United States tends to reinforce existing trends in internal migration toward the coasts and away from the heartland, Appalachia, and poor and largely rural counties. Rural and suburban areas also tend to have higher concentrations of poor people as a percentage of the overall population, although urban areas have the greatest absolute numbers of poor people. The status and trends in population distribution have consequences for the drivers of climate change, mediating processes, vulnerability, and adaptive responses (see section 2.5).

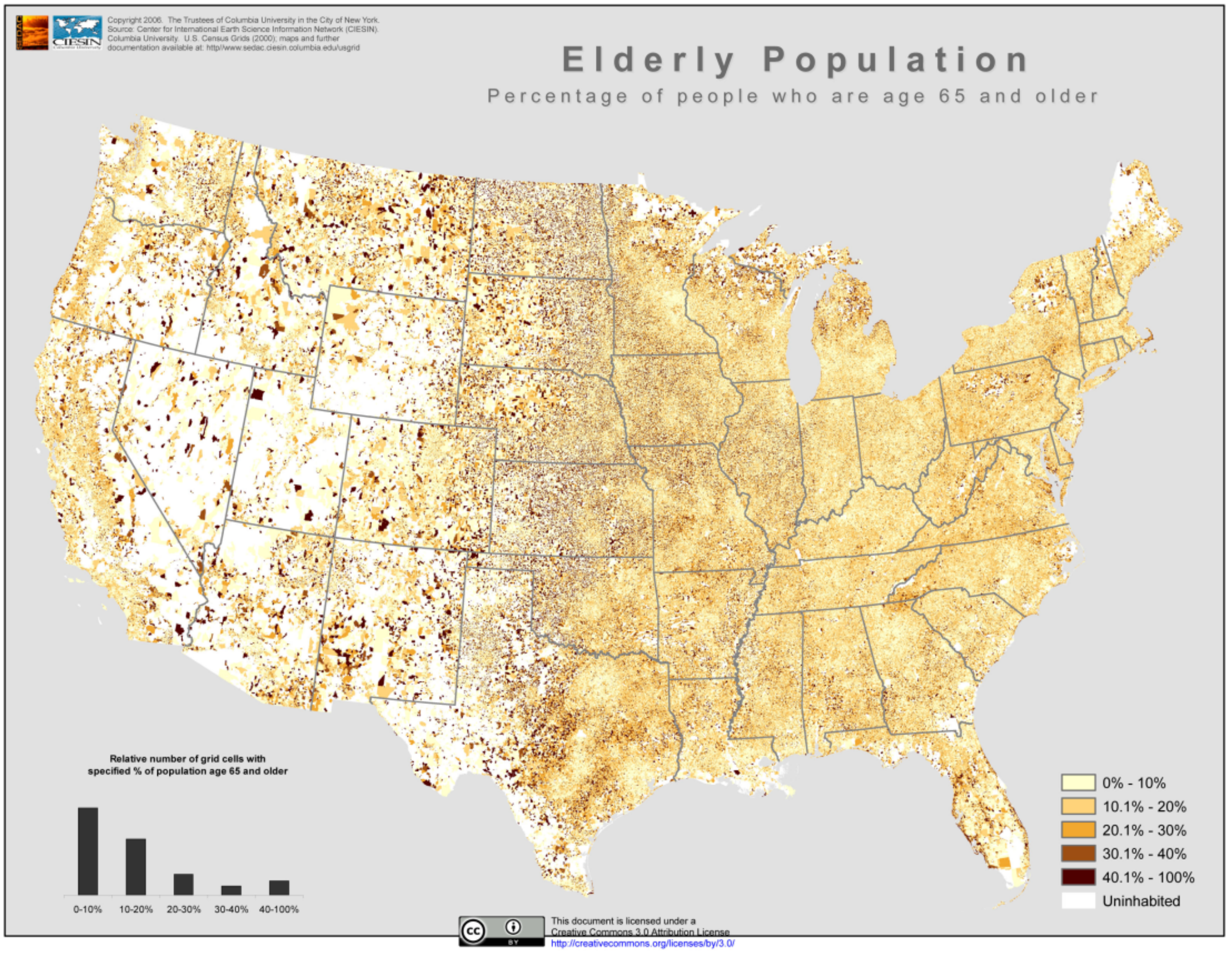


Figure 2.8. Map of the elderly population in the United States. Source: US Census Grids, NASA Socioeconomic Data and Applications Center.

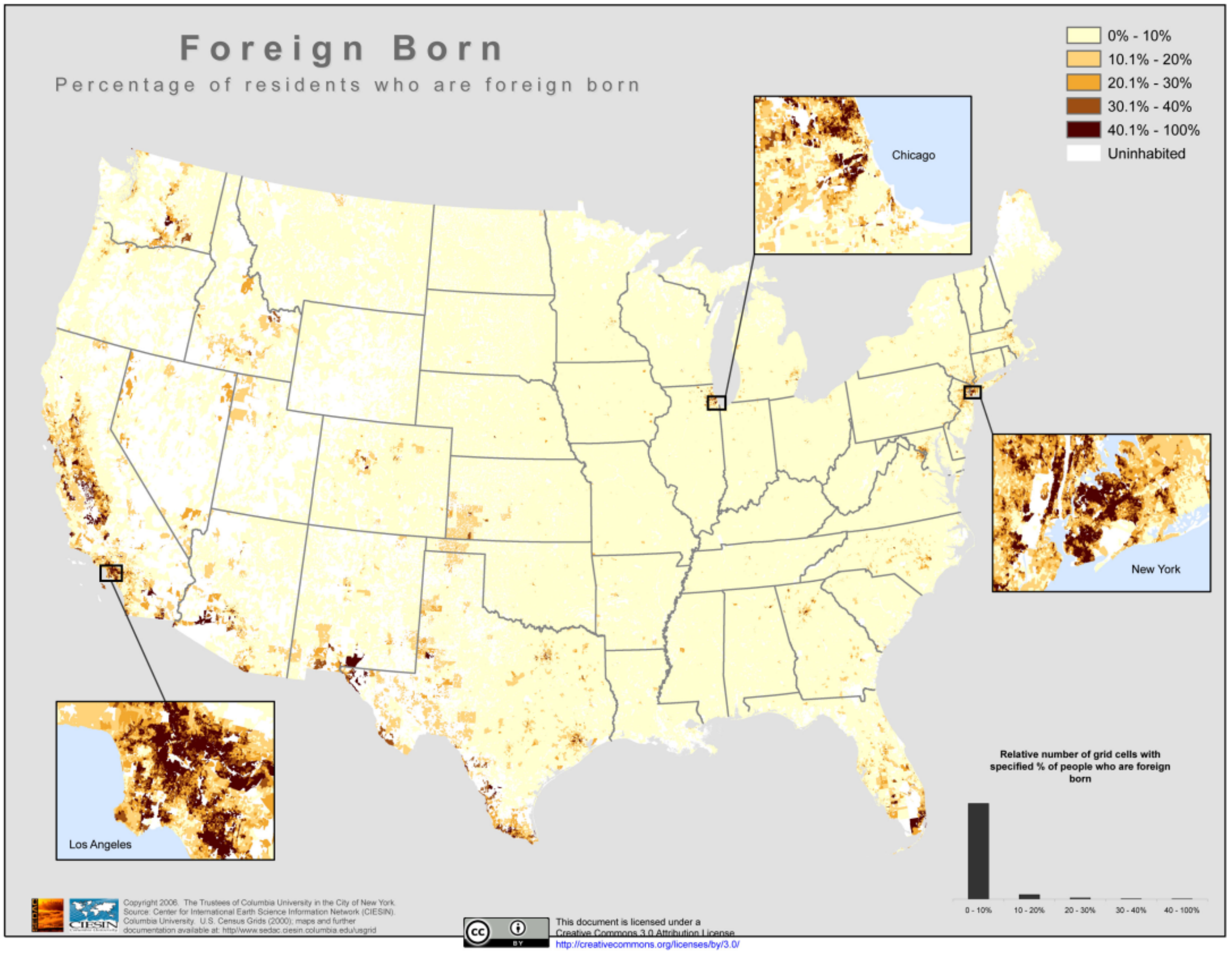


Figure 2.9. Map of foreign-born population in the United States. Source: US Census Grids, NASA Socioeconomic Data and Applications Center.

2.4 The nature of urban climate change

The impacts of climate change on urban areas in the United States can have potentially far-reaching effects, locally, regionally, and even globally. The continued demographic transition toward urbanization will likely exacerbate the challenges presented by climate change (USGCRP, 2009). Urbanization will affect the atmosphere above and around cities by changing the physical parameters that govern the land-atmosphere interface over urban areas. In turn, regional atmospheric phenomena and interactions encompassing large-scale physical and environmental processes will be affected. There is also potentially a feedback mechanism from urban effects on physical parameters and interactions to local and regional meteorology and, in the long-term, the climate.

As urbanization continues and forest, agricultural, and natural open land is consumed as part of urban growth, land-cover change in and around cities creates an (UHI), which manifests as a dome of elevated air temperatures over cities resulting from transitions from pervious to impervious surfaces (Landsberg, 1981; Voogt, 2002; Souch and Grimmond, 2006; Grimmond, 2007; Weng et al., 2004; Hua and Weng, 2008; Liu and Weng, 2008). Development of the UHI is related to land-atmosphere interactions that occur over cities. Factors driving these interactions include surface geometry, surface thermal properties, surface conditions (e.g., dryness), anthropogenic heat, and the urban greenhouse effect (Voogt, 2002). Major questions to address within the overall scope of climate change are how will cities, as they continue to grow in the future, be affected by climate change and conversely, affect the local and regional climate? Research using historical meteorological and satellite data illustrate that the size and dimension of the UHI is correlated with urban growth (Oke, 1973; Remar, 2010; ELI, 2011). This trend is expected to continue in cities in both developed and developing countries (Goldman, 2004; Dodman, 2009*b;* Zhang, et al., 2011; Zhou, 2011; Peng, et al., 2012). Moreover, it is becoming clear that the amplitude of thermal intensity of the UHI has an effect on periurban biomes (Imhoff et al., 2011). Research on New York City and environs (Rosenzweig et al., 2005; Solecki et al., 2011), incorporated extrapolation of current trends in maximum and minimum temperature into Global Circulation Models (GSCMs) to project that temperatures will continue to warm in the current century, as they have for the past century. Research by Hitchcock for Texas further supports these findings (Hitchcock, 2011).

The UHI has been shown to reduce air quality through production of increased levels of O_3 and to some extent $PM_{2.5}$ (EPA, 2011a; Lai and Cheng, 2009). Additionally, research has indicated that the UHI, associated mesoscale-induced circulations, and convergence from urban landscapes can initiate, enhance, or modify precipitation events over and downwind of the city, particularly during the warm season (Zhang et al., 2011, Ashley et al., 2011, Niyogi et al., 2011, Shepherd et al., 2010 (a,b), Bentley et al. (2010), Mote et al. (2007)). Additionally, it is increasingly likely that aerosols in urban environments may also modify precipitation via indirect microphysical effects (Rosenfeld et al., 2008). Ongoing research is exploring the relative contributions of UHI destabilization and mesoscale dynamics, building induced convergence, and aerosols, to observed precipitation changes. Likewise, research is examining whether the urban rainfall effect (Shepherd et al., 2010b) predominantly leads to enhanced (most dominant finding in the literature) or suppressed precipitation.

Urban Dry Islands—UHI-driven drought conditions—have been found over cities (Grossman-Clarke et al., 2005; Niyogi et al., 2011). A persistent decrease in precipitation directly over cities appears to be a consequence of extensive impervious surfaces with very low surface moisture content for evapotranspiration and humidity exchange (Kaufmann, et al., 2007). Additionally, urbanization can have a “splitting” effect on severe storms passing over cities, in which the “roughness” of the urban surface (i.e., buildings, vegetation, etc.) effectively diverts storms around the city, thereby diminishing their impact on the city itself (Bornstein and Lin, 2000; Niyogi et al., 2011). Events driven by convective processes, such as flooding (Shepherd et al., 2011) and lightning (Rose et al., 2008), have also been linked to urban forcing.

2.4.1 Assessment of climate change impacts on urban areas in the United States

The overall impact of climate change on cities in the United States is embedded in the regional interaction of degradation of air quality, dynamics of the UHI, changes in the amount and intensity of precipitation, and sea-level rise and occurs in the context of each city's unique socio-ecological character. In many cases, interactions among stressors involve not only the direct impacts (e.g., more or less precipitation), but also second- or higher-order impacts, the synergies of which have greater effects than the direct impacts alone. For example, a prolonged heat wave may trigger mortality and morbidity related to heat stress, which may be exacerbated by the absence of air conditioning systems in lower-income neighborhoods (Gaffen and Ross, 1998; Harlan et al., 2006). The cascading of interrelated impacts of these factors, therefore, may greatly exacerbate the impact of a single factor (World Bank, 2010; Lankao, 2008).

Besides having a host of such interactions, the impacts of climate change on urban areas will likely have thresholds, below which effects are incidental or of mild consequence, but beyond which the effects quickly become major (Ebi et al., 2007). Hence, a city may be able to cope with prolonged heat waves, but if this is combined with severe drought, the overall result could be significant or even catastrophic, as accelerating demand for energy to cooling taxes water supplies needed both for energy supply and municipal water needs. Changes in climate extremes are often of more concern than changes in climate averages, although the latter may have a compounding effect. In addition to severe weather events, urban areas may be affected by changes in daily or seasonal high or low temperatures or precipitation, which may have a much more prolonged impact than the direct effect of these events (Smith, 2004, SAP 4.6, 2008). Thus, the cumulative impacts of multiple events, coupled with changing mean conditions, may be more severe than those of any single event.

2.4.2 Key impacts

The key impacts described in this section of the report focus on the physical impacts of climate change on urban areas and the potential impacts that cities will have on the local and regional climate (e.g., urban land–atmosphere interactions). These include deterioration in air quality, the UHI effect and its concomitant impacts, effects on precipitation over urban areas, urban flooding, and challenges of addressing the 'urban signal' and climate change.

2.4.2.1 Air Quality

The relationships of air quality with temperature are well known, with increased temperatures as a result of climate change contributing to more stagnant air in many regions due to weaker global circulation (Millstsein and Harley, 2009). An observed correlation between surface ozone and temperature in polluted regions suggests a detrimental effect of warming (Sillman and Sampson, 1995; Jacob and Winner, 2009; Stone, 2011). Coupled global climate model (GCM) and chemical transport model (CTM) studies show that climate change alone will increase summertime surface ozone in polluted regions by 1-10 ppb over the coming decade, with the largest effects in urban areas and during pollution episodes (Jacob and Winner, 2009). Particles with diameters between 2.5 and 10 micrometers are referred to as "coarse." Sources of coarse particles include crushing or grinding operations, and dust from paved or unpaved roads. Other particles may be formed in the air from the chemical change of gases. They are indirectly formed when gases from burning fuels react with sunlight and water vapor. These can result from fuel combustion in motor vehicles, at power plants, and in other industrial processes (EPA, 2011b).

The effect of climate change on particulate matter, however, is more complicated and uncertain than for ozone. GCM-CTM studies illustrate that climate change will affect PM in polluted environments by $\pm$0.1-1 µg m^{-3} over the coming decades (Jacob and Winner, 2009). This was further corroborated in a study of the impact of climate change on photochemical air pollution in southern California (Millstein and Hartley, 2009). These projections are also described as part of MEGAPOLI (Megacities: emissions, urban regional and Global Atmospheric POLution and climate effects, and integrated tools for assessment and mitigation), a program that in part, seeks to assess the impacts of megacities and large air-pollution "hot spots" on climate. MEGAPOLI brings together leading European research groups, state-of-the-art scientific tools and key players from non-European countries to investigate the interactions among megacities, air quality, and climate. MEGAPOLI bridges the spatial and temporal scales that connect emissions, air quality and weather with global and temporal scales that connect air quality and weather with global atmospheric chemistry and climate. Extensive information on MEGAPOLI and the scientific findings from the study can be found at http://megapoli.dmi.dk/publ/MEGAPOLI_sr11-24.pdf (MEGAPOLI, 2011).

Ozone (O_3) is not emitted directly into the air, but at ground level is created by a chemical reaction between oxides of NO_x and volatile organic compounds (VOCs) in the presence of sunlight. (Figure 2.10). Motor vehicle exhaust and industrial emissions, gasoline vapors, and chemical solvents also contribute to ozone formation (Perera and Sanford, 2011; Yip et al., 2011). Sunlight and hot weather cause ground-level O_3 to form harmful concentrations in the air. Ozone that is close to the ground can cause eye irritation; headaches; coughing; impaired lung function; and eye, nose, and throat irritation. Asthmatics and children are most at risk. The chance of experiencing adverse health effects from elevated ozone levels increases during heavy exercise or outdoor activity. Ground-level ozone can also damage trees, plants, and reduce visibility (National Safety Council, 2011). As a result, it is a known summertime air pollutant. Peak O_3 levels typically occur during hot, dry, stagnant summertime conditions that are exacerbated by the UHI effect. The length of the ozone season varies from one area of the United States to another. Therefore, southern and southwestern cities may have an ozone season that lasts for prolonged periods of time (e.g., months).

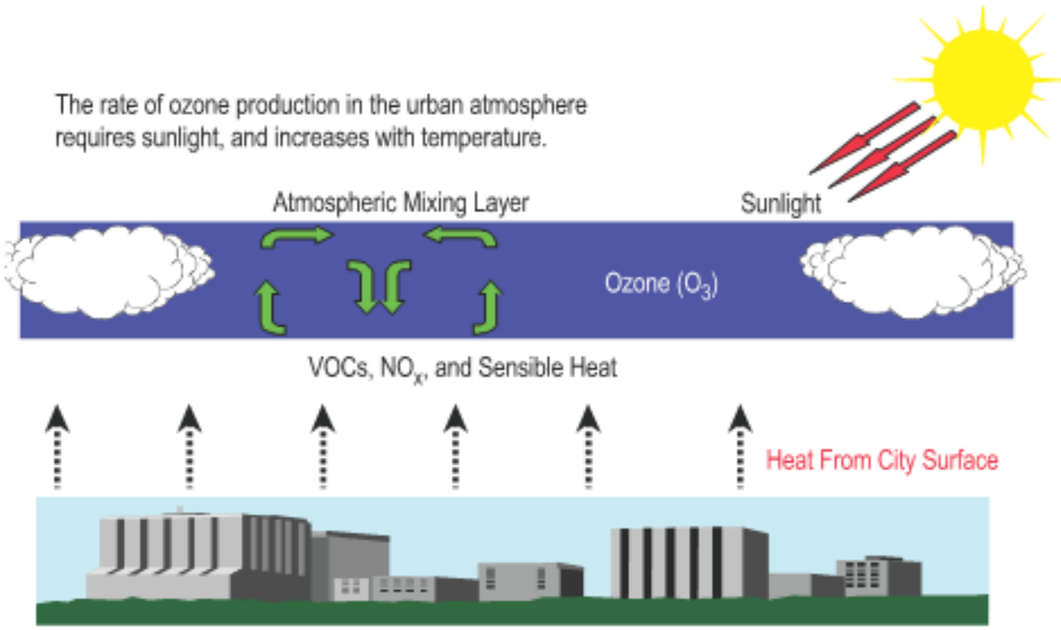


Figure 2.10. Ozone formation in the urban atmosphere (from Quattrochi et al., 2006).

2.4.2.2 The Urban Heat Island Effect

A wealth of research dating back to the 19th century has demonstrated that four principal characteristics of cities typically render these environments hotter than the surrounding countryside, creating the UHI (Figure 2.11) (Landsberg, 1981). The first is a *reduction in evaporative cooling* when streets, parking lots, and buildings replace vegetative cover. Because these materials are generally impervious to water, a smaller proportion of rainfall is retained by urban surfaces and consequently less is available for evaporation, which is a cooling process. Similarly, the reduced surface area of vegetation limits the quantity of moisture retained for transpiration in plants. Reduced moisture availability causes a shift in the surface energy balance from latent to sensible heat flux, increasing the quantity of heat released to the air.

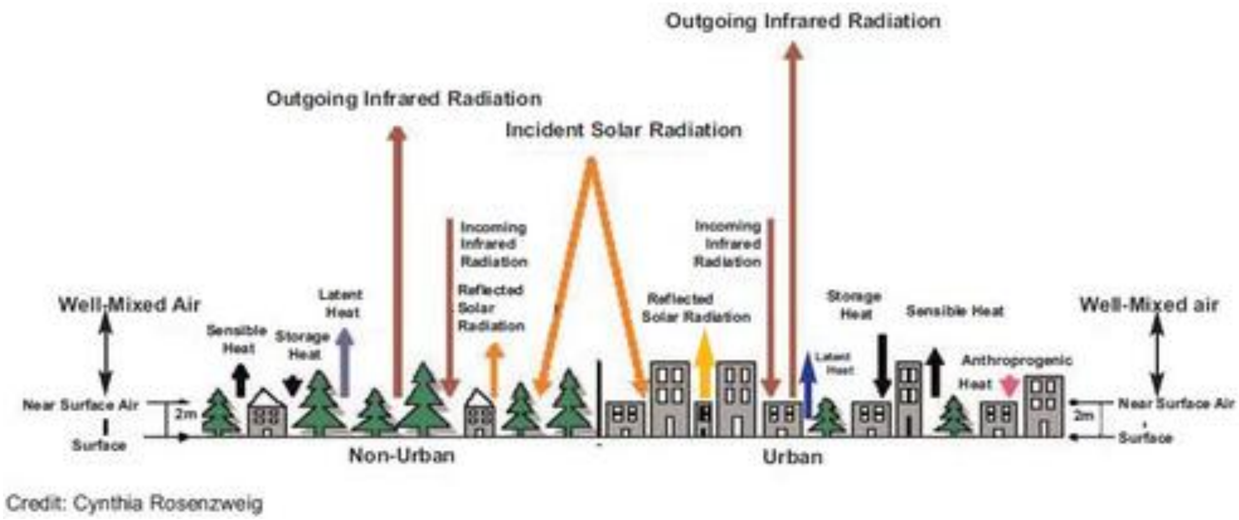


Figure 2.11. Land-atmosphere interactions that govern the UHI and energy balance exchanges over cities. (Source: Rosenzweig, 2011)

A second characteristic of urban areas conducive to enhanced warming is *low surface reflectivity.* Darkly hued paving and roofing materials, such as asphalt, are abundant surface covers in most cities, contributing to lower albedo and greater absorption of solar energy in cities than in rural areas with higher surface reflectivity. Unvegetated surfaces cannot compensate for enhanced absorption of solar energy through increased evapotranspiration, so a larger percentage of this energy is returned to the atmosphere as sensible heat and longwave radiation, raising temperatures.

Compounding the problem of diminished reflectivity is the *re-absorption of reflected radiation* by the vertical surfaces of buildings. Because solar radiation reflected by the land surface travels in all directions, some proportion of this reflected radiation is absorbed by the surfaces of buildings blocking a clear path to the sky. Once absorbed by these surfaces (or re-reflected toward other buildings and the ground), additional heat energy is released into the near-surface atmosphere. The urban canyon—the localized environment formed by closely arranged buildings in high-density districts— constitutes a third characteristic of cities that tends to enhance temperatures relative to the surrounding countryside.

Finally, in addition to the enhanced quantity of heat energy absorbed and retained from the sun, cities generate copious amounts of *waste heat* from mechanical processes that can further elevate near-surface temperatures. Such anthropogenic sources of heat, including vehicle exhaust, waste heat emitted from power plants and other industrial operations, and heat mechanically removed from buildings via air conditioning systems, constitute an important source of heat generation that is largely absent from non-urbanized areas.

The degree to which these four characteristics of cities elevate temperatures has been the subject of climate research for many decades. Recently, urban climatology has sought to distinguish the relative contribution of global-scale, GHG-driven processes and regional-scale, UHI-driven processes to observed warming trends. The results suggest that local processes are often the dominant driver of warming trends at the urban scale. The certainty of this UHI-based warming trend has been verified in numerous studies, particularly those using remote-sensing data (from both satellite and aircraft) to measure urban growth relationships with the UHI (Steutker, 2003; Dousset and Gourmelon, 2003; Chen et al., 2006; Quattrochi et al., 2009; Weng, 2009; Jiang and Tian, 2010). Moreover, the certainty of the impact of climate change on photochemical air pollution over urban regions has been established by Millstein and Harley (2009), wherein climate perturbations led to combined peak 1-hour ozone increases of up to 11 ppb. The climate perturbations having the most effect on photochemical pollution were: 1) effect of increased temperature on atmospheric reaction rates; 2) effect of increased temperature on biogenic emissions; and 3) effect of increased water vapor concentrations.

Box 2.2. An Example of UHI management strategies for the Atlanta, GA metropolitan area

Quattrochi et al., (2006) conducted a study over the Atlanta, GA metropolitan area to evaluate the effectiveness of Urban Heat Island (UHI) management strategies in reducing urban air temperatures. Scenarios for baseline or "business as usual" (BAU) land cover/land use changes to, 2030, along with conservative measures of modifications to vegetation (e.g., tree planting) and albedo (e.g., lightening the color of rooftops) were modeled separately along with a combined vegetation-albedo modification strategy. This simulation was performed for the five-county built-up area that comprises the Atlanta 'main core' and for a 13-county area that exists as the urban and periurban complex of the metropolitan area. Only the role of land surface temperature was investigated and the study did not include any greenhouse gas mitigation scenarios. The effects of temperature changes between the 2000 baseline period and the 2030 BAU are illustrated in Figure 2.12.

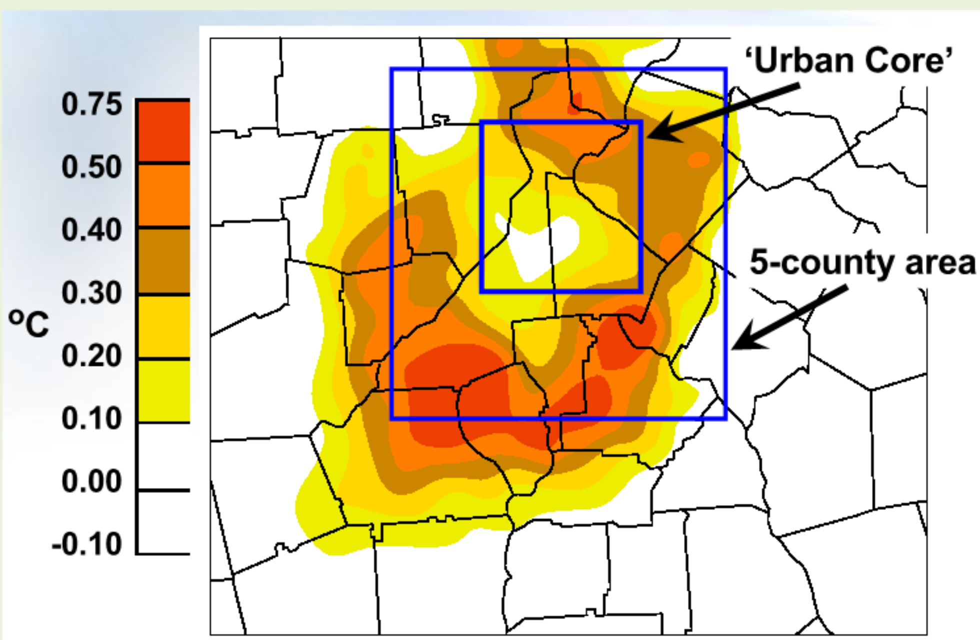


Figure 2.12. Difference in air temperature between 2030 BAU and 2000 baseline simulations (Quattrochi et al., 2006).

Results show that in the urban center, there is very little change in air temperature as this area is already nearly completely urbanized. The largest warming occurs in the suburban region, where temperatures are projected to be more than 0.5°C warmer in 2030 than in 2000. The impact of the UHI mitigation strategies (i.e., higher albedos and vegetation cover) in 2030, in contrast, is to cool the urban core by nearly 0.5°C (Figure 2.13). Smaller cooling values extend out into the suburban areas, while rural areas outside of the periurban environment show virtually the same temperature for the two simulations. It must be reiterated that the modeled data express only a limited change in vegetation cover and albedo. More extensive modifications in these factors would have a greater cooling effect.

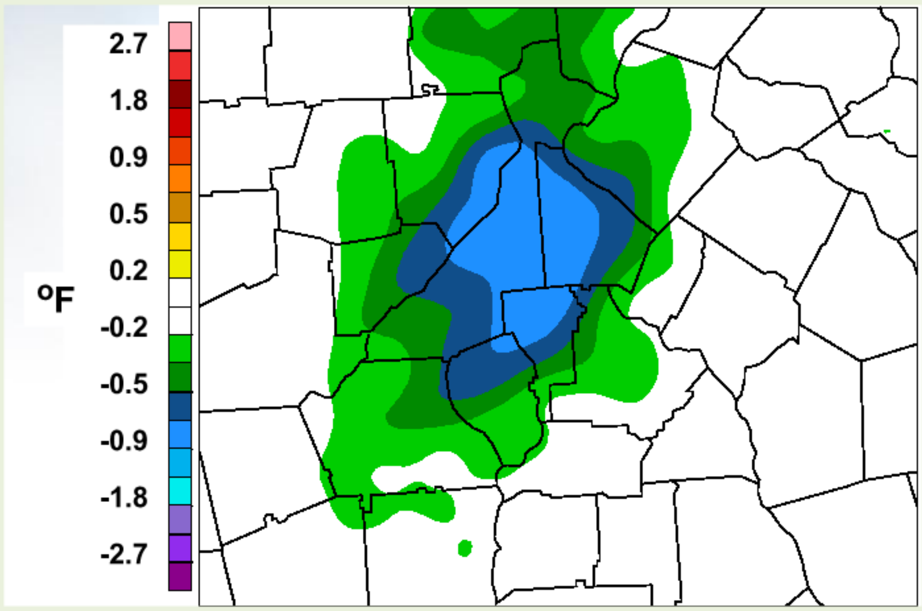


Figure 2.13. Difference in air temperature between 2030 combined mitigation and 2030 BAU simulations (Quattrochi et al., 2006).

Numerous studies focused on the United States and elsewhere have found urbanization and other land-use changes to be a major contributor to observed warming trends (e.g., Zhou et al., 2004; Lim et al., 2005; Hale et al., 2006). Through the comparison of land-based weather station data with weather balloon temperature observations that are insensitive to land surface conditions, scientists have estimated that deforestation and other land-use changes across the United States have resulted in about 0.35°C of warming per decade since the 1950s, accounting for roughly 50 percent of the observed changes in the diurnal temperature range during this period (Kalnay & Cai, 2003).

The most comprehensive study of urbanization and climate change in the United States focuses on 50 of the most populous metropolitan regions (Stone, 2007). Monthly temperature records dating back to the 1950s were obtained for urban and nearby rural weather stations to assess the extent to which the UHI effect is increasing in these regions over time. The results of this study found urban temperature trends in the majority of these cities to be increasing at a rate of 0.31°C per decade compared to a rural rate of increase of 0.12°C per decade, which is consistent with the observed global average rate of warming (Stone, 2007). The average decadal rate of warming based on the NASA Goddard Institute for Space Studies global temperature index for this period was 0.12°C (NASA/GISS, 2011). These findings suggest that most large United States cities are warming at a rate more than double that of the planetary warming rate (Stone, 2007).

The pace of warming in urban environments in the United States carries the potential to not only enhance the magnitude of future warming trends but also to amplify the intensity of heat waves in the present period (McCarthy et al., 2010). For example, recent studies have found the UHI effect to be contributing to a rising number of extreme heat events in southeastern cities (Stone, Hess & Frumkin, 2010), as well as to an amplification of heat wave events in large cities such as Atlanta, Georgia (Zhou & Shepherd, 2010). Other work finds that future heat waves globally will be more intense, of greater frequency, and longer lasting (Ganguly et al., 2009; Meehl & Tebaldi, 2004; Lankao, 2008; McCarthy et al., 2010; Peng et al., 2012). There is also evidence that the incidence of extreme heat events increases for sprawling cities more than it does in spatially compact urban areas, a relationship that is independent of climatic/geographical context (e.g., humid southeastern United States) or city characteristics, such as metropolitan population size or growth rate (Stone et al., 2010).

Evidence of the direct role of the urban areas in urban-scale climate change means there is potential for health threats associated with extreme heat events to be abated through UHI mitigation (Wilhelmi et al., 2012). Both experimental and modeling studies have found land use strategies, such as the enhancement of urban tree canopy cover and surface albedo, to measurably slow warming trends when implemented extensively throughout urbanized regions. Over the last two decades, many studies have found variable combinations of tree planting and vegetative cover, albedo enhancement, and reductions in waste heat emissions to reduce urban temperatures by between 1 and more than 6°C (Kikegawa et al., 2006;Rosensweig et al., 2006; Gaffin, et al., 2009; Lynn et al., 2009; Rosenzweig, et al., 2009; Rosenzweig, Solecki, & Slosberg, 2006; Taha, 1997; Zhou & Shepherd, 2010). Of the various approaches to heat island mitigation, tree planting and other vegetative strategies are generally found to be the most effective, where water resources are sufficient (Gober et al., 2009), with surface reflectivity and waste heat management typically accounting for somewhat lower reductions near surface air temperatures, depending upon the spatial extent of coverage and the regional landscape type (Hart & Sailor, 2009; Lynn et al., 2009; Zhou & Shepherd, 2010).

Importantly, many synergies exist between strategies designed to control GHG emissions and strategies designed to mitigate the heat island effect. In addition to the potential for emissions control programs to yield co-benefits in the form of reduced waste heat emissions, a direct cooling of the ambient air through vegetation and albedo enhancement carries benefits for reduced energy consumption in the summer (Akbari and Konpacki, 2005; Akbari et al., 2001). While such strategies may serve to increase energy consumption for winter heating, studies have found the net benefits of reduced cooling for GHG emissions to be greater for mid- to low latitude settings, a geographic region encompassing most large United States cities (Akbari, Konopacki, & Pomerantz, 1999). When implemented extensively throughout a metropolitan region, such approaches have been shown to reduce energy consumption by as much as 10 percent, suggesting the potential for emission reductions and surface heat abatement to be managed concurrently (Akbari, Pomerantz, & Taha, 2001) (See Box 2.2).

2.4.2.3 Precipitation

Seto and Shepherd (2009) articulated various pathways by which urbanization can impact the climate system. In particular, they characterize the urban areas as a "*significant forcing function on the weather-climate system because it is a heat source, a poor storage system for water, an impediment to atmospheric motion, and a source of aerosols (e.g., pollutants)*." Table 2.3 (following Seto and Shepherd, 2009) summarizes these process; several recent publications (National Research Council, 2012; Mahmood et al., 2010; Grimmond et al., 2010; Trenberth et al., 2007) provide insight on the current knowledge, physical processes, and implications of urban climate interactions.

While UHIs and urban air pollution are fairly common in the public and scientific vernacular, the "urban rainfall effect" (Shepherd et al., 2010a) is not as common. Yet, the literature conclusively

Table 2.3. Impacts of the weather–climate system (adapted from Shepherd and Seto, 2009).

	Urban land cover	***Urban aerosols***	***Anthropogenic greenhouse gas (GHG) emissions***
Urban heat island and mean surface temperature record	Surface energy budget	Insolation, direct aerosol effect	Radiative warming and feedbacks
Wind flow and turbulence	Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow	Direct and indirect aerosol effects and related dynamic/thermodynamic response, dispersion and transport	Radiative warming and feedbacks
Clouds and precipitation	Surface energy budget, UHI destabilization, UHI meso-circulations, UHI-induced convergence zones	Aerosol indirect effects on cloud-precipitation microphysics, insolation effects	Radiative warming and feedbacks
Land surface hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud-microphysical and precipitation processes	Radiative Warming and Feedbacks
Carbon cycle	Replacement of high net primary productivity (NPP) land with impervious surface	Black carbon aerosols	Radiative warming and feedbacks, fluxes of carbon dioxide
Nitrogen cycle	Combustion, fertilization, sewage release, and runoff	Acid rain, nitrate	Radiative warming and feedback, NOx emissions

confirms that urban land cover and pollution can influence precipitation and alter other components of the hydroclimate (e.g., clouds and surface runoff). Both observational and numerical modeling research have indicated that one or a combination of the following process contribute to urban precipitation effects: (1) atmospheric destabilization related to the heat island and thermal mixing; (2) enhanced convergence and disaggregation from building-induced mechanical turbulence and mixing; (3) modified dynamic and microphysical processes related to urban aerosols; and (4) bifurcation-physical modification because of physical or thermodynamic barriers (e.g., thermal energy balances emanating from the urban landscape) (Bornstein and Lin, 2000; Shepherd et al., 2010b). Research must continue to extract the relative contributions of these processes while considering other factors like topography, urban geometry, seasonality, diurnal effects, and moisture. Historical perspectives, global confirmation of urban precipitation effects, and societal implications are discussed in Shepherd, 2005, 2006; Hand and Shepherd, 2009; Ashley et al., 2011; Shepherd et al., 2011; Niyogi et al., 2011; and Shepherd et al., 2010b). The literature is rich with examples, but a two are highlighted in Boxes 2.3 and 2.4.

Ashley et al. (2011) conducted a climatological synthesis of how the urban environment modifies convection in cities in the southeastern United States. They used lightning data and high-resolution radar to study convection over cities and their adjacent control regions over a 10-year period (June-August). Their results confirmed positive urban amplification of thunderstorm activity (both frequency and intensity) for larger cities such as Atlanta. Figure 2.14 illustrates that, for Atlanta, convective frequency counts and occurrences decrease from the higher values in the central business district (city) to relatively lower values in rural areas.

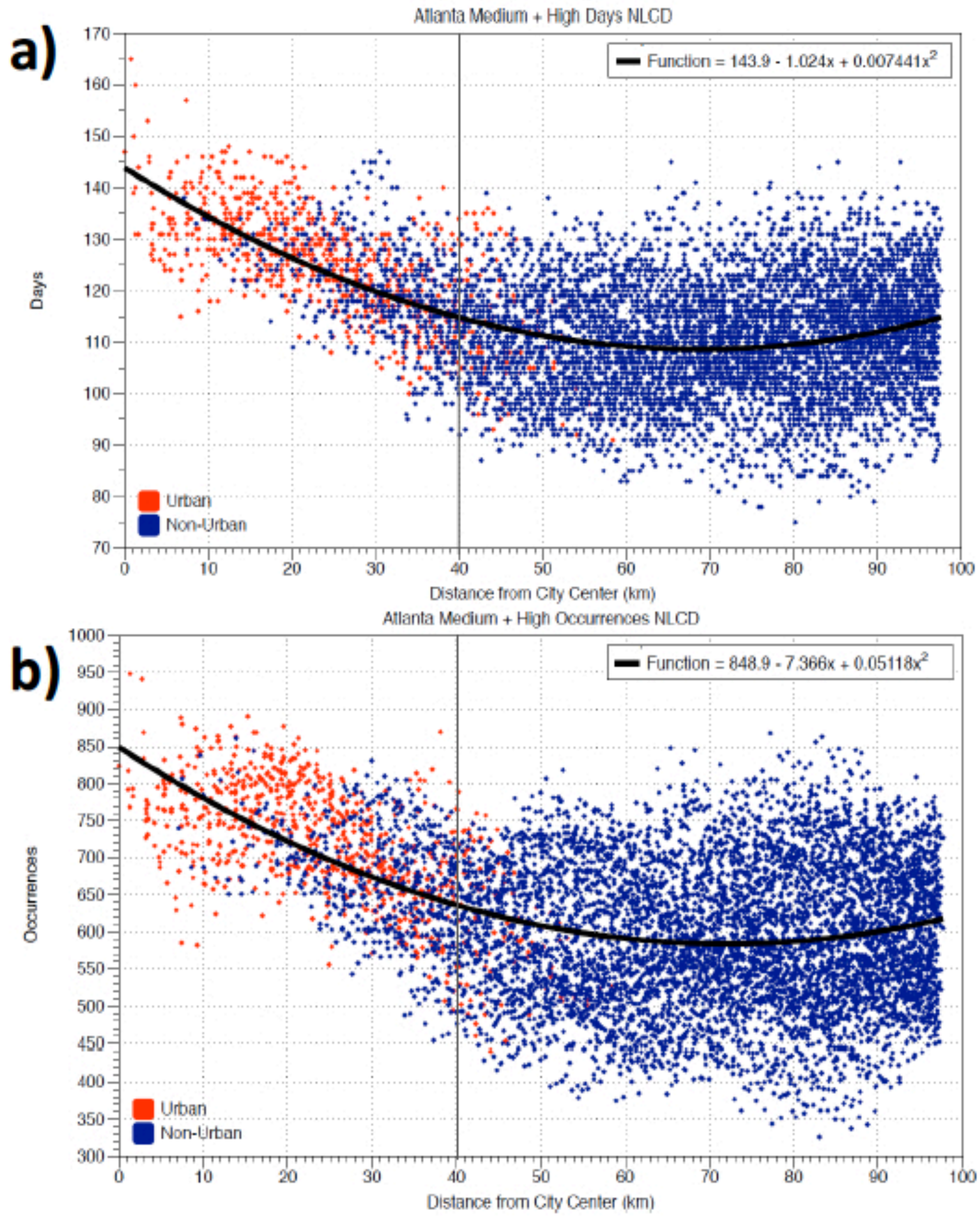


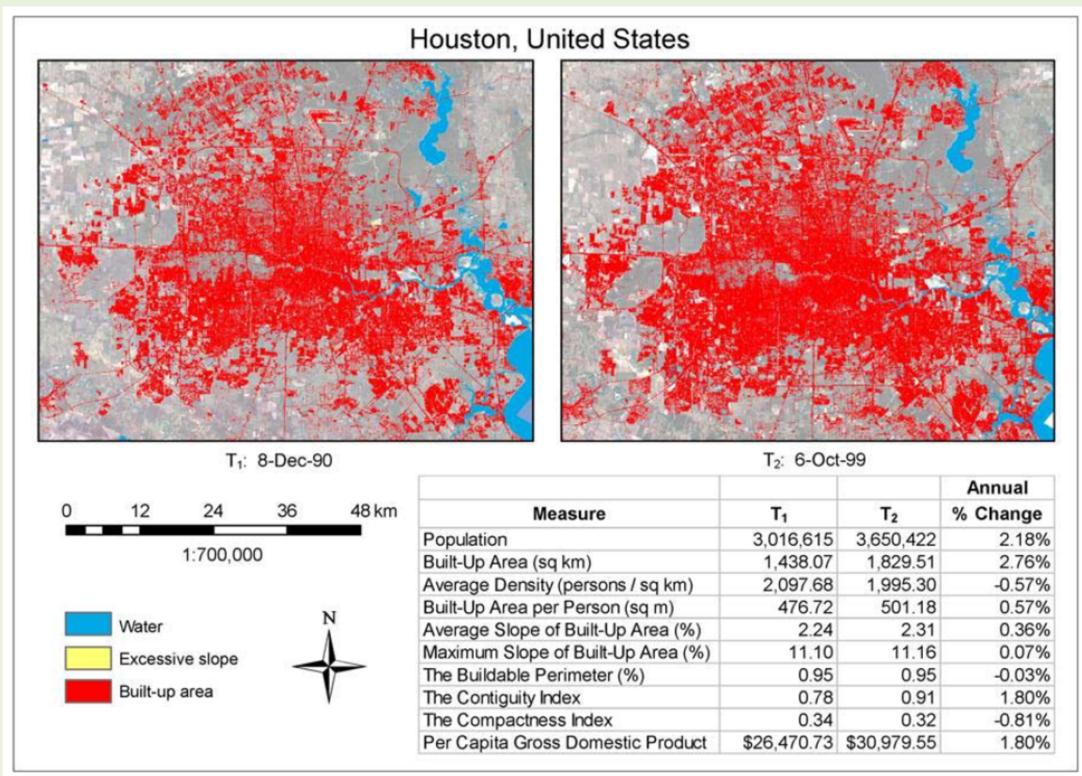
Figure 2.14. Composite radar analysis for Atlanta, Georgia. a. The total number of day ≥ 40 dBZ b. Total number of 5-minute occurrences ≥ 40 dBZ for each 2-km grid cell versus distance from city center in the Atlanta domain for the 10-year, June-August period of record. NLCD urban delineated cells are colored red, whereas non-urban cells are blue. (Figure and caption following Ashley et al. 2011).

On the other hand, Rosenfeld et al. (2008) have discussed the seemingly conflicting role of aerosols in precipitation processes. Aerosols may enhance or suppress convection under certain atmospheric conditions. While research on urban aerosol effects on precipitation has been conducted globally (Lin et al., 2011; Stjern et al., 2011; Jin and Shepherd, 2008), more research is required in the United States.

Box 2.3. The Growth of Houston, TX and its Effect on Precipitation

The trend in urbanization in the United States, especially continued low-density development, is likely to amplify the impacts of the projected increase in numbers, duration, and intensity of heat waves. An early harbinger of these changes can be found in Houston, TX, which has expanded significantly in the past decades (Figure 2.15, and which experienced a 1:10,000 year heat wave during the summer of, 2011 (Berger, 2011), with several successive weeks of temperatures in excess of 95^{o}F (35^{o}C).

Shepherd et al (2010a) projected the growth of Houston, Texas urban land cover to the year 2025, and used the new land cover as a boundary condition for a set of regional modeling studies using current meteorological conditions. Their results illustrated that the regional precipitation climatology of southeastern Texas could be significantly altered, irrespective of greenhouse-gas driven climate changes, by changing the urban land cover and the interactions between the urban areas and sea-breeze circulations (Figure 2.16).



Measure	T_1	T_2	Annual % Change
Population	3,016,615	3,650,422	2.18%
Built-Up Area (sq km)	1,438.07	1,829.51	2.76%
Average Density (persons / sq km)	2,097.68	1,995.30	-0.57%
Built-Up Area per Person (sq m)	476.72	501.18	0.57%
Average Slope of Built-Up Area (%)	2.24	2.31	0.36%
Maximum Slope of Built-Up Area (%)	11.10	11.16	0.07%
The Buildable Perimeter (%)	0.95	0.95	-0.03%
The Contiguity Index	0.78	0.91	1.80%
The Compactness Index	0.34	0.32	-0.81%
Per Capita Gross Domestic Product	$26,470.73	$30,979.55	1.80%

Figure 2.15. Expansion of Houston's Urban Area. Source: Angel et al., 2005, *The Dynamics of Global Urban Expansion*, Washington, DC: World Bank.

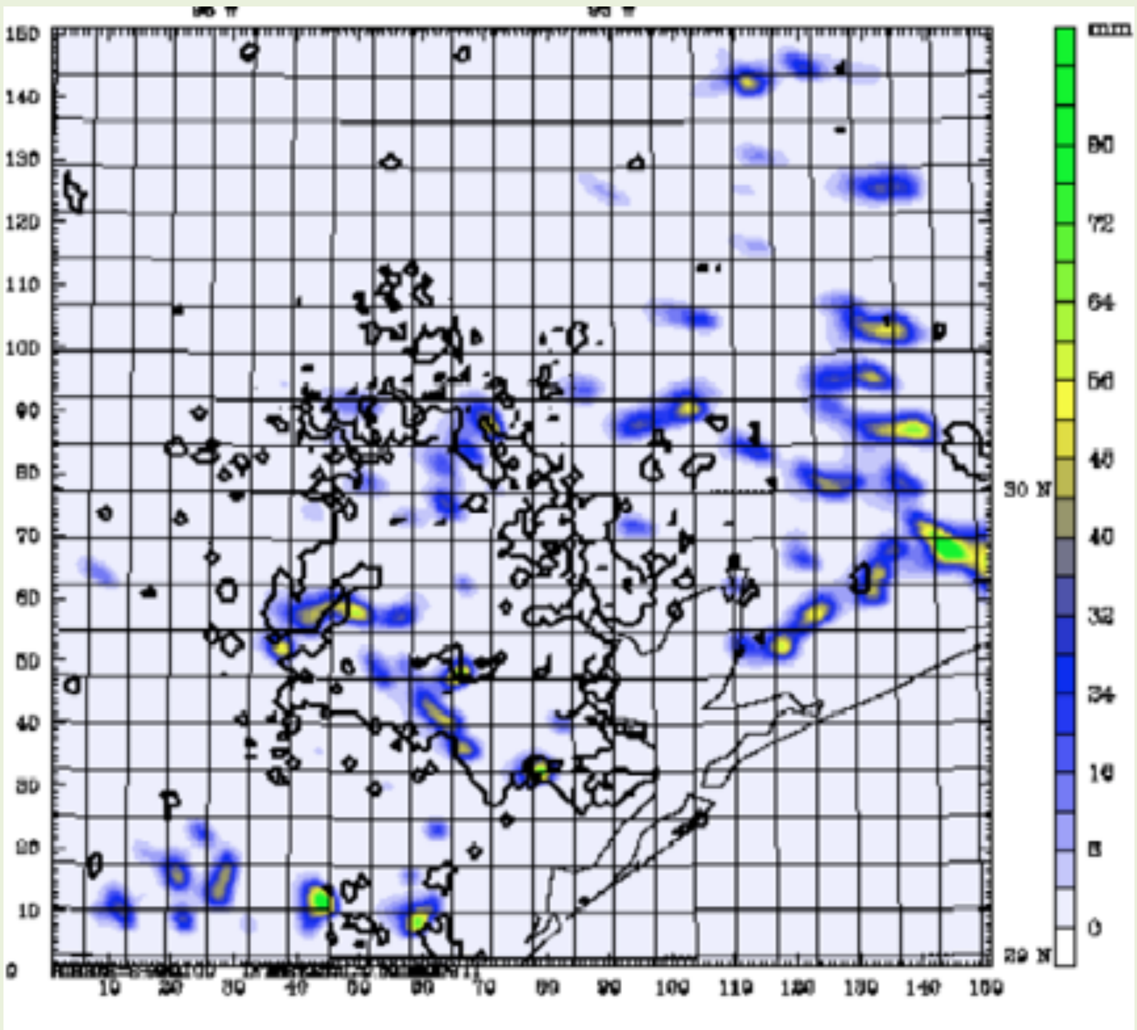


Figure 2.16. Difference (2025 – Current Land Cover) in simulated rainfall amount for a typical case day in Houston, Texas. Black outline represents 2025 urban land cover. Source:

The urban rainfall effect is an important scientific issue but with vital connections to contemporary research and prediction problems in climatology, meteorology, hydrology, and geographic systems. Importantly, precipitation in a built, urban environment is coupled with key societal processes and potential vulnerabilities from urban flooding, with implications for urban planning, public health, water resources, and hazard management.

2.4.2.4 Urban Flooding

Conversion of natural landscapes to built, urban environments changes various water-cycle components including evapotranspiration, surface runoff, infiltration, precipitation, and groundwater recharge (see Box 2.4). In discussing the Atlanta floods, Shepherd et al. (2011) noted that urban impervious surfaces increased the land surface hydrological response in Atlanta in a similar to manner observed in other urban locations:

"*Previous studies have noted the role that the urban environment has on the hydrologic cycle, including runoff, infiltration, evapotranspiration, and precipitation (see Reynolds et al., 2008 for a review). Reynolds et al. (2008) found that impervious surfaces in Houston distributed stormwater to conveyance systems with more volume over a shorter amount of time, which increases the risk of overwhelming the capacity of the system*."

Hydrological modeling systems are useful tools for assessment and prediction of hydrological flows (Poelmans et al., 2010). Urban impervious surface area and morphological parameters are represented in such models using varying degrees of complexity (remote sensing, aerial photography, high-resolution optical imagery, LIDAR; Jacobson, 2011). However, Coon and Reddy (2008) noted that hydrological modeling still suffers from uncertainties related to input precipitation data, calibration errors, assumptions and parameterizations, land-cover classification errors, and catchment-scale transfer errors. Mitigation of such errors will be required as increasingly complex urban landscapes and processes become more explicitly represented in models.

Box 2.4. Increased Flooding Impact on Urban Areas

The IPCC AR4 notes that both the intensity and duration of hydrological extremes, such as flooding and drought episodes, have increased markedly in the last three decades (Trenberth et al., 2007). Analysis by NOAA's National Climatic Data Center (NCDC) suggests that in the southeastern United States, an increasing trend is detectable in the extreme precipitation record (Figure 2.17). The United States and several global regions experienced severe urban flooding. The southeastern United States has experienced some of the most extreme urban flooding in recent years in cities such as Atlanta and Nashville. Further, Seager et al. (2009) commented that the southeastern United States will be increasingly vulnerable to extreme hydroclimatic events because of increasing populations and population density. While many urban floods are explained by large-scale meteorological and hydrological forcing, it is also clear that the urban environment may modify or increase the likelihood of flooding (Shepherd et al., 2001). Ntelekos et al. (2007) suggested that urban land cover and aerosols may have created meteorological pre-conditions for a flood event in the Baltimore–Washington area. Shepherd et al. (2011) speculated that the urban landscape, through urban-enhanced precipitation, could have explained various regions of enhanced flooding around Atlanta during the historic North Georgia floods of, 2009, even as large-scale hydro-meteorological processes governed the main flooding event (Figure 2.17).

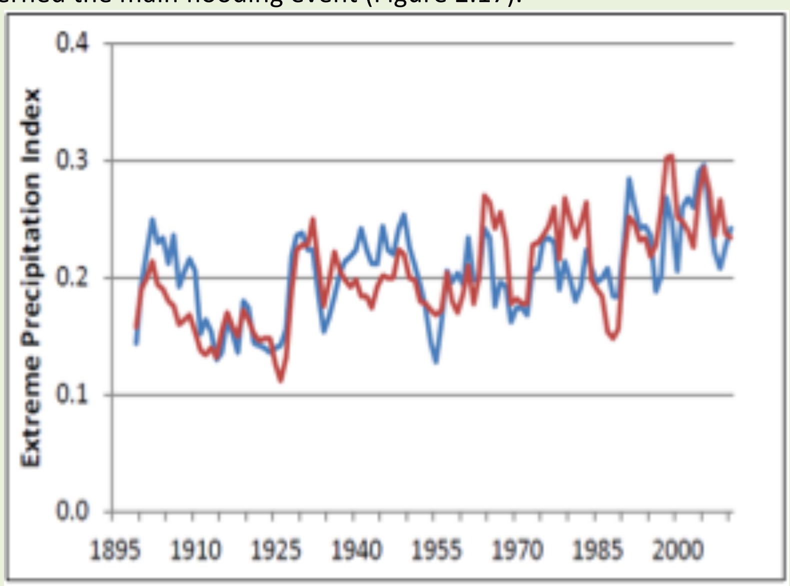


Figure 2.17. Trends in the extreme precipitation index for the southeastern United States. Red line is 1 day, 1 in 5-year event. Blue line is 5-day, 1 in 5-year event. Provided by K. Kunkel (NOAA).

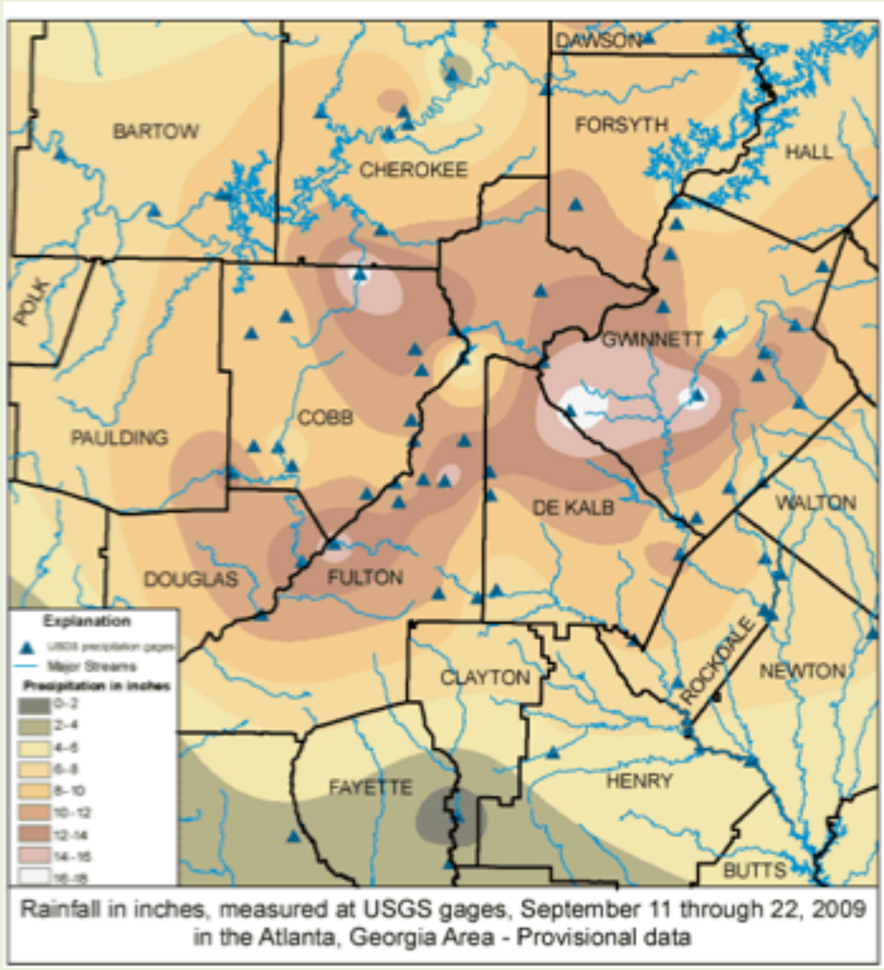


Figure 2.18. Flood totals from the Atlanta floods of 2009. Note the enhanced areas in Gwinnett and Cobb counties (Figure courtesy of USGS).

2.4.2.1 Global Climate Change and Cities

Cities are important components of the complex climate change discussion (Grimm et al., 2008a). Cities are sources for GHG emissions (Grimmond, 2007; Mills, 2007; Satterthwaite, 2008) and can be forcing functions for local climate change (Seto and Shepherd, 2009). Extreme weather and climate events often are associated with unfavorable regional conditions complicated by global climate trends and localized urbanization effects (Hunt et al., 2007). For example, regional-scale heat waves, which may become more frequent, combined with urban temperature anomalies (heat islands) amplify heat-related health issues for urban populations (Zhou and Shepherd, 2009; Stone et al., 2010; Ruddell et al., 2011).

A recent NRC report (2012) is scoping the needs and deficiencies related to urban meteorology. It also addresses important aspects of the "urban" signal and climate. There are several challenges in addressing the two-way interactions between broader global climate change and urban environments. First, meteorological and climate services have routinely attempted to create an unbiased global temperature record by adjusting meteorological records to filter out the

UHI signal (Karl et al., 1988, Peterson, 2003). While possibly mitigating urban biases in the climatological record, this practice also serves to obscure possible real climate signals in urban environments. Studies continue to establish two-way interactions between urban and broader GHG-based climate changes. For example, Stone et al. (2010) noted that large urban regions are warming faster than smaller cities or rural regions. Because of such findings, it is reasonable to question whether mitigation or adaptation strategies are properly designed to address such compounded warming.

Cities are also poorly represented in GCMs, yet it is increasingly apparent that GCM resolutions and the influence of urban footprints (e.g., impervious surfaces and aerosol loads) are converging. Current GCMs are moving forward with efforts to parameterize urban processes (Jin et al., 2007; Oleson et al., 2008; Fruh et al., 2010) and have recently introduced a method to downscale GCM data to urban scales. In their cuboid method, the frequency of air temperature threshold exceedances and urban heat load were simulated using several microscale urban-climate simulations for an array of meteorological regimes and regional models. While this is experimental and only one methodological approach, the intent to downscale climate impacts on urban areas is an emerging and important paradigm (Horton et al., 2011).

Finally, monitoring stations are poorly represented in urban areas, particularly in dense, commercial business districts. Data requirements to study and diagnose the needs of cities are not properly matched with routine observation frameworks. Emerging systems like the Oklahoma City micronet (Basara et al., 2011), a series of observing stations in the downtown area, are promising, but there is clearly a need for quality-controlled urban observations.

2.5 Intrinsic characteristics, contexts, and variability within and among cities of the United States: implications for climate-change impacts and vulnerability

Given the role cities play as drivers of climate change, as microcosms of global change through local environmental change, and as home to over 80 per cent of the United States population, an understanding of the characteristics of cities that contribute to their vulnerability and/or resilience is urgently needed. Characteristics of individual cities include their size, density, age, building materials, urban form, neighborhood cohesion, and cultural history and identity, among others. These characteristics may be emergent, giving a city its unique identity, but also variable within the boundaries of the city. Regional or cross-continental variation among urban areas arises due to geophysical setting and history; thus, eastern coastal cities may share certain characteristics that differ distinctly from inland western cities. Variation at both scales (local and region/continental) has consequences for how climate change will affect urban populations as well as their infrastructure.

2.5.1 Intrinsic characteristics of cities

Many variables in an urban area affect how it will respond to, as well as how it influences, climate change. The density, form, and location of a city all relate to its resilience to weather-related, social, and economic disruptions from climate change.

Table 2.4. Estimates of Greenhouse Gas Reductions from Compact Development Patterns

Estimated reduction	Assumptions	Source
7 to 10%	Assessed the effect of compact development patterns on transportation energy use	Ewing et al., *Growing Cooler: The Evidence on Urban Development and Climate Change*, Urban Land Institute: 2008
9 to 15%	Assessed bundle of land use measures and improved travel options	Cambridge Systematics, Inc., *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions*, Urban Land Institute: 2009
to 11%	Assessed a variety of development scenarios	Transportation Research Board, *Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO_2 Emissions*, Special Report 298, National Research Council of the National Academies: 2009

A more compact urban design with a mix of land uses means that destinations are closer together, and alternate travel modes such as transit, walking, or bicycling are more feasible. The shorter distances and availability of alternate transportation modes allow people to drive less or not at all, reducing GHG emissions and other air pollution. Research suggests that compact development in the United States has the potential to reduce GHG emissions by anywhere from 1 to 15 percent by 2050, depending on the assumptions used and the policies examined (Table 2.4). Compact design also can save people money in an era of unpredictable energy prices; alternate transportation options can reduce expenditures in times of high gas prices, and compact, energy-efficient homes are less costly to heat and cool. For example, a scenario analysis for the statewide Vision California project found that a more compact development scenario could reduce annual vehicle miles traveled statewide by 30 percent by 2050 compared to a business as usual scenario, which would reduce fuel costs. The same analysis found that energy-efficient homes developed in a compact pattern could save California residents $15 billion on energy costs in 2050 (Calthorpe 2011).

In regard to climate adaptation, compact, mixed-used communities offer more places accessible without a car for low-income and/or elderly people to find a refuge during a heat event, a major storm, or other weather-related emergencies. A vibrant mix of land uses, such as a variety of retail, commercial, and live/work spaces, may also prove helpful in making elderly people feel safer about walking the streets and going to a cooling center during a heat wave. A study of the 1995 heat wave in Chicago that killed almost 800 elderly people found "higher-than-average mortality rates in areas where businesses were run-down" (Browning et al., 2006).

Development density also affects the amount of infrastructure a community has to maintain and the new infrastructure it must build (Burchell et al., 2000; Muro and Puentes, 2004). Less dense, dispersed development requires more infrastructure to be built and maintained. This expansion of infrastructure takes away resources needed to maintain infrastructure in older areas. This can reduce the ability of stormwater infrastructure to handle heavy precipitation events (Kessler, 2011). It can also increase the amount of drinking water lost to leaks.

Large lots with lawns use significantly more water per capita than homes on smaller lots. For example, the Envision Utah scenario planning process determined that daily per capita water use is approximately 220 gallons for homes at two units per acre, but 110 gallons for homes at five units per acre, and a study of Seattle-area homes found that homes on a 6,500-square-foot lot use 60 percent less water than homes on 16,000-square-foot lots (EPA, 2006). Nationally, lawn care accounts for about half of household water use, with significant variations by region (Mayer, 1999). As water supplies become constrained or unpredictable, development patterns that encourage small lots, with less water consumed by outdoor uses, will be more sustainable. As discussed in section 2.4.2.2, more compact development could increase the UHI, but this could be mitigated with green infrastructure, including green roofs, street trees, and plantings such as rain gardens that also naturally manage stormwater (Pyke and Andelman, 2007).

The location of development also helps determine its vulnerability to weather events. Building in a floodplain, for example, not only puts the structures in the floodplain at greater risk of inundation, but it also increases the chances that nearby structures not in the floodplain will flood because there is no longer open land to absorb rising waters. Similarly, building in an area that used to be a buffer between developed land and wildlands increases the risk from wildfires for not only the new development, but the nearby existing development as well (Westerling et al., 2009).

Developing compactly makes it easier for communities to keep development out of vulnerable areas like floodplains and the wildland–urban interface interface by directing development to infill rather than expanding into hazardous areas. In areas at risk from wildfire, it can help communities meet the FireWise guidelines. The FireWise Communities program (*www.firewise.org*) recommends that homes in wildfire-prone areas thin out trees within 100 feet of the house to keep tree canopies from touching. If homes are spaced far apart, this would mean cutting down or thinning a substantial amount of the forest. Compact development allows the homes to cluster together and maintain one perimeter, which reduces the number of trees that must be cut.

2.5.2 Variability within cities and implications for vulnerability

A key characteristic of cities is their spatial heterogeneity in relatively compact spaces. Built environments and social composition can vary greatly over small distances, sometimes city block by city block. These distinctive subsets of cities are often expressed as neighborhoods, clusters of people and spaces that reflect and reinforce group identity and social ties (Guest et al. 2006). In American cities, neighborhoods are segmented along many social characteristics, including class, race, ethnicity, sexuality, age, language, religion, and lifestyle (Johnston et al. 2007). These patterns are a function of preferences but also often repeat enduring forces of segregation, discrimination, and constrained opportunities (Massey et al. 2009).

Because cities are physically and socially heterogeneous—consisting of a mosaic of neighborhoods—and environmental risks are often spatially uneven, some groups are more likely than others to be exposed to hazards, including climate-related ones. At the same time, some groups have greater sensitivity to environmental risks and less adaptive capacity to respond to risk than others. For instance, from a physiological point of view, older adults are more sensitive to heat than younger people, which increases their risk of heat-related morbidity and mortality (White-Newsome et al., 2011). Exposure to extreme heat may differ across a city because of amplified temperatures in densely built-up cores (Smargiassi et al., 2009). However, the capacity to adapt to extreme heat is a key factor in reducing morbidity and mortality during heat waves (Kinney et al. 2008). During the 1995 Chicago heat wave, more deaths occurred in the predominantly African-American neighborhood of North Lawndale (40 per 100,000 residents) than the adjacent Hispanic neighborhood of South Lawndale (4 per 100,000 residents) despite similar rates of exposure and built-environment characteristics in the two neighborhoods. One possible explanation was the higher rate of social cohesion in the Hispanic neighborhood, leaving the elderly in that neighborhood less isolated than the elderly in the adjacent North Lawndale neighborhood (Klinenberg, 2002).

Climate change in cities, especially the possibility of increased extreme events such as heat waves, flood, heavy precipitation, and water shortage from acute drought, has the potential to differentially affect different segments of the population based on their exposure (where they live, how they get around), sensitivity (health or safety pre-conditions), and adaptive capacity (including economic wherewithal as well as social aspects). This differential creates environmental justice disparities. Environmental justice research has demonstrated that environmental burdens, such as toxic-release facilities and hazardous waste sites, are unevenly distributed in cities and that neighborhoods of racial/ethnic minorities and lower-income groups are disproportionately burdened with environmental disamenities (Mohai and Saha, 2007; Crowder and Downey, 2010). Environmental benefits, including the relative absence of burdens as well as good access to amenities such as parks and open space, have also been an object of inquiry in environmental justice research (Cutts et al., 2009; Pincetl, 2010). In the case of Los Angeles, Latino and African-American neighborhoods are 'park poor,' that is with low walking access (<= 400 meters) to relative few and smaller parks (Wolch et al 2005). For Baltimore, African Americans have greater walking access to parks but compete with more people for less acreage than parks in primarily white neighborhoods (Boone et al, 2009). In addition to health benefits from opportunities to exercise (Giles-Corti et al., 2005), parks and other open spaces, depending on configuration and vegetation, provide local cooling oases (Harlan et al. 2006, Jenerette et al. 2011). A meta-analysis of 47 cities from the around the world found that urban parks are on average 0.94°C cooler than surrounding non-green areas (Bowler et al., 2010).

Rather than focusing solely on the distribution of risk, scholars who study environmental justice have developed a fairness framework that also examines distributional and procedural equity (Schlosberg, 2007). This framework evaluates the fairness of procedures, such as opportunities for public hearings or application of environmental laws. Climate justice focuses on the inequities of uneven consequences of climate change, including who benefits and who loses. In a case study of the sister cities of El Paso, Texas and Ciudad Juarez, Chihuahua, people living in lower social class neighborhoods on both sides of the border were disproportionately exposed to extreme heat, and peak ozone, and were more likely to live in flood zones (Grineski et al., 2012). Since climate change is likely to exacerbate heat, ozone, and flooding in this region, the disproportionate impacts are likely to increase for these vulnerable populations.

2.5.3 Interactions between urban demographic characteristics and climate impacts

Changes in population distribution and particularly urbanization over the past decades have changed the overall risk profile of the United States, as more people move into areas subject to hurricanes and droughts. For example, the top five fastest-growing metropolitan areas include Palm Coast and Cape Coral-Fort, FL, and Raleigh-Cary NC, all of which are at significant risk of major hurricanes, and St. George, UT, and Los Vegas, NV, which are at risk of drought (Table 2.5). Since the intensity of hurricanes is expected to increase under a changing climate, and the Southwest is expected to see a progressive drying, the fact that these metro areas all saw in excess of 40 percent growth over the last decade is a major cause for concern (Black et al., 2011). The New Orleans, LA metropolitan area grew by 4.1 percent during the 1990s, but experienced the greatest percentage point decline of any metropolitan area (-11.3 percent) during the past decade, when in the aftermath of Hurricane Katrina many people who were temporarily displaced never returned.

Table 2.5. Metropolitan Areas with the Fastest Rates of Growth. Source: PRB, 2011.

Metropolitan area	2010 Population (thousands)	Change, 2000 – 2010: Number (thousands)	Change, 2000 – 2010: Percentage
Fastest rate of growth			
Palm Coast, FL	96	46	92.0
St. George, UT	138	48	52.9
Las Vegas–Paradise, NV	1,951	576	41.8
Raleigh-Cary, NC	1,130	333	41.8
Cape Coral–Fort Myers, FL	619	178	40.3
Fastest rate of decline			
New Orleans–Metairie–Kenner, LA	1.168	–149	–11.3

Another interaction of climate impacts and urban demography is the increase in fire incidences at the urban–wildland interface. Climatic changes in the western United States have led to more frequent and longer duration forest fires (Westerling et al. 2006). Land-use decisions that permit housing in fire-prone areas have led to higher exposure of people to risks exacerbated by a changing climate. For example, the fire in West Texas of the summer/fall of 2011 destroyed several hundred houses in rapidly suburbanizing Bastrop County, near Austin, where growth has quadrupled since 1970 (Revkin.com, 2011). Over all, between November 2010 and November 2011 nearly 4 million acres of land in the county were burned and nearly 3,000 homes were lost. Agricultural and grazing lands were severely damaged (Incident Information System, 2011). Southern California, with extensive public lands interspersed with inholding and adjacent private areas, has also experienced dramatic fires at the urban wildland interface with serious housing loses (Pincetl et al., 2007).

One of the most consistent findings in comparative research on UHI gradients across countries is that cities with larger populations and that cover larger geographic areas tend to have higher UHIs (Kuttler, 2008). Imhoff et al. (2010) found that impervious surface area explains 70 percent of the variance in land surface temperatures. A longitudinal study of Washington DC (Cheung, 2002) found that from 1951 to 2001 the number of degree days above 35^{o}C increased substantially, a period during which the metropolitan area rapidly expanded. Thus, the trend in urbanization in the United States, especially continued low-density development, is likely to amplify the impacts of the projected increase in numbers, duration, and intensity of heat waves (see Box 2.3).

The concentration of foreign-born populations in coastal cities has additional impacts on vulnerability. Communications and early-warning systems prior to a disaster may be less effective and reconstruction and post-disaster assistance may be less accessible for these populations. The Hazards and Vulnerability Research Institute (undated) includes race and ethnicity in the Social Vulnerability Index (SoVI), indicating that "these factors impose language and cultural barriers and affect access to post-disaster funding and occupation of high-hazard areas."

2.5.4 Urban demographic consequences for the energy use–climate nexus

Energy use is intimately tied to a changing climate. For example, increases in energy use are to be expected to cool public spaces and homes in summer while higher winter temperatures will *reduce* energy use for heating. Studies on interactions among demographic factors and energy use have found that it is more appropriate to use the household rather than individuals as the unit of analysis because a large portion of energy consumption related to space conditioning (heating and air conditioning), transportation, and appliance use is shared by household members (de Sherbinin et al. 2007). This sharing results in significant economies of scale, with large households generally showing lower per capita energy use than small ones. For example, O'Neill and Chen (2002) drew on household survey data to quantify the influence of household size, age, and composition on residential and transportation energy use in the United States and found that declines in household size caused 14 percent of the increase in per capita energy use over the past several decades. In the year 2000, average household sizes were larger in urban areas compared to rural areas, at approximately 3.5 persons versus 2.4 persons in rural areas (CIESIN 2006). Thus, larger household sizes in United States urban areas actually serve to reduce per capita energy use.

Energy use is correlated to land use, building type and location, as well as building age. Buildings account for approximately 40 per cent of domestic energy use (DOE, 2008). Energy use by residential building type type is better documented than for commercial buildings. According to the 2005 Residential Energy Consumption Survey, about 80 per cent of residential energy consumption is by single-family homes, while 15 per cent is by multiple family units and the remainder by mobile homes. Most residential energy goes to space heating, thus smaller units and multiple family buildings that share walls tend to require less heating and cooling than single-family, detached homes, which again speaks to the climate benefits of characteristically urban residential arrangements. Location and transportation are also significant factors linking energy use to residential location (Jonathan Rose Companies, 2011).

The building boom at the turn of the 21st century in places like California, Arizona and Florida led to increased demand for energy and water supplies, even after economic decline set in. The embedded energy in the construction materials for new housing, roads, commercial centers and institutional buildings such as schools, hospitals and administrative offices for such expansion in built area can be substantial, but is largely undocumented. Such development patterns have impacts on fuel consumption through longer commuting distances, lack of public transportation options, and the embedded energy required to build out and pave larger areas (Nelson and Lang, 2011; Kennedy at al., 2009; Norman et al., 2006).

2.5.5 Consequences of Climate Impacts for Urban Supply Systems

Beyond causing direct impacts on populations, there will be significant climate change effects on supply systems for water and potentially energy, should hydropower systems be affected by reduced runoff. In the Southwest, warmer weather will reduce snowpack and disrupt water supplies originating from the Sierra Nevada Mountains and the Rockies for the region's large and rapidly growing urban areas (MacDonald, 2007). Not only is there likely to be less water to transfer to population centers, but the ability of the dams on the Colorado River, for example, to supply electricity will be greatly diminished as the levels of water drop to below the intake level for producing hydroelectricity. This may also affect agricultural productivity in southwestern growing regions, as there will be greater competition for water resources between urban areas and agriculture (Cooley et al., 2010). For example, there has already been a significant water transfer from California's Imperial Valley – the winter salad basket of the nation – to San Diego County's urban area (Pincetl and Katz, 2007).

2.6 Risk and opportunity for adaptation, mitigation, and transformation

As cities are complex entities, the potential impacts of climate change on urbanization are also multifaceted, with affects that range from fine (e.g., local) to broad (e.g., extra-regional or perhaps even global) in scope. As Figures 2.3 and Figures 2.4 and 2.5 suggest, any perturbation on the urban ecosystem has effects that ripple through its entirety as a cascading series of events. Depending upon the magnitude of the stressor or 'pulse' events precipitated by climate change, the resulting impacts could surpass a series of thresholds, or a synergistic or total threshold, wherein vulnerability of the ecosystem is seriously threatened. Moreover, climatic change could impact specific aspects of the urban ecosystem and not others. For example, an increase in sustained heat events would augment the development and persistence of the UHI effect, which in turn, would have deleterious effects on human heat stress morbidity and mortality. Impacts on the natural ecosystem however, may only be minor depending upon the sensitivity and exposure of its components within the overall the urban ecosystem (e.g., if precipitation is normal even though there is a persistent heat event, there will be sufficient evapotranspiration to sustain natural vegetation). Hence, the resiliency and adaptability of the human and natural constituent parts of the collective urban ecosystem are of key importance. But, the outcomes of climate change can significantly be mollified or mitigated by adaptation measures that diminish the impacts on the entire urban ecosystem, and by retaining the resilience of the 'captial' on which the ecosystem is founded. Additionally, the ability of an ecosystem component to be transformed, yet still be functional and sustainable, is also critical in how resilient and adaptable they are to the impacts of climate change.

Perhaps the most essential message of this chapter is that although cities and their supporting human, biophysical, atmospheric, hydrologic, and socioeconomic individual components are subject to climate change impacts, assessing what adaptation measures can be taken to sustain these separate components, will ultimately make the entire ecosystem more resilient and adaptable. Therefore, although it is paramount that we look at the 'grand scale' of climate change impacts to the entire urban ecosystem, this is in many ways a myopic perspective, equivalent to 'missing' the 'trees' from the 'forest". Because of the complexity of the city and its supporting ecosystems, we must really operate at a component-by-component level to assess what kinds of adaptability measures are needed to make the individual systems sustainable and resilient. Here it is both good stewardship of the resources that comprise the subcomponents of these individual ecosystems, and an understanding of what adaptation measures work best from a cost-benefit purview that matter most. This will govern the success of how transitions and transformations are implemented and what their resulting outcomes will be. The success of achieving adaptability and resilience is really dependent, however, on a penultimate step: that of research and education and in understanding how the components of the urban ecosystem operate individually and synergistically. Investigation of climate impacts on separate aspects of the overall ecosystem will inevitably lead to findings that elucidate potential and real responses to adaptation and resilience measures predicated on scientific understanding. The critically important next step – that of 'following through" – is in how these scientific results are translated into educating policy and decision makers, urban planners, and most importantly, the general public, so they can be implanted effectively, efficiently, and with the desired outcomes.

Urban jurisdictions are increasingly affected by the complex hydrometeorological–urban interactions brought about by global climate change, and must develop appropriate strategies to deal with these impacts. As an example, scholars and stakeholders are increasingly questioning whether stormwater management, drainage systems, and urban planning have properly considered shifting precipitation regimes (intensity and/or frequency) associated with urban and GHG-driven hydroclimate changes coupled with expanding areas of impervious surfaces (Burian et al., 2004). Assessments such as the NPCC (2011) have warned that current urban flood assessment is based on hydroclimate stationarity assumptions and outdated assumptions concerning rainfall intensity and frequency. Intensity, duration, and frequency tools and methodologies must be updated to account for non-stationarity and new understanding of local-to-regional hydrometeorological forcing.

As constructed social-ecological systems, cities incorporate large investments of energy and materials in their infrastructure. Once developed, urban their morphology is costly and difficult to change; beyond physical challenges, private property rights and economic investment reinforce historically sucessful development patterns. Realizing the opportunities for redesign of cities by looking at the urban fabric as a coupled socio-ecological system may provide decentralized and locally appropriate solutions to the challenges of a changing climate. These might include opportunities for distributed energy generation, urban agriculture, stormwater infiltration, small-scale gray-water systems, and infill building using locally available resources. Awareness of ecosystems services can support a new paradigm for urban infrastructure design.

Applying a coupled socio-ecological lens to urban systems reveals the suite of natural processes that occur, but which may be neither recognized nor utilized, and which, if used, could reduce climate impacts and foster greater resilience and adaptation in the face of climate change. Understanding locally available resources may enhance the ability of urban systems to adapt to system shocks as globalization burdens these systems with an increased reliance on extensive and vulnerable supply chains. Governance structures will need to integrate ecosystem-based management practices into urban administrations to accommodate local resource use.

A new paradigm for urban planning that uses the socio-ecological framework may be useful for dealing with the impacts of climate change. Twentieth-century cities have been engineered for economic efficiency while creating infrastructure that has, by and large, treated natural processes as potential health hazards. For example, drainage systems treat stormwater as a waste product rather than a resource. With potential increases in storms and flooding from climate change, treating stormwater as a resource may be a challenge. Urban regions are projected to experience increasing risks of both flood and droughts. Treating urban areas as social-ecological systems provides opportunities for adapting urban systems to take advantage of place-based resources and opportunities, potentially enhancing resilience.

In summary, the organizational principles of complex adaptive systems and socio-ecological (-built) systems theories provide a conceptual underpinning to understand the dynamic functioning of urban systems in the context of climate change. Coordinated development of tools and procedures with these concepts in mind, modular for different sectors, and compatible for different urban areas, would facilitate a more comprehensive assessment for urban vulnerability in the United States.

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[i] In this chapter, we will use the terms "cities" and "urban areas" interchangeably. For more information on official definitions of "urban" see endnote 2. Metropolitan regions are officially defined by "Metropolitan Statistical Areas" (MSA), but here we refer to them more generally as urbanized areas, including urban cores, suburbs, and exurbs linked by transportation and other service networks.

[ii] The definition of what constitutes "urban" according to the US Census Bureau has evolved over time. For example, the Census Bureau's 1990 definition included populations residing in urbanized areas or in places of 2,500 or more persons outside urbanized areas. By the, 2000 census, the definition had evolved to take into account multiple criteria such as population density, though the lower-end threshold for a Census Designated Place of 2,500

population remained. The *Federal Register* for August 24, 2011 contains a complete history of the designation of urban areas, noting that “The revisions over the years reflect the Census Bureau’s desire to improve the classification of urban and rural territory to take advantage of newly available data, as well as advancements in geographic information processing technology.”

3 Urban Systems and Services

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Introduction

Cities face real and significant climate risks today, even without climate change. Heat waves, coastal storms, torrential downpours, tornados, droughts, high winds, snow, and ice cause billions of dollars of damage a year in the U.S., impacting urban, suburban, and rural communities. Since 1980, 114 individual climate events have occurred in the U.S. with damages exceeding $1 billion (Lott 2012). For example, flooding along the Mississippi River in the spring of 2011 caused $320 million in damage to Memphis, Tennessee alone and severe weather in October 2010 caused over $2 billion in damages in Phoenix and surrounding cities (Lott 2012). These risks and their impacts on cities' critical sectors and services will increase as the climate changes, shifting the environmental baseline for which cities were designed and increasing the intensity and frequency of extreme events.

Understanding and addressing climate risks in cities has become increasingly important as the number and percent of U.S. residents living in urban areas has risen over the past 50 years. In 1950, approximately 60 percent of the country's population lived in urban areas; in 2000, this increased to 79 percent (U.S. Census 2000). According to the U.S. Census, almost 60 percent of the U.S. population lived in cities with over 200,000 residents in 2000 (U.S. Census 2000). In addition, cities are a vital driver of the national and international economy. In 2006, the top 20 cities in the U.S. in terms of GDP represented nearly 43 percent of the national GDP ($5.6 trillion of total U.S. GDP of $13 trillion) (vom Hove 2012). In 2007 more than 20 percent of global GDP was generated by 190 North American cities (Dobbs 2011).

This chapter provides a broad overview of the potential impacts, vulnerabilities, and adaptations related to climate change for major urban sectors and services. These sectors and services include energy, transportation, telecommunications, water (including drinking, storm, and waste water), public health, and ecosystems. It is not intended to be an exhaustive list of the impacts, vulnerabilities and adaptations related to climate change and cities, but seeks to illustrate the enormous scope and complexity of the challenges cities face from climate change. While food production is not included in this discussion, cities will be increasingly affected by climate events that impact agriculture in urban areas, surrounding regions, and international markets that serve urban populations. In addition, the transportation sector, which is responsible for conveying food to (and to a lesser degree from) urban areas, will also be impacted by climate change, potentially harming cities' ability to reliably access food.

While not an urban sector or service, this chapter also highlights the climate risks experienced in coastal zones given the elevated vulnerability faced by cities along the coast by sea level rise and coastal storms and the high percentage of urban population that live in coastal cities and the vital services that support them. Fourteen of 20 largest cities and 19 of the 20 most densely populated counties in the U.S. are on the coast (Beach 2002) and in 1999, approximately 55-60 percent of Americans lived in the 772 counties adjacent to the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes (Hinrichsen 1999).

Several factors pose challenges as cities attempt to adapt their critical sectors and services to climate change. Cities are linked to their surrounding regions through economic, political, and infrastructural connections. As a result, many potential adaptation strategies, such as holistic infrastructure system upgrades, need to occur on a regional scale—well beyond the political and fiscal control of city governments—to effectively reduce risks to urban areas. Cities often lack the funds needed to maintain the state of good repair of their existing infrastructure, much less upgrade their systems to be more resilient to climate change or build new infrastructure. The U.S. Environmental Protection Agency estimated that publicly owned and not-for-profit non-community water systems in the U.S. will need to invest $276.8 billion by 2023 to upgrade or replace aging infrastructure (National Academies of Science 2008). This cost does not include actions needed to mitigate risks posed by climate change.

Another challenge for cities is that municipal governments often do not own, operate, or regulate large amounts of the critical infrastructure found in urban areas. When New York City convened infrastructure operators and regulators in 2008 to identify climate risks to the city's critical infrastructure and develop coordinated adaptation strategies to reduce the city's vulnerabilities, 15 of the 40 members of the City's Climate Change Adaptation Task Force were private companies and only 12 were City agencies, reflecting the fact that New York City does not own or operate its energy generation or transmission infrastructure, telecommunication networks, or mass transit and rail freight systems. Infrastructure sectors are also increasingly dependent on and interdependent within one another, which can magnify the consequences of a failure of a given type of infrastructure (Zimmerman and Faris 2010). As articulated by Zimmerman and

Faris, these interdependencies and dependencies can be geographic or spatial, or functional and can occur between infrastructures as well as within them.

Despite these challenges, municipal governments have taken concrete actions to address climate change. A key reason for this is that cities do have control of many of the policy levers that can reduce climate risks. In most cities, local zoning determines what kinds of buildings can be built where; local building codes determine how buildings are designed; local governments have primary responsibility for providing emergency services in response to potentially climate-change-exacerbated situations such as flooding and heat waves; and local governments or authorities generally own and operate the water systems that are among the most important systems to be considered in climate change adaptation planning. A recent report by Arup in partnership with the C40 Climate Leadership Group that analyzed climate actions in megacities across the globe found that cities that are members of the C40 have implemented 452 actions related to climate adaptation and have considerable authority to set policies and regulations over land use, storm water management, wastewater treatment, water supply, and parks and green spaces (Aggarwala 2011). This demonstrates the need for and capacity, and willingness of municipal governments to recognize and respond to the risks posed by climate change.

3.1 Transportation

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3.1.1 3.1.1. Context

The urban context is defined by relatively large populations and high population density as compared to rural and ex-urban areas. These factors lead to differences in the amount, nature and utilization of transportation services. With more people comes a higher demand for services which in turn results in high concentrations of transportation infrastructure – including roads, bridges, rail, ports and airports, as well as related infrastructure. The nature of the services provided is also different in urban areas. While 98 percent of demand for surface transportation services is met by the personal automobile in the U.S. (calculated from Dunn, et al., 2010), a much larger proportion is met by higher occupancy services in urban areas, especially bus and rail transit. The Washington Metro, for example, carries about 21 percent of commuter travel in the Washington D.C. area (MWCOG 2011). Even greater percentages are carried in other cities. There is also a great demand for walking and biking paths toward improving not only the livability of urban areas but the sustainability of transportation services, as well. In urban areas, modes of travel are integrated in an interdependent system. Many coastal cities also rely on public- and privately-operated ferry services to augment mass transit systems. Travel beyond cities is supported by air and passenger and freight rail service, which is generally operated by entities outside of municipal jurisdictions. Finally, travel demand frequently outstrips available infrastructure and services in urban areas, resulting in road congestion and crowding on transit services.

Travel of all kinds is on the rise. Road-dependent travel is increasingly reflected in the steady rise in vehicle miles of travel since the 1960s and slowed down in the latter part of the 2000s (U.S. DOT, FHWA 2011) and the increased popularity of biking. Rail-dependent travel is also on the rise reflected in increasing and record levels of transit ridership (APTA 2011, p. 10). The growing congestion on these road and rail systems produces even more stress on increasing demand. People are dependent on road and rail networks for rapid egress in emergencies. The proximity of roads and rail to areas that are subject to coastal and inland flooding from rising sea levels and storms and their increasing fragility due to rising temperatures put these travel activities and needs at risk.

3.1.2 Key Impacts

The key climate drivers that are expected to have important impacts on urban transportation systems are sea level rise, increases in heat spells and heavy downpours, and intensification of tropical storms. Table 3.1.1 below summarizes the key climate change effects and their potential impacts on transportation infrastructure.

3.1.2.1 Sea level rise

Seas have been rising at a rate of about 3 mm per year in recent decades, and the rate may be accelerating. Local conditions, such as land subsidence or uplift, can exacerbate or mitigate rising seas. Some areas, like the Gulf Coast where the land is sinking have already experienced a significant change, an increase of eight inches in mean sea level in the period from 1958 to 2006. By the end of the century, increases in sea level could reach three to four feet (Karl et al., 2009) and result in widespread inundation of transportation infrastructure in coastal urban areas.

3.1.2.2 Heat

More and better information is becoming available about increases in heat waves. Average temperatures are rising nearly everywhere in the U.S. and future temperatures could go up by as much as 11.5 degrees F. With increasing average temperatures, both the extreme high temperatures and the distribution of high temperatures are likely to shift. Extreme high temperatures will go up, as will the number of high heat days over the course of a year. Parts of Texas, Arizona and Southern California could see as much as 120 days over 100 degrees (Karl et al., 2009). Periods of high heat could cause more rapid material failures, more frequent equipment breakdowns, work and construction stoppages which will have an impact on transportation services.

3.1.2.3 Precipitation

Climate models disagree on trends in average precipitation for some U.S. locations in certain seasons, making future projections difficult to employ with confidence. More importantly for urban transportation infrastructure is that precipitation has increasingly fallen in heavier downpours, overwhelming drainage systems and disrupting transportation services. The incidence of the heaviest 1 percent of daily precipitation events has increased by 67 percent in the heavily-populated Northeast between 1958 and 2007, and 9 percent in the arid Southwest (Karl et al., 2009). All regions of the country demonstrate this trend.

3.1.2.4 Storm intensity

The intensity of tropical storms is of particular interest to the eastern and gulf coasts of the U.S. Cities located here are subject to high winds, storm surge, and debris that can cause severe damage to transportation infrastructure. The intensity of tropical storms is anticipated to increase. While the number of storms may remain unchanged, wind speeds and the height of storms surges is expected to increase thus raising the potential for damage.

Table 3.1.1. Selected Impacts of Climate Change on Urban Transportation Infrastructure. Compiled from: CCSP 2008, FTA 2011 and UNCTAD Expert Meeting 2011.

Higher high temperatures, more hot days	• Asphalt deterioration
	• Thermal expansion of bridge joints, paved surfaces
	• Worker safety and customer discomfort

	• More night time work, longer construction season
	• Pavement & structural design changes
	• Rail buckling
Wind speeds	• More frequent sign damage, truck rollovers
	• More frequent bridge closures and damage
	• Need for stronger materials
	• Loss of visibility, lane obstruction
More frequent, intense precipitation	• Increase in weather-related delays, traffic disruption
	• Increased flooding of subway tunnels, roads, bus lots, evacuation routes
	• Increased bridge scour rates
	• Undermine road, rail base
	• Increased storm surge and wave impacts on roads, bridge structures, signs, etc.
	• Increased delays in air travel
Sea level rise	• Permanent inundation of subways, airports, roads, ports and maintenance facilities
	• Decreased expected lifetime of highways exposed to surge
	• Damage to infrastructure caused by the loss of coastal wetlands and barrier islands
	• Erosion of land supporting coastal infrastructure
	• Reduced route options for passenger and freight travel
	• Erosion of road, rail base
	• Reduced clearance under bridges
	• Amplification of storm surges magnifying impacts

Many of these effects on the physical infrastructure translate into effects on users in terms of increased cost, delays, inconvenience, and even compromising safety.

3.1.3 Key Vulnerabilities and Risks

With relatively large populations and high densities, vulnerabilities to climate impacts are likely to be magnified in urban settings. The sheer numbers of people and quantities of goods moving into, out of and through cities will make the impacts of climate change worse in urban areas. Beyond the direct impacts on travel, the secondary economic impacts will also be enhanced by these quantities, and by the critical nature of many of the transportation services provided by cities to the regions in which they reside. Urban areas serve as important portals for larger areas of the country through their ports and airports. On the positive side, urban areas have more resources to bring to bear than many other parts of the country and numerous redundant transportation services that can ameliorate some of the worst impacts, but there is no way to avoid the relatively important effects that climate change can have on urban transportation.

Beyond economic impacts, urban areas are home to important subpopulations that may be disproportionately affected by service disruptions. Low income populations, people with disabilities and the senior citizens typically have fewer resources compared to the population at large to address daily stressors including those from climate change. They are more dependent on transit services and disruptions to those services leave them with fewer options (FTA 2011) to meet their travel needs to their jobs, health care, and other daily activities.

Cities and transportation agencies are increasingly studying the vulnerabilities of their networks toward making them as resilient as possible. While the study of impacts and adaptation has just begun and will need to be an ongoing process, major efforts on transportation vulnerabilities have been undertaken in several major cities, including New York, San Francisco, Boston, Seattle, Chicago, Houston and New Orleans.

Severe weather events occur today disrupting transportation services in ways that are a harbinger of the vulnerabilities of urban transportation systems under a changing climate.

In 2007, extreme rainfall completely closed 19 major sections of track in the New York City subway system that affected two million riders (FTA 2011). Mississippi river flooding in 1993 paralyzed surface transportations in St. Louis, Kansas City and as far north as Chicago. A second record-breaking flood happened just 15 years later in 2008 disrupted east-west traffic and flooded 9 square miles of Cedar Rapids, IA (Karl et al., 2009). In 2010, flooding of the Cumberland River devastated the city of Nashville, including its transportation system, flooding its bus lots, maintenance facility and administrative buildings. Heat waves along the East Coast of the U.S. caused subway rails to buckle in Washington D.C. and Boston (FTA 2011). Flight schedules are regularly disrupted over Chicago and Dallas due to severe summer storms. Finally Hurricanes Katrina and Rita devastated all modes of transportation, as well as the cities of Houston, Galveston, New Orleans, and Mobile in 2005 (CCSP 2008).

Notable progress has been made in several urban settings in understanding the vulnerabilities of the transportation system from sea level rise. Sea level rise has been studied along the coasts. San Francisco has an observed sea level rise of about 7.5 inches per century. Consistent with guidance from the State of California, city agencies have estimated the impacts of additional increases. Widespread flooding at San Francisco International Airport is anticipated with an additional rise of just 16 inches by 2100, and more with an anticipated rise of 55 inches (San Francisco Bay Conservation and Development Commission 2011). Southeastern Florida has also examined the impact of sea level rise. With only a one-foot rise, about 81 miles of roadway from Miami to Palm Beach would be inundated. Sea-level rise in the area between Houston, New Orleans and Mobile is anticipated to experience an increase of two- to four-feet over the next 50 to 100 years. Four-feet of sea level rise will permanently flood more than 2400 miles of major roadway, three-quarters of the ports, and 3 airports, including Armstrong International (CCSP 2008). It is difficult to estimate how much more frequent extreme rainfall events will occur.

Vulnerabilities to heavy downpours have been examined and many city transportation systems already experience flooding. For example, the NY Metropolitan Transportation Authority estimates that 30 subway stations are subject to shut down due to temporary flooding from major storm events (FTA 2011). In this case, precipitation compounds an existing challenge with subterranean systems as the Metropolitan Transportation Authority in New York pumps over 8 million gallons of groundwater out of its subway system every day—without rain. With heavy rains, several negative effects on the transportation system have been noted by Koetse and Rietveld (2009). The incidence of crashes on roadways goes up, and travel times and congestion increase. With heavy rainfalls, the potential for landslides also increases potentially disrupting freight, road and transit service. Kirshen et al. (2006) estimated that aggregate traffic delay in Boston could increase by 80 percent by 2100 due to flooding events.

Heat waves which can cause asphalt to deteriorate more quickly and rail lines to buckle are expected to become more frequent. Excessive heat that currently happens every 20 years could occur as frequently as every two years (Karl et al., 2009). Further they will likely occur even more frequently in urban settings due to the heat island effect. Rail kinks have been reported in many cities, and orders for reduce speed as a precautionary measure are routinely instituted in places like, Portland, Philadelphia and Washington DC. Reduced speeds slow transit times and increase operating costs. A study of the intercity rail system in the United Kingdom indicated that heat-related delays to travelers alone will double to about 23 million pounds per year by the end of the century (Dobney et al. 2010). Excessive heat can also cause communication equipment in underground stations to overheat and impact passengers waiting in stations without air-conditioning, adding to train delays.

In coastal areas, the incidence of tropical storms with high winds and associated storm surge pose significant challenges for transportation infrastructure. The Gulf Coast Study (CCSP 2008) indicated that temporary flooding from a relatively modest 23-foot storm surge hitting the southern Louisiana coast could extend all the way to Baton Rouge. Long term flooding can undermine roadbeds and rail, washing away the ballast on which it rests. Surges leave debris fields which must be cleaned up before service can be restored. It interferes with river traffic, causing vessels to flounder and requiring dredging to maintain depths affecting port operations. If storm intensity increases with warmer ocean waters, these impacts will only worsen absent effective adaptation measures.

Cities, states and transportation agencies are still exploring the full range of potential vulnerabilities to the impacts of climate change. This is but a short list of the most likely impacts. Synergistic and secondary effects that examine the combination of stressors on urban and other areas are just beginning to be studied. Preliminary indications are that the impacts will likely be worse than those indicated here. What is clear is that due to the population density and clustered development in urban areas the value of the infrastructure at risk is very high. San Francisco found that about $62 billion of investment would need to be replaced if sea levels rose by 1.4 meters (San Francisco Bay Conservation and Development Commission 2011). The State of Massachusetts estimates that a sea level rise in Boston of 26 inches could damage investments worth $463 billion. It is critical to note that these estimates do not include the economic value of the services lost to the urban area (Massachusetts 2011).

3.1.4 Adaptations

Adaptation strategies to address heat, sea level rise and inundation, and storm and precipitation extremes encompass the full spectrum of transportation functions including design, construction, operation and maintenance. Mitigation strategies in some cases can meet the needs of or coincide with adaptation. For example, Meyer (2011) emphasizes the need to consider transportation infrastructure components including underlying structure upon which the infrastructure is built and its stability, materials used, design (cross-section) and dimensions, facilities to capture water (drainage) and soil movement, strength (structure) primarily for bridges, and siting. The U.S. DOT FTA (2011, p. 10) underscores the overlap between mitigation and adaptation measures that involve green infrastructure. Longer term actions such as altering development, land use and population distribution can complement adaptation with mitigation advantages in the form of greenhouse gas (GHG) reduction.

Adaptation strategies are generally contextual, that is, tailored to the mode of transportation and type of hazard (Jacob et al. 2011, p. 313), as well as the materials and design elements of each mode, the type and attributes of the impact and its relationship to location, and the relative disruption and cost of immediate vs. long-term measures of relocation of people and the redesign and fortification of infrastructure. The attributes of the impact are critical in designing adaptive mechanisms, and key attributes include magnitude, duration and recurrence of the impact.

The Transportation Research Board (TRB) (June 2011, p. 8) has identified a number of illustrative adaptive measures by the type of hazard and its impact:

- For sea level rise, the TRB includes protective structures such as dikes and levees, the elevation of infrastructure components where possible, movement of transportation to inland locations, and identification of alternative routes for evacuation and ways of operating the infrastructure facilities that seem to require more planning and preparation time.
- For heat, the use of materials that are resistant or resilient to heat and attention to particularly susceptible components such as expansion joints for bridges and rail lines are suggested.
- For increases in storm and hurricane intensity, updating flood delineation maps, hydrologic information, and knowledge of storm frequency are a first step followed by the development of design standards for drainage structures that accurately reflect that

information. Storm retention structures and barriers are considered protective of immediate flooding needs.

The U.S. DOT, FTA (2011, p. 63) categorizes adaptive strategies into those that aim at managing the impact through the provision of ongoing information, designing infrastructure with protective features and stronger materials and structures, and incorporating alternatives or redundancy to improve mobility. The ability to move structures to prevent damage to assets and avoid injury to users may involve a new sense of design of facilities that can easily be deconstructed and reassembled. Relocating vital transportation facilities needed for evacuation in areas of higher elevation and in cooler environments is another strategy (U.S. DOT, FTA 2011, p. 65).

For the management of water impinging upon transportation facilities whether from flooding associated with sea level rise or severe storms, the U.S. DOT, FTA (2011, pp. 65-71) identifies an extensive set of water management strategies that involve movable structures, water withdrawal facilities, and barriers in anticipation of flooding. Jacob et al. (2011, p. 315) emphasize a similar set of measures including barriers, elevation and moving of structures associated with transportation facilities. Others look at innovative approaches to rainwater storage in sewage systems (Dircke, Molenaar and Aerts 2012, p. 315). A wide range of stormwater management and water drainage approaches were also reviewed by Zimmerman and Faris (2011, p. 183) in the context of climate change plans and by Zimmerman (2012 forthcoming).

For adaptation to heat, the U.S. DOT, FTA (2011, pp. 73-75) identified various design elements to enable rail to withstand buckling during heat events such as the use of concrete for ties and redesign of rail connections for more flexible expansion capability. Jacob et al. (2011, p. 315-316) identify a similar set of measures including more heat resistant materials, the improved performance of air conditioning, upgrading various components that are prone to failure in extreme heat, and also, the need to protect electric power resources upon which the cooling systems for transportation depend.

Ultimately, the success of adaptation depends on flexibility to move people and facilities or redesign spaces to avoid climate change consequences, such as rerouting transportation services (Zimmerman and Faris 2010; Zimmerman 2012 forthcoming).

Different adaptation measures will be applicable at different spatial scales (Jacob et al. 2011, p. 313). Therefore, adaptation measures need to be placed in the broader context of land use planning (Zimmerman and Faris 2011, p. 183; Jacob et al. 2011, p. 313). Equally important are the institutional arrangements available to implement such adaptation measures (for New York State applications see Jacob et al. 2011, p. 317-320; Major et al. 2011) and the social and economic benefits and costs that they yield. The distribution of costs and benefits of adaptation measures can result in equity issues (Jacob et al. 2011, p. 313). Adaptation can have many social benefits. For example, increasing the resilience of transportation against global climate change (GCC) effects has the potential of reducing accidents and reinforcing performance and condition requirements for transportation in general. Economic benefits exist as well. For example, while the retrofit and rehabilitation for climate change alone may be prohibitively expensive, timing such improvements with reconstruction timetables may reduce the costs of both adaptation and routine reconstruction. Understanding the conditions that lead to larger consequences for life, health and welfare and incorporating that knowledge into adaptation methods inevitably yield critical social and economic benefits. Flood damage depends on the degree of the warning time, the size and depth of the water area, and the duration of the flood (Aerts et al. 2012, p. 5) and that knowledge and the ability to act on it can contribute to reducing or avoiding the consequences.

3.1.5 Overcoming Barriers and Stimulating Innovation

The long term goal of addressing climate impacts and mainstreaming adaptation planning into the routine activities of transportation planners and decision makers requires that leadership, technical and communication barriers be surmounted. Much is being done already but more is needed.

Leadership is key to demonstrating that integrated assessments can be and should be done and that appropriate adaptation measures will insure more robust transportation service in the future. Many cities and transportation agencies are demonstrating that leadership despite difficult budgetary times. Urban areas like New York and San Francisco are incorporating adaptation planning into their planning and development approaches. The Federal Highway and Federal Transit Administrations have funded pilot programs across the country to examine the impacts of climate change and incorporate adaptation measures to address them. The U.N. Conference on Trade and Development has sponsored expert meetings to share information on climate change and ports between 2009 and 2011.

While individual leaders can be cited, the practice of adaptation planning is not yet widespread in urban areas. Federal leadership is critical toward preparing transportation networks in these population centers and vital gateways for the country. That leadership may take many forms—funding for assessment and/or adaptation activities, access to relevant climate information, technical guidance on conducting integrated assessments, or simply promoting them – but action is necessary to expand the practice.

Technical barriers are also being addressed but remain major hurdles. Transportation agencies are finding ways to address uncertainty in climate modeling and long planning horizons through the use of scenario planning and vulnerability matrices which can provide useful but imprecise information about how to better adapt to future conditions. As climate science evolves, better information is needed to reduce the imprecision in these approaches. In the shorter term, it is critical that transportation decision makers and climate scientists be brought together as they have in New York to better understand the needs of decision makers and the limits of climate data. Forums and other means of information exchange need to be more consistently conducted and widespread. More sophisticated analytical tools and guidance to conduct integrated assessments are needed. New modeling efforts are demonstrating the synergistic impacts of climate effects and other stressors in places like the Gulf Coast, but these are very much at the cutting edge of impact assessment and need to become the state-of-the-practice.

The establishment of communication pathways for climate information and technical assistance is another hurdle that must be overcome. Transportation decision makers must be aware of the availability of the latest and most useful data on a regional, or local, basis. While numerous federal agencies have established services to provide climate information, their efforts so far remain uncoordinated, and the mechanisms to retrieve useful climate data unclear. Decision makers must be able to rely on information services to assist climate assessment, particularly in the planning and development phases of transportation projects. More than $100 billion is invested annually by all levels of government in the U.S. (FHWA 2011). Project developers need to have the latest climate science information at hand when deciding where to locate, how to design, what materials to use, and how to engineer these facilities.

3.2 Energy

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3.2.1 Context

Energy systems are a fundamental and vital form of infrastructure, supporting basic commerce and quality of life needs across the United States. Although energy systems are designed to operate under a range of weather and supply and demand conditions, climate change may stress the system in ways that damage equipment, disrupt critical fuel supply chains, or otherwise exceed current design limits, increasing the risk of breakdown (Hammer et al., 2011). By almost any measure, energy use and the resources to support it have been increasing over the past century.

3.2.2 Key Impacts

Climate change risks will affect both energy supply and energy demand.

Supply impacts are of particular concern because of the long-lived nature of most energy system assets. Power-generating facilities are built to last many decades, while transmission or distribution assets may last even longer. Repairing or replacing these systems can be extremely costly and logistically challenging, particularly in urban areas, because the repair or replacement process can take some time and be highly disruptive. In New York City for example, the city's electricity transmission system consists of over 90,000 miles of underground cables, making wholesale upgrades to the system prohibitively complex and expensive.

Demand-related impacts relate to both heating or cooling demand. On a net basis, climate change may either increase or decrease overall energy use in a specific city or region, depending on the level of climate change-related temperature change, and whether that locale experiences its peak energy demand in the winter or summer.

3.2.2.1 Impacts of rising temperatures

Temperature changes may affect both fossil and renewable-based forms of energy. In the case of fossil fuel stocks, access is the primary consideration, as warmer temperatures may ease harsh weather conditions or ice cover that currently limit access to those resources, such as those found under the polar ice cap. Conversely, in the case of Alaskan oil and gas fields and pipelines constructed on permafrost, warming conditions may force the shutdown of these facilities as the ground becomes less stable (Bull et al., 2007). The effects of these changes on cities will tend to be indirect, as supply chain impacts ripple across regional, national, or global energy markets.

Rising temperatures may cause power lines to sag or fail (Hewer, 2006), while heat waves can force equipment to operate beyond its rated performance capacity, leading to breakdowns. Heat waves in Southern California led to the failure of thousands of transformers in 2006, as the equipment was unable to cool down sufficiently at night before demand spiked again the next morning. More than one million customers around the state eventually lost power (Miller et al., 2008; Vine, 2008). Warmer temperatures may also extend the growing season for plants and trees, increasing the need for tree trimming programs to ensure falling trees or tree limbs do not damage transmission and distribution assets (Hammer et al., 2011).

Climate impacts on the supply of energy available from fossil fuel-fired, nuclear, and biomass-based thermal power plants are generally linked to cooling water requirements and the efficiency of a given facility's generation cycle under changing climate conditions. Cooling water is potentially problematic if drought decreases water availability (Bull et al., 2007; Feeley et al., 2008; NETL, 2009), or if the temperature of the water entering the plant exceeds design or government imposed operating permit limits. Climate change may also increase the risk that cooling water exiting the plant will raise the temperature of receiving waters to a higher-than-allowed level. There have been several instances in the US and Europe when nuclear power facilities were forced to scale back or halt operations because of this water temperature problem (Letard et al., 2004; Jowit and Espinoza, 2006; Flessner, 2010; Kopytko and Perkins, 2011), imposing price or supply impacts in cities and regions heavily served by these facilities.

Thermoelectric power plant production levels may also be affected by climate change. As temperatures rise, air density declines, increasing energy consumption in the compressor and decreasing power output (ICF, 1995; Schaeffer et al., 2008). Impacts are relatively modest, however, compared to output level changes already occurring at power plants resulting from normal variations in seasonal temperatures.

The most significant demand impacts associated with climate change are likely to occur in energy demand for heating or cooling services, taking the form of a U-shaped demand curve. At low temperatures heating demand is high; energy demand drops as temperatures moderate, but then rises (in the form of increased demand for cooling services) as temperatures increase (Ebinger & Vergara, 2011). On a net basis, the impact of climate change on total energy use will depend on whether a city or region is winter or summer peaking. In the northwestern United States, climate change is likely to decrease winter temperatures, reducing heating-related energy demand (Hamlet et al., 2010). In the southern US, temperature increases are expected to increase already high cooling-related energy demand (Lu et al., 2010). Nationally, changes in winter-related demand are expected to outweigh cooling-related demand increases, resulting in a net decline in total energy use (Wilbanks et al., 2008). Because of differences in how seasonal energy demand is typically satisfied (e.g. natural gas or liquid fuels for heating versus electricity for cooling), impacts may fall disproportionately on certain energy sectors or household or company budgets. Research on utilities in California projects that decreases in natural gas use (for winter heating) could be sizable (Lebassi et al., 2010).

Looking solely at electricity demand, climate change may result in different impacts depending on whether the focus is on total annual demand (e.g., in MWh or GWh) or peak demand ($MW_{p\ or}$ GW_p) as they may highlight important differences in the adequacy of a region's energy supply network. A city or region's existing supply will generally be capable of handling warmer nighttime temperatures and a longer cooling season because demand during these time periods is typically lower than peak demand on summer afternoons, meaning there is excess capacity available in the supply network. Increases in peak daytime demand, by contrast, may exceed this supply capacity, raising the prospects of more frequent blackouts or brownouts (Miller et al., 2008; Hayhoe et al., 2010).

A key variable affecting summer cooling demand is the baseline level of air conditioning units deployed in a city or region. Areas with low levels of current deployment or use may see more significant demand growth than cities where most buildings already have air conditioning installed (Wilbanks et al., 2008). There may also be differences in terms of potential demand growth depending on whether window or central air-conditioning units predominate, as they reportedly tend to have different usage patterns (Linder et al., 1987). Data supporting that argument are rather old, however, and usage patterns may have changed over the past 25 years. Recent research focused on manual and programmable thermostat usage in California found that programmable thermostats are set to the 'off' position during the cooling season less frequently than manual thermostats (Peffer et al., 2011). Whether this is a proxy for current day differences in usage patterns between manually controlled window air-conditioning units and automatic thermostat controlled central air-conditioning units is unclear.

There is a sizable amount of research examining the relationship between temperature change and energy use in buildings (Amato et al., 2005). Wilbanks et al (2008) summarize many older studies which found that a 1°C upward temperature increase results in a decrease in heating-related energy demand of roughly 1.5-10 percent in residential buildings and 1.5-16 percent in commercial buildings. The same report also noted that national studies found cooling-related energy demand increases 5-22 percent per 1°C temperature increase, with regional studies finding even more significant gains.

There is less research exploring the link between climate change and energy demand, although one study in New York did seek to project the impacts of climate change on electricity demand for the period 2011-2039. The effects were found to vary widely across the state. For example, in New York City, climate change may increase peak power demand in the summer by up to 497 MW_p (or 4 percent) beyond current peak demand levels. In western and northern parts of the state, peak demand increases are lower but nonetheless sizable, collectively totaling nearly 340 MW_p in the cities of Rochester, Buffalo, and Syracuse (Hammer et al., 2011).

Industrial power demand is generally considered less temperature sensitive, as a much smaller fraction (~6.8 percent) of sectoral energy use is associated with space conditioning (US EIA, 2007). More research is necessary, however, to fully understand climate change impacts on other forms of this sector's energy use (Wilbanks et al., 2008).

3.2.2.2 Changes in Precipitation Patterns

In the U.S., hydropower generates more electricity than any other renewable source of energy, with certain regions of the country heavily dependent on its availability. The amount of water available for hydropower already varies widely each year, due to localized weather patterns, local hydrology, and the need to accommodate competing uses for the water (Wilbanks et al., 2008). Studies exploring the impact of climate change on hydropower output levels in the western US project there will be some change, although it may be more a matter of timing than volume (Aspen Environmental Group and M Cubed, 2005; Vine, 2008; Hamlet et al., 2010). Precipitation falling as snow can extend the hydropower season, as the snowpack 'banks' the water until it is completely melted. Warmer temperatures may result in higher winter rainfall levels, affecting winter hydropower output levels.

Location may also play an important role, as retention dams often have different operating rules depending on their elevation and function (e.g. water storage, flood control, or hydropower production), factors that dictate whether water is stored or released.

In the Great Lakes region, a series of studies, most dating back 10-20 years, have attempted to forecast how future precipitation, runoff, and lake evaporation levels will change as a result of climate change, with some analyses projecting minor lake elevation declines, depending on which GCM scenarios are employed (c.f. Quinn, 1988; USEPA, 1989; Mortsch and Quinn, 1996; Chao, 1999; Lofgren et al., 2002; Croley, 2003; Fay and Fan, 2003). Even minor lake change levels can have sizable impacts on hydropower production, however, with strong regional supply and price consequences. The New York Power Authority has estimated that a 1-meter decrease in the water level of Lake Ontario could reduce power output at their St. Lawrence/FDR hydropower facility by 280,000 megawatt-hours per year (Hammer et al., 2011).

The transmission and distribution of electricity, gas, and other fuels can be also affected by changes in precipitation patterns. The energy transmission and distribution system is already subject to stresses from high winds, snow, ice, flooding, landslides, and siltation and erosion (Ebinger & Vergara, 2011). Snow and ice storms regularly damage electricity transmission towers, distribution poles, pole-top transformers, and wiring. In some cases, damage can run into the billions of dollars, and take months to repair (Ostendorp, 1998), creating extensive service disruptions for customers. Climate change may either increase or decrease the incidence of this damage on a localized basis, as snow, ice, and heavy wind events become more or less prominent.

3.2.2.2 Changes in Wind Patterns

Shifts in either the distribution or variability of wind patterns may occur as a result of climate change (Pryor and Barthelmie, 2010). One study estimated wind speeds could decline 1-15 percent over the next century (Breslow and Sailor, 2002), although other studies argue the evidence for such significant decline is less conclusive (Pryor and Barthelmie, 2011). Seasonal differences in wind power output could be particularly prominent (Edwards, 1991; Segal *et al.*, 2001; Breslow and Sailor, 2002). These changes could affect both existing wind farm locations, and lead to changes in areas sought for future wind technology deployment.

To the extent extreme weather events become commonplace, high winds may result in short-term increases in power output levels, although if wind speeds are too high, wind turbine damage can occur (Soto, 2010). Such damage may point to wind speeds that exceeded the design specification of the equipment or deficiencies in construction or equipment manufacturing practices (Chou and Tu, 2011).

There is little experience to date with wave and tidal energy in the U.S., so impacts may partly depend on the extent to which this sector develops. Wave formation is directly linked to wind levels, with Harrison and Wallace (2005) concluding a 20 percent increase in wind speed will raise wave power levels by 133 percent. The link between wave height and climate change is unclear, although wave modeling of the southern California coast has found wave height is trending down over the past several decades, which could limit future wave energy production in that area (Cayan et al., 2009). No references have been found detailing the relationship between climate change and tidal energy.

3.2.2.3 Changes in Solar Levels

There is little research thus far that has focused on potential impacts on solar power production resulting from climate change. Cutforth and Judiesh (2007) suggest climate change will change atmospheric water vapor content and cloudiness levels, with Pan et al (2004) estimating these impacts could cut seasonal solar resources in the Western U.S. by as much as 20 percent. The extent to which this creates a supply impact in urban areas is unknown, as cities vary widely in their level of deployed solar power.

3.2.2.4 Extreme Weather Events

Almost all energy facilities are affected by extreme weather through the movement and impact of wind and water. For example, oil and gas pipelines are vulnerable to storm damage, flooding, frost heaves, and permafrost thawing. Considerable damage occurred to underwater gas and oil pipelines in the Gulf Coast region as a result of Hurricanes Katrina and Rita; pipelines were also damaged from the flooding that ensued on land (Cruz and Krausmann, 2008). Natural gas price spikes attributable to this damage extended all the way from the Gulf Coast to New York State (New York State Energy Planning Board, 2009). High winds can also impact power plants that use air cooling towers, forcing the facilities to shut down during storms to avoid damage.

3.2.3 Key Vulnerabilities and Risks

Climate change variables directly impacting the urban energy system include temperature change, precipitation, and sea level rise. Other climate change-related factors that may affect the energy system include water temperature, ice and snow, wind, cloudiness, humidity, stream flow rates and levels (Ebinger & Vergara, 2011), and extreme weather events. How these factors will manifest themselves, and the corresponding energy system impacts, will vary significantly by locale. Some effects may be very localized, affecting a single power line, transformer, or power plant in or near a particular city. Others may have ripple effects that carry across a much broader region, reflecting the highly interconnected nature of today's energy system.

3.2.4 Adaptations

Adaptation strategies appropriate for urban energy systems will vary. Some may have a temporal focus (e.g. short vs. long term); be proactive or reactive; and be structured as a no-regrets, low-regrets, or win-win strategy. They can also be market or policy-led, and have a localized or systemic focus (Ebinger and Vergara, 2011). Wilbanks et al (2008) emphasize the role that enhanced knowledge can play in driving adaptive capacity, arguing that data gaps reduce public or policymaker understanding of the need for adaptation initiatives. Because the energy system relies heavily on mechanisms that balance energy supply and demand, power production dispatch orders and pricing signals may also depend on improved data monitoring or forecasting ability (Troccoli, 2010).

In general, adaptation responses can be categorized as technological, behavioral, or structural (Ebinger and Vergara, 2011).

3.2.4.1 Technological change

Technological responses focus on the hardening of existing system assets to reduce their vulnerability to climate change risks. Dikes, enhanced pumping capacity, or salt-water resistant transformers all reduce potential impacts from sea level rise or storm-induced flooding (Mansanet Bataller et al., 2008). Pipeline footings can be reinforced to reduce the risk of shifting resulting from permafrost thaw (Ebinger and Vergara, 2011). Smart grid technology may allow damaged networks to recover faster by rerouting power around damaged areas. Smart grid technology may also allow for increased integration of distributed generation technology, reducing the load on system assets stressed by heat waves or other extreme weather events. Such load reductions can reduce the incidence of blackouts or brownouts.

3.2.4.2 *Behavioral change*

Behavioral strategies may involve the relocation of critical energy system assets away from risk-prone areas (Ebinger and Vergara, 2011). This can include changing the methods of fuel storage or increasing the elevation of new power generation facilities to reduce flooding risks (Hammer et al., 2011). Changes in emergency planning procedures can also facilitate faster response times to problems, or avoid them altogether. Tree trimming programs reduce the likelihood that falling trees or limbs will be a problem during ice or snow storms, or high wind events (Hammer et al., 2011). Energy efficiency and peak demand management programs can also reduce the amount of energy needed for base and peak loads, offsetting some of the increases in demand expected from higher temperatures.

3.2.4.3 *Structural change*

Structural changes promoting adaptive capacity may include changes to fundamental energy market rules to create demand response programs that incentivize power load reductions during heat waves. Utilities and local authorities can also pursue citywide building efficiency upgrade or tree planting programs that reduce solar gain in buildings during summer, thus reducing demand for air conditioning. Policy strategies that promote energy supply diversification can also reduce the risk of supply shortfalls due to drought, flooding, or breakdowns associated with extreme heat events. In particular, on-site distributed generation can enhance energy security for individual buildings as well as providing systemwide load relief (Vine, 2008).

3.2.5 Overcoming Barriers and Stimulating Innovation

Although many cities obtain a portion of their energy supply from power plants located within or near the city limits, many cities are highly dependent on power supplied by power generation facilities (thermal power plants, hydroelectric dams, wind farms, etc.) located far from the city. High voltage transmission lines import power from these facilities to distribution networks serving the city. These power plants and transmission and distribution systems form the nucleus of single or multi-state wholesale energy markets, where prices are set based on demand levels and supply availability.

The nature of this system design means that cities may feel the impacts of climate change even if certain impacts are not felt locally within the city. Drought or excessive precipitation in regions producing hydropower have ripple effects in the cities they serve, both in terms of supply and price. Cities dependent on biomass harvested elsewhere for biomass-fired power plants are similarly vulnerable to supply chain impacts if trees or energy crops supplying the city begin to decline due to drought.

As noted previously, climate change-related impacts can also affect oil and gas markets, as pipeline failure or damage due to permafrost thaw or extreme weather events may slow or cutoff supply from those areas, affecting the market price of energy, with ripple effects regionally, nationally, or globally.

Climate change may have significant impacts on urban energy systems, depending on the type of risk, the design of the energy system, and the consumption patterns of local energy users. Although energy systems are designed to operate under a range of weather and supply and demand conditions, climate change may stress the system in ways that disrupt critical fuel supply chains or otherwise exceed the system's current design limits, increasing the risk of breakdown.

Some climate-related impacts may be very localized, affecting a single power line, power plant, or neighborhood, while others may have ripple effects that carry across a much broader region, reflecting the highly interconnected nature of today's energy system and markets. Supply-side impacts may be extremely costly and logistically challenging, because replacing lost supply capacity or transmission and distribution assets can take some time and be highly disruptive and involve significant capital investment.

Demand-related impacts relate to both heating and cooling demand. Climate change may either increase or decrease net energy use in a city depending on the level of climate change-related temperature change, and whether that locale experiences its peak energy demand in the winter or summer.

Adaptation strategies appropriate for urban energy systems may be technological, behavioral, or structural in nature. Technological responses focus on the hardening of existing system assets to reduce their vulnerability to climate change risks. Behavioral strategies may involve the relocation of critical energy system assets away from risk-prone areas, while structural changes may include modifications to fundamental energy market rules to reduce demand, thereby alleviating stress on the system.

Because of the highly interconnected nature of the energy system, cities may feel the impacts of climate change even if certain impacts are not felt locally within the city, affecting both their supply and the prices customers pay for energy.

3.3 **Telecommunications**

Lead Author: *Klaus Jacob*

3.3.1 Context

The telecommunication sector is the lifeline for modern societies, in developing and developed countries, and rural and urban habitats alike. While the US communications sector contributes "only" about 4.5 percent (ca. $ 660 Billion) directly to the GDP of about $ 14.7 Trillion[1], much of the rest of the economy could not function without it. The telecommunications industry represents the largest portion within the more encompassing communications/information category. Because telecommunication has a large economic multiplier effect (much of today's economic output depends on its services), interruptions in its services cause economic losses far beyond the direct losses to the telecommunication sector itself. This fact demands high reliability and redundancy, and the lowest possible vulnerability of the telecommunication sector. Much (but not all) of the telecommunication's operational service continuity is strongly tied to the reliability of the electric power grid (or lack thereof). This, in turn, requires continued investments by the industry, and effective oversight by the regulatory authorities.

The telecommunication sector comprises land and mobile telephone and fax services, satellite, cable, the Internet, TV and radio, specialized closed telecommunication links (government, financial, public security and emergency services, dedicated microwave links, etc.) and is still in a mode of rapid expansion, especially the Internet[2]. While the expansion in the U.S. is not as rapid as in international markets that have not yet reached the level of saturation/penetration typical for the U.S., the increase in bandwidth and throughput just from the international traffic from and to the U.S. alone is substantial. To satisfy this and some domestic growth, new capital investments continue to be made. Because of the often-centralized nature of the Internet backbone network, the potential vulnerability of choke points needs to be carefully monitored as network expansion proceeds, especially when the choke points are at locations potentially vulnerable to climate change threats.

The boundaries between operators and providers of services (hardware, software), and of content (programs, applications, data, entertainment) are not static but are in a sustained rapid flux. The telecommunications industry is in a state of fierce internal competition (hardware, services, and access to information content) and tends towards consolidation to fewer, larger business entities

3.3.2 Key Impacts

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[1] US Bureau of Economic Assessment, 2010 data. National Income and Product Accounts Tables; http://www.bea.gov/scb/pdf/2011/08%20August/NIPA_Section2.pdf

[2] http://www.telegeography.com/page_attachments/products/website/research-services/global-internet-geography/0002/4221/telegeography-global-internet.pdf

Telecommunication operations are vulnerable to extreme weather events now. Provided current vulnerabilities will be minimized in the near future, it appears likely that there will be only moderate additional impact from the expected changes in climate because of the unusually fast turnover of the rapidly advancing telecommunication technology.

The rapid development and changes in telecommunication technologies will allow, at least in principle, incremental adaptation to climate change as telecommunication technology revolutionizes about once every decade (or even faster). It is very likely to continue to do so for many decades to come. As capital investments are made to implement the new technologies, the costs for adaptation to climate change are expected in most cases relatively modest. Exceptions to this finding are concentrated on locations and system components where important network links and nodes, central offices or other critical structures are located in low-lying coastal areas subject to sea level rise and related increase in frequency and severity of coastal storm surges. There, fundamental relocations and rerouting or other protective measures may be necessary.

Despite the continuous upgrading with modern technology such as fiber optics and others, that -- if properly designed and installed -- can be quite climate-resilient, there is still in many cities a stock of old copper-wire-based infrastructure in the ground that often is collocated with other infrastructure. Such older installations can be potentially quite vulnerable, for instance, to urban or coastal flooding.

The above-mentioned multiplier effect for losses to the general economy from outages of telecommunication services needs attention nationally to minimize negative economic (and in some cases life threatening) impacts. Disaster response and recovery are severely handicapped without reliable, continuous telecommunication services.

In general, key extreme weather and climate change impacts on telecommunications are related primarily to the corrosion of infrastructure due to floodwaters, road wash from winter road salts, or the infiltration of salt from seawater in low lying coastal areas and disabled or fallen cell towers, the focal point for wireless communications, due to extreme wind events. This could result in limited cellular communication in the aftermath of extreme events or natural disasters.

3.3.3 Key Vulnerabilities and Risks

Weather-related vulnerabilities of the telecommunications sector are closely tied to similar vulnerabilities of the electric grid. Vulnerabilities vary greatly for above ground versus below ground landlines, and for wireless, radio and satellite based technologies. Generally, the vulnerability of the land-based telecommunication infrastructure is lower in cities than in rural areas because a larger portion of the infrastructure tends to be below ground, and therefore has reduced exposure to snow and ice loads, wind, and falling trees, or even heat effects. On the other hand, once the infrastructure in a city is damaged during an extreme event, the impact tends to be more intense and typically affects larger numbers of customers.

Services in cities tend to be restored faster than in rural areas because of higher customer density per restored line mile or network node. Also, to the extent that side-by-side wireless and landline services provide more redundancy, there are generally more alternatives available in cities than in remote rural areas that do not always have dual services available. Also in life safety cases there is a greater chance to reach first responders in cities, even without normally functioning telecommunication, than in a remote rural area.

Telecommunication networks face several vulnerabilities from extreme weather and climate change. Networks are likely to experience increased flooding risks from sea level rise and coastal storm surges in coastal cities and more outages are likely to occur as the result of storms (including hurricanes, tornadoes, lightning, severe wind, snow and ice storms and falling trees). In certain regions of the U.S. prone to heat waves and extended draught conditions, severe fire hazards, especially when combined with severe winds, could lead to conflagrations that could impact service.. All of these events could result in outages of the electric power grid, which would have a direct impact on telecommunication networks.

In regions of melting permafrost (Alaska), telecommunication towers could be subjected to sinking and tilting, which is expected to become more widespread as warming accelerates. Service providers could also experience limited fuel supply at stand-by back-up power generators (UPS) at both central offices and remote transmitters / wireless antenna towers.

From the above factors, telecommunications infrastructure and services are vulnerable to breakages in connections producing service interruptions due to facilities such as cell towers and transmission lines being broken or interruptions in power supply.

The telecommunication industry is largely privately operated, and the oversight by regulatory agencies is limited or not always enforced to the fullest extent (either by the *Federal Communication Commission*; or by the state *Public Service Commissions*). Related outage data are rarely released by the regulatory agencies, or by the industry itself. Therefore detailed operator-specific performance data on service continuity and reliability, or vulnerability, respectively, are generally not available to customers and the general public, which while often justified by security concerns; also makes it difficult for customers to make informed business choices on the basis of telecommunication performance records of continuity, reliability and redundancy of services (or absence thereof) during emergency situations and extreme events.

Because of the scarcity of publicly accessible performance records, there also are relatively few studies and reports published that can provide informed insight into the vulnerability of the telecommunications sector to extreme weather events and climate trends. The published data for the electric power sector seem to indicate that weather related outages have been on a strong rise for at least a decade[3]. Because of the strong coupling of electric grid and telecommunication vulnerabilities, it is likely that weather related telecommunication outages have been rising as well.

The following is a sampling of some available reports and analyses from recent years.

Thorough technical reports of the impacts of Hurricane Katrina and some subsequent hurricanes on the telecommunications industry, their economic ripple effects, and on remedial actions, have

[3] Figure on p. 58 of: Karl et al. 2009: Global Climate Change Impacts in the United States.

only emerged during the last few years. Kwasinski[4] provides several penetrating technical reviews of the linked vulnerabilities of telecommunication and electric power as revealed by Katrina and some subsequent Gulf Coast hurricanes. Other authors focused more on the vulnerabilities of the electric power grid itself rather than of telecommunication, and on urban policy implications[5]. Wilson 2009 points out that some cities were able to reduce the weather-related vulnerabilities of publicly owned critical infrastructure systems that were under their own control (water, sewer, some transportation), but were less successful for the largely privately owned critical infrastructure systems such as electricity and telecommunication, since they had little control over them; yet, the cities' economic losses from the failures of these private systems had been severe.

While some cities and/or states have commissioned studies to assess the current and future risks from extreme weather events and climate change, respectively, only few cities have paid close attention to the climate vulnerability of the telecommunications infrastructure, and related impacts on their economies. An exception is a commissioned study for New York State[6] in which the close link between weather related outages of the electric grid and telecommunication outages is documented in some detail. In many instances -- whether from severe ice- or snow storms, or from tropical or other rain and wind storms -- outages affected more than 100,000 customers initially, and for decreasing numbers up to several weeks, in some regions. Services (both electric and telecommunication) in cities were typically restored faster than in remote rural areas. Landlines were more persistently affected than mobile phone services, although mobile services were also interrupted. This typically happened after some initial delay, because diesel-powered back-up generators at cell towers often worked initially but then ran out of fuel after a few hours of providing back-up power. More extended fuel supplies stored on site would provide a potential remedy.

The most recent widespread outages in the telecommunication occurred in August 2011, during Hurricane Irene (downgraded to a tropical storm before landfall in the northeastern U.S.). According to initial reports[7], 1,400 cell towers and cell sites were damaged or disrupted -- mainly in Virginia, New Jersey, New York and North Carolina. In addition to cellular service disruptions from power outages or other problems, land line phone service and other forms of communication were also affected: 132,000 wired voice subscribers had lost service on the first day, while 500,000 cable customers lost service, mostly in Virginia. After the initial FCC reports on wired voice subscribers and cable customers, the agency increased the numbers for the East Coast a day later to 210,000 and 1 million, respectively.[8] The reports also cited that 6,500 cell sites were down along the East Coast, and that Vermont had 44 percent of its cell sites down—a higher percentage than that in other states.

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[4] Kwasinski 2009, 2010, 2011;
[5] Reed et al 2010;Wilson 2009
[6] See Chapter 10: Jacob et al.: *Telecommunication*; *in*: Rosenzweig and Solecki, 2011.
[7] http://www.computerworld.com/s/article/9219556/Irene_takes_out_cell_towers_disrupts_communications
[8] http://spectrum.ieee.org/tech-talk/telecom/wireless/hurricane-irene-tests-resilience-of-communication-networks

3.3.4 Adaptations

Several options exist to increase the climate resilience of telecommunications infrastructure. Overhead lines can be moved to underground cables where possible and economically feasible. This applies to wire and fiber optic cables alike. Trees can trimmed, where applicable (more often in suburban than urban areas), to avoid or reduce downed lines during wind, snow and ice storms. Extreme weather-related outage times can be shortened by planning ahead of storms to mobilize additional field crews, and having stored sufficient supplies of replacement poles, cable, other critical hardware, and fuel for back-up power.

Increasing fuel supplies for back-up power generators at cell phone towers, central offices, and radio/TV antennas, can sustain communication options during extended electric grid outages. At roof-mounted wireless antennas, which provide mobile phone services in city neighborhoods, battery packs, potentially combined with photovoltaic charging devices, could provide interim power to bridge electric grid outages.

Raising (or otherwise flood-proofing) key telecommunication infrastructure, at flood-prone central offices, fiber optic repeater stations, power supplies; and fortifying cell phone towers against failure from ice, wind, and flooding would increase the resilience of the telecommunication network, as would increasing the redundancy and general robustness of backbone networks (Internet; broadband high-speed links and nodes), especially where vulnerability to flooding or other climate hazards has been identified. To the extent possible, opportunities should be identified to decouple the vulnerabilities of the telecommunication networks and infrastructure from the vulnerabilities of the electric grid.

Service providers can also educate customers how to prepare for short and extended electric grid outages. This includes, for instance, having at least one hard-wired line installed instead of only wireless handsets in homes; storing a charged spare battery for the central fiber-optic home terminal; and/or recharging options for batteries of mobile phones by either using car-based, photovoltaic or other chargers; charging from small power generators (only an outdoor option and rarely applicable in cities with high-rise and apartment buildings; there, community-based recharging "posts" could be organized, or provided by emergency first responders).

Adaptation need not be based solely on improved engineering, technology or preventive operational measures. Some may require changes in policy and regulations and may need to take into account the larger economic context in which the reliability of critical infrastructure systems, including telecommunication, must be seen. Such economic aspects of adaptation to climate change, the costs, benefits and policy instruments, albeit often in a broader international context, are discussed in an emerging literature on this topic[9].

3.3.5 Overcoming Barriers and Stimulating Innovations

If existing telecommunication infrastructure can be made more robust and resilient to survive

[9] Agrawala and Fankhauser 2008; OECD

current extreme climate (weather) events, it will greatly facilitate adaptation to continued future changes in climate, for which the frequency *and* severity of extreme weather events is expected to increase significantly in most regions of the U.S. Stronger and/or more consistent enforcement of existing regulations may be needed to ensure higher resiliency within the telecommunications sector. Voluntary measures by the industry to improve its performance during and after extreme weather events are hampered at least partly by the fierce market competition, pressure on profits, and consolidation. Ensuring the reliability of the telecommunication networks is critical as telecommunications will play an ever more important role for early warnings, for disaster emergency response, and public disaster preparedness and public education. Telecommunication's resilience to climate change and extreme weather events is fundamental to public safety on a local, regional and national scale. While largely a privately operated infrastructure, telecommunication has been entrusted with an important public safety function, on which economic continuity, and often lives and livelihoods depend.

3.4 Water

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3.4.1 Context

According to the Intergovernmental Panel on Climate Change, water is the most significant resource that is currently threatened by climate change (IPCC 2007). Water not only sustains our environment, but it also impacts the lives of individuals and the economic security of nations. Throughout the world the effects of more frequent and more intense droughts are already visible. This is true even in the US where infrastructure is highly developed and communities have come to rely on safe, inexpensive and reliable water supplies. In addition, rising sea levels coupled with more intense rain and snow events are making the management of stormwater and wastewater more challenging. Without the careful management of drinking water, wastewater, and stormwater, the quality of our nation's limited fresh water will deteriorate, and current sources may become less reliable.

Our nation's cities are susceptible to a variety of climate change impacts related to water supply, waste water treatment, and stormwater runoff and these impacts are often interrelated. The impacts of climate change on cities will not only be wide ranging and spatially diverse, but will often exacerbate other social and demographic trends that are already being experienced by cities. Diminished quality or quantity inevitably increases costs on account of the monitoring, treatment, energy consumption, and remediation needed. Although climate change will certainly influence many features of the complex web that links water and cities, this system covers three distinct but often interrelated areas: 1) Water Supply, 2) System Reliability (including water quality) and Water Distribution, and 3) Urban Drainage.

3.4.2 Key Impacts

The water resources available to cities have changed during the last 50 years and are likely to change even more dramatically during the next 50 years. The most obvious impacts on resource systems will include the effects of warmer temperatures, increased precipitation, increased climate variability, increased storm intensity, sea level rise, changes in hydrologic cycles, and decreased snowpack.

Impacts to existing resources will occur at a variety of time scales with some that materialize immediately, while others will develop over the long term. Under climate change modeling, the factors influencing evaporation increase the rate at which water re-enters the atmosphere. The effect of climate change on groundwater resources depends upon the change in volume and distribution of groundwater recharge.

Streamflows, both forecasted and observed, from snow-dominated watersheds have shown increasing proportions of winter precipitation falling as rain rather than snow, decreased maximum snow pack, earlier and intermittent winter snowmelt (Barnett 2005), increased winter runoff, earlier spring runoff (Burns et al. 2007; Zion et al. 2011), lower summer flows due to warming (Burns 2007; Zion 2011)), increased intensity of precipitation and, and corresponding increases in peak stream discharge, and floods. There is a shift in historical streamflow timing, the peak flow moves earlier in the year and changes in snowmelt and runoff timing appear to have an effect of increasing reservoir storage levels, spills, and releases during winter and early spring (Matonse et al. 2011). All of these factors will affect both the quantity and quality of water stored by water supplies, as well as impacting water treatment and water system operation and urban drainage networks.

The Puget Sound area is an example of the potential hydrologic effects of climate change. There is evidence that long-term climate change has altered streamflow patterns in the Puget Sound region, particularly during spring and summer months, due to a decrease in snowpack (Polebitski et al. 2011). Reservoirs in the Puget Sound region are very susceptible to drought conditions if winter snowpack is low followed by minimal spring and summer precipitation. The same has been observed mid-continent in the Rockies (Pederson et al., 2011) and in the east in the Catskill Mountains (Burns, 2007).

Sea level rise related to climate change is another significant source of impacts on water systems. Impacts include saltwater intrusion of coastal freshwater aquifers, advancing salt fronts to river intakes, and increased pumping requirements for coastal WWTPs. Twenty of the largest 25 cities in the US are located on the coastlines and they will suffer the impacts of sea level rise that potentially affect water supply and wastewater infrastructure, including New York City, Boston, Miami, San Francisco, and others.

Urban water systems will encounter a variety of issues that will become an even greater problem in the future. These systems face changing water demands based on urbanization, population growth, per capita consumption, pricing, irrigation, and fish flow requirements, all of which potentially compound or contribute to climate change impacts.

3.4.3 Key Vulnerabilities and Risks

Climate change will create many associated urban water vulnerabilities including the disruption of reliable water supplies due to storms, floods, and droughts. These conditions lead to reduced water quality both in drinking water and in our natural environment, increased energy costs for operation and maintenance, increased urban drainage flooding and overflow of combined sewer systems (CSO), and increased potential for flood damage of facilities in river floodplains or low lying coastal areas. Extreme conditions make our water systems vulnerable because access for operation and repair is greatly hindered while the need for rapid response is critical and costly.

Warmer temperatures will lead to increased stresses on urban water supplies and waste water treatment by both increasing water demand and the probability of drought in many cities that have experienced drought in the past, increasing the requirements for reservoir releases to augment flows needed to maintain healthy aquatic habitats (both in terms of temperature and water quality) and effects on watershed processes that regulate surface water quality.

Access to sufficient quantities of high quality drinking water is essential in order to maintain the health, economic well-being and future growth of urban areas. This is achieved through the development of water supply infrastructure, which varies greatly among urban areas, but in general consists of common elements of supply, storage, treatment and distribution. Water supply systems, unlike other urban infrastructure, often exist far beyond traditional urban boundaries, and include reservoirs and aquifers as well as the watersheds that supply water to population center tens of hundreds of miles away. The vulnerability of water supplies to climate change will therefore be dependent on the specifics of the water supply system, as well as the effects of climate change on processes expected to impact both the quantity and quality of water entering water supply storage.

Flooding from major storms notoriously affects surface water supplies in a negative way. Water quality deteriorates due to large amounts of debris, turbidity, toxic substances, and nutrients that are washed in during flooding events. Flooding typically results in tremendous amounts of natural and man-made debris being washed in to reservoirs and streams. Skimmer boats are sometimes necessary to remove massive amounts of trees and dead wood from reservoirs in forested watersheds. Storage tanks, many of which hold hazardous materials, and vehicles are typically found in reservoirs after severe floods. There are significant costs in first evaluating the extent of the threats to the water supply, then removing this material from the reservoirs, with much of it accomplished on an emergency basis. This leads to increased expense for monitoring and treatment in terms of both manpower and equipment.

3.4.3.1 Flooding

Floods inevitably result in deterioration of water quality and often in the destruction of major infrastructure features that are essential in providing safe and reliable water supplies. Bacteria and pathogens from landscape sources (septic systems, animal farms, wastewater treatment plants, etc.) are washed into the water supply. Organic carbon sources such as leaf litter and humic substances from wetlands are also washed in from the landscape and these boost carcinogenic disinfection by-products (DBPs) in distribution systems. Increased nutrient loads from the landscape may also lead to algal blooms that contribute to DBPs, oxygen depletion, fish kills, and taste and odor problems.

Turbidity impacts due to floods can be extensive and long-lasting. In the Catskill Mountains at the headwaters of NYC's Catskill system, the glacial clays are eroded by storms, and when they are intense, the turbidity can reach values of over 1000 NTU and remain in suspension for more than six months at a time. As such, flooding events require high intensity monitoring for all analytes that pose potential threats and continuous interaction with regulatory agencies for authorization of emergency permits needed to take remedial action.

3.4.3.2 Droughts

The impacts of droughts are typically handled initially with water alerts, then voluntary water use restrictions and finally, if necessary, with mandatory water use restrictions. Droughts are typically metrological in nature, due to long periods of unusually low precipitation (either in the form of rain or snow). Drought like events can also occur from insufficient infrastructure (as in the inability to provide sufficient distribution pressure) or due to shutdown of infrastructure for repair. Repairs can sometimes take years to complete. If droughts are not too severe, they may result in personal inconvenience or temporary damage to landscaping. When more severe, low water pressure results in a decreased ability to fight fires and this may be devastating. Droughts call for increased costs associated with monitoring, treatment, and public notifications.

Droughts can also lead to wildfires that can have devastating effects on watersheds. In 1996 the Buffalo Creek fire, followed by intense thunder storms led to severe erosion and turbidity in the Denver water supply. This led to tens of millions of dollars for dredging and treatment over an extended period of time (Miller & Yates, 2006).

3.4.3.3 Hydrology

Regional differences in climate will greatly affect the quantity and quality of water supply sources and the infrastructure and operational policies associated with their distribution systems. Studies on both the east and west coasts have predicted that there will be more water entering the reservoirs, particularly during the fall and winter, with a greater uncertainty in the balance between increased precipitation and evapotranspiration during the summer period. In the humid east, the consequence of a wetter climate will apparently be a reduction in droughts and an increase in water system reliability when these metrics of system use and status are based solely on predicted changes in reservoir storage (Matonse et al. 2011 Matonse et al. submitted). However, many studies in the west suggest that increased climate variability and increased temperatures may result in a degradation of the safe yield of major water supply systems.

Changes in watershed hydrology will also affect changes in reservoir water quality, since changes in hydrologic transport will directly impact the loading of nutrients and turbidity to the reservoirs. This could result in greater loading during the winter due to changes in winter/snowmelt hydrology and during all times of the year as a consequence of increased frequency and magnitude of storm events. Consequently, complete analyses of system reliability need also to account for changes in the usability (quality) of the water stored in the water supply, and Northeastern urban water supplies may impacted to a greater extent by water quality issues under future climate conditions. Portions of the New York City water supply are particularly susceptible to the turbidity effects associated with stream channel erosion. Extreme events such as Hurricane Irene and Tropical Storm Lee that impacted water supply during 2011 (Klug, J et al, in prep.) have restricted the use of the Catskill system (approximately 40 percent of the water supply annually) thereby changing reservoir system operations, and increased the need for treatment (coagulation) of the turbid water that must be used. Increased microbial and DOC loading associated with extreme events can also lead to additional water quality concerns, potential use restrictions, and increased treatment costs.

3.4.3.4 Drainage and wastewater treatment

Depending upon local hydrologic conditions, drainage systems are usually designed for 6 hour or 24 hour duration events that have recurrence intervals ranging from 10 years to 100 years (e.g., Massachusetts Storm Water Regulations, Colorado Urban Drainage and Flood Control District). Combined sewer overflows under some regulatory conditions are permissible with a recurrence interval of three months, or on the average, four occurrences per year (U.S. Environmental Protection Agency, 1994). It is only recently that urban drainage managers are being explicitly required to manage the negative water quality impacts of drainage. This is in response to the US EPA Phase I and Phase II Storm Water Regulations, which require that "minimum control measures" be implemented in urban drainage areas to better manage nonpoint source pollution.[10]

There is evidence of recent trends in increases in extreme precipitation volumes (Douglas and Fairbanks, 2011 - annual maximum daily precipitation and annual number of daily precipitation events greater than 2 inches in northern New England; Interagency Climate Change Adaptation Task Force, 2011 - increase in heaviest 1 percent of all daily events). For the larger events customarily used in design of civil engineering infrastructure, such as 50 or 100 year storm, however, Bonnin (2010) reports that historic rates of changes are small compared to the errors of the estimates themselves. It is generally agreed, however, that the volumes in extreme events of these and other frequencies will increase under conditions of a changing climate (IPCC 2012, Interagency Climate Change Adaptation Task Force, 2011). Researchers have estimated future changes in volumes by analyzing daily data from Generalized Circulation Models (GCM, e.g., Kharin et al, 2007, Rosenberg et al, 2010, Kirshen et al. 2011), trend analysis (Denault et al, 2006), and sensitivity analysis (e.g., Pyke et al, 2011). Kharin et al (2007) using frequency analysis of daily data from GCMs determined changes in the amount of precipitation in the 20 Year, 24 hour storm. The multi-model median showed 5 to 10 percent increases by midcentury, and 10 to 15 percent or more increases by end of century over the continental U.S. Kharin et al (2007) estimates also generally agree with those given in Kirshen et al (2011) for the Denver and Boston areas. The Water Utility Climate Alliance (2009) reports, however, that GCMs may not be adequate for these purposes.

Urban drainage is important because most urban social, economic, hazard, and emergency management activities have developed around having relatively minor flooding due to rainfall runoff collecting in low laying areas. Urban drainage management is also a stress because urban runoff carries many pollutants harmful to water bodies[11] and, in older cities in the U.S., some urban drainage networks lead into sewers that also carry sanitary sewage. These combined systems have been designed to overflow into receiving waters with only a few inches or less of rainfall. Visitacion et al. (2010) analyzed the costs and benefits of drainage management in the Puget Sound Region.

Wastewater treatment plants receive sanitary or combined sewage and are often situated in low-lying coastal or riverine environments. Treatment plants that receive combined flow of sanitary waste and stormwater runoff are required to treat significantly more flow than during dry weather conditions (perhaps two or three times as much). Therefore, increasing rainfall may challenge the capacity requirements of treatment plants (NYCDEP, 2008). For treatment plants located on the water, the facility may also be physically vulnerable to flooding (NYCDEP, 2008; King County, 2008). For coastal facilities there is the added challenge of sea level rise not only enhancing the plant's physical vulnerability to storm surge, but also affecting the treatment

[10] http://www.epa.gov/npdes/pubs/fact2-0.pdfm, accessed November 7, 2011
[11] http://cfpub.epa.gov/npdes/home.cfm?program_id=6, accessed November 7, 2011

plant's hydraulic capacity to discharge by gravity. Several cities are considering sea-level rise impacts on wastewater treatment facilities (NYCDEP, 2008; King County, 2008).

There is recent literature on assessing the drainage vulnerabilities of urban areas to these potential changes in extreme rainfall. Water Environmental Research Foundation (2009) presents general flow charts of vulnerability networks and possible resulting drainage stresses in urban areas under climate change. Rosenberg et al (2010) cites research previous done in the U.S. and Canadian cities prior to 2009. For three major urban areas in the State of Washington Rosenberg et al (2010) found that drainage impacts varied by GCM. Kirshen et al (2011) found in Somerville MA that by 2040 under a range of precipitation changes from multiple GCMs CSO volumes from the 3 month storm at the low range would change insignificantly from present but at the high range would increase by 10 percent. Hazardous street flooding under the 10 year storms increased similarly. Under the 100 year storm, the volumes of flooding increase from 10 percent in the low range to 50 percent in the high range. None of these included continued deterioration of urban drainage networks.

3.4.3.5 Social and development factors affecting vulnerability

Water Demand. Changes in water demands are a growing concern for many water supply and wastewater treatment plants. Impacts on changing water demands in cities include urbanization, climate warming, population growth, per capita consumption, water pricing, municipal and industrial use, irrigation, and fish flow requirements. According to the U.S. Census Bureau, the current population of the United States is approximately 312 million and is predicted to increase to 392 million by 2050.[12] Access to water will need to be balanced with the importance of managing water itself in a sustainable way while taking into account the impact of climate change, and other environmental and social variables. Per capita water use has decreased since the mid-1970s, and current levels are now the lowest since the 1950s. This trend is due to increases in the efficiency of industrial and agricultural water use and is reflected by an increase in the economic productivity of water (Pacific Institute 2009). In contrast, per capita water use in the home has decreased less per capita (Kenny et al. 2009), but many major cities that meter their water have shown significant decreases in per capita demand. Efficiency and conservation have reduced per capita household consumption in some states and regions, but these efforts have been countered by increasing populations in hot and arid regions of the country—including the Southwest, Rocky Mountains, and Far West—where there is greater domestic demand for outdoor water use (Pacific Institute 2009; USCB 2000, 2010). Simulations of future water supply availability under climate conditions in Phoenix indicate that current levels of per capita water consumption cannot be supported without unsustainable groundwater use. Feasible reductions in residential water consumption should allow the region to adapt under the worse climate projects. Delaying any action reduces the sustainability of the groundwater resources under some climate scenarios (Gober et al. 2010).

Urbanization. Urbanization has been accelerating throughout the last century and continues to grow. Some metropolitan areas have lowered their per capita water consumption. For example, Seattle has reduced per capita water use from 152 gallons per day in 1990 to 97 gallons per day in 2007 through a comprehensive water conservation program including pricing policies,

[12] http://www.census.gov/population/www/pop-profile/natproj.html

education, regulations and rebates for water-saving appliances (Polebitski et al. 2011). This same trend has been observed in NYC and water consumption has decreased from 1.5 to 1.1 billion gallons per year. Many other cities are seeing this trend such as Boston, Chicago, Los Angeles, Phoenix, Miami, and San Diego.

3.4.4 Adaptations

The managers of urban infrastructure have begun to respond to climate change through adaptation measures that include both traditional and nontraditional approaches. Planning paradigms are changing, moving the range of adaptations from the traditional brick and mortar solutions (physical barriers and/or the movement of vulnerable infrastructure) to those that alter land-use and land management policies and the institution of "green solutions." There are many feasible adaptation methods that can aid to future urban water resources challenges associated with climate change. Redesign of stormwater systems, water demand management, water pricing, new infrastructure, changes in operating policies, and an increased use of climate forecasting to inform decision making are a few achievable approaches. Adaptation can occur both through science based management of the existing water supply infrastructure and through improvements to infrastructure

One method to mitigate the impacts of climate change on water supplies is through adaptive management of the existing water supply system, which includes altering the way that systems are designed, operated and maintained. Such a strategy can be most successfully employed when the water supply system consists of multiple sources, a flexible system allowing water transfer from and between different storage/source components and distribution, and frequent data on system storage and water quality to guide operations. Management strategies can include, shifting the use of different storage components based on available quantity and present quality of the reservoir so that the blending of water is optimized to reduce treatment while maintaining acceptable levels of water quality. Such a strategy is dependent on accounting for many different factors such as variations in quality throughout of the system, the balance of storage between different parts of the system, aqueduct flow capacities, system demands, and regulatory requirements governing system operation and distribution water quality.

NYC DEP has employed such a strategy to mitigate the effects of event driven increases in turbidity in parts of the NYC water supply system and has successfully reduced alum treatment during periods of elevated turbidity, through the use of adaptive management strategies. NYC DEP is developing a model based operations support tool (OST) to aid in determining reservoir operations in response to changes in system quantity and quality. The core of this tool will be the OASIS system operation model (Hydrologics 2009) coupled the CE Qual W2 turbidity transport model (Cole and Wells 2002). Components of the OST will also import monitoring data and forecasts of reservoir inflows, meteorological conditions, reservoir thermal conditions and water quality, as well post process model output to provide summary statistics to aid in decision making. Adaptive management through the uses of systems such as the OST is one way water utilities can mitigate the impacts of extreme events occur under present climate conditions and future challenges that arise from climate change. Modeling systems such as the OST also provide an excellent tool to evaluate future impacts and proactively develop adaptation strategies

(Matonse et al. 2001, Matonse et al. submitted)

The New York City Panel on Climate Change (2010) recommends development of "flexible adaptation pathways" that can be adjusted periodically to new climate information. The NPCC's Adaptation Assessment Guidebook (AAG) recommends that city agencies initiate an inventory of infrastructure and assets at risk, link adaptation strategies to capital and rehabilitation cycles, and periodically monitor and re-assess plans in response to updated climate projections.

Water pricing is another water adaptation. In the last year, the price of water in 30 U.S. metropolitan areas has increased an average of 9.4 percent for residential customers with medium consumption levels, according to data collected by Circle of Blue. The median increase for medium consumption was 8.6 percent. There are plans for multiple cities to reduce customer consumption of water and increase reuse of captured water.

Approaches for urban drainage are similar to those of other sectors. They should be robust (actions implemented over time and space that function acceptably well under all future uncertainties and risks), flexible, and adjustable; include no-regret (valuable even without climate change) and co-benefit (valuable to multiple sectors) actions, integration with sustainability planning to respond to other pressures on the region, GHG mitigation, and a portfolio of approaches for multiple levels of safety; evaluated with multiple social, economic and environmental criteria; respect equity and adaptive capacity needs; responsive to climate surprises; and be resilience and employ adaptive management as needed. In addition, because adaptation is often implemented at the local level, local stakeholders must be integrated into the planning process. (Stakhiv 2010, Lempert and Groves 2010, Ray et al 2011, Kirshen et al. 2011, Yohe 2009)

Thus researchers are stressing the possibilities of using flexible, decentralized approaches to adapt to the increased drainage flooding and associated water quality impacts under climate change (Kirshen et al, 2011, Auld et al, 2010, WERF, 2009, Roseen et al, 2011). This is in contrast to large scale solutions such as sewer separation, which might be effective and robust, but also can be expensive and inflexible.

One of the most flexible and decentralized approaches is Low Impact Development (LID), in which even, without climate change, there is currently much interest and some such as Heaney and Sansalone (2009) view as one of the best approaches for the future management of urban drainage. Thus this approach is no-regrets policy. LID is "an approach to land development (or re-development) that works with nature to manage storm water as close to its source as possible. LID employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat storm water as a resource rather than a waste product."[13] LID techniques essentially let the water stay where it falls either through storage or infiltration and are seen as particularly promising to better manage runoff by keeping the water out of the built drainage network and not letting the flows concentrate and cause damage (Roseen et al, 2011).[14] LID techniques include decentralized approaches such as porous pavement, preservation of buffers, bioretention, distributed storage,

[13] U.S. Environmental Protection Agency, http://www.epa.gov/owow/NPS/lid, accessed July 5, 2011
[14] Ibid

and rain gardens. Conventional approaches are generally designed for singe large events such as 10 or 100 year events and may actually be designed to pass through storms of higher frequency and, in any case, do not have the water quality benefits of LID. LID techniques also provide the additional benefits of providing more open, green space in communities, aiding GHG mitigation, promoting natural cooling, and increasing property values. As WERF (2009, page 62) states " It is conceivable that, under the right conditions, the long term answer may lie in green infrastructure strategies designed to reduce runoff and prevent it from entering combined sewers or leaky sewers. As more and more green infrastructure is added to such a program year after year, it may be capable of keeping up with the gradually increasing rainfall intensity phenomenon over the course of time". Roseen et al (2011, pages 1-4) also support this; "The same strategies that are applied to managing increased runoff volume from impervious surfaces can be used to manage increased storm size from climate change."

Some drawbacks of LID include potential construction and maintenance costs, presently unknown long term performance, possible attraction of waterborne diseases, and ability to only manage the first inch or few inches of a storm. Management of the first inch or so may be adequate for water quality but will not stop large scale local flooding.

Effective management of storm water may require mixing green and gray (conventional) approaches to meet both storm water quantity and quality management goals (Roseen et al, 2011). Gray infrastructure manages large flooding events and LID provides for water quality treatment. LID is particularly effective in meeting new water quality goals for storm water management, which traditional methods are not. LID can be economical if life cycle and total benefits are included. Economic benefits are due to cost savings in land space for large ponds, and less reliance on below ground conduits, curbs, catch basins and other gray features. As noted earlier, LID techniques also provide the additional benefits of providing more open, green space in communities, aiding GHG mitigation, promoting natural cooling, and increasing property values.

Roseen et al (2011) report the storm drainage cost for a shopping center in the northeast was able to reduce costs by 26 percent or approximately $1 million using LID instead of conventional approaches. Combined approaches by Portland OR reduced CSO management costs from $144 million to $ 81 million. LIDs enabled Chicago to divert 70 million gallons in one year from its CSO system resulting in energy savings as well as green space benefits. New York City Department of Environmental Protection expects to reduce its CSO costs from $6.8 billion using a gray-only strategy to $5.3 billion using a mixed LID-gray strategy. In addition, the combined strategy will result in other benefits related to sustainability including reduced UHI effect, better air quality, and higher property values.

Other drainage management techniques are also attractive for adaptation. For present and future drainage systems, Heaney and Sansalone (2009) recommend load management by removing pollutants from overland surfaces such as by street cleaning. They also advocate for the use of real-time monitoring and control to improve the management of urban drainage and sewage systems.

One common theme to these approaches is they use Green Infrastructure, "An adaptable term used to describe an array of products, technologies, and practices that use natural systems – or engineered systems that mimic natural processes – to enhance overall environmental quality and provide utility services."[15] Green infrastructure also provides for carbon capture and storage.

Another approach to storm water management is to combine it with the holistic management of storm water, flood waters, water supply, and wastewater management, an approach advocated by many (Novotny and Brown 2007, Zoltnay et al 2010, Daigger 2009). For example rainwater harvesting not only contributes to management of storm water but can also be used for water supply. Water infiltrated in LID recharges groundwater, which improves water supply and baseflows in rivers. Gleick (2010) advocates it for adaptation in the southwestern U.S. Morsch and Bartlette (2011) report that some states presently have policies to encourage these types of strategies as part of their adaptation plans. It is now the policy of California to integrate for water supply management the following water sources: groundwater, surface water, recycled municipal water, flood flows, urban runoff, imported water, and desalination. Demand management can also be mandated by the state. Pennsylvania has policies to encourage the use of green infrastructure and ecosystem based approaches to manage storm water and flooding.

Daigger (2009) notes that the need to replace aging drainage infrastructure will provide the opportunity to modernize drainage over time. Thus adaptation can also be implemented at the same time. Infrastructure planning should incorporate climate change as a factor in its asset management and rehabilitation of critical facilities (NYCDEP, 2008; King County, 2008). There may also be need for operational changes to account for changes in hydraulics (King County, 2008). An iterative approach that considers and regularly revisits climate observations and projections can allow planners to determine when the benefits of taking adaptive measures will outweigh the costs.

3.4.5 Overcoming Barriers and Stimulating Innovations

Managers of water supply and wastewater systems should incorporate climate change impacts and vulnerabilities into design criteria and into the operation of these systems. Many innovations now exist to reduce vulnerabilities and impacts through effective adaptation strategies. The next step is to create or extend local capacity along with the institutional arrangements to support that capacity with federal, state and private sector guidance.

[15] http://cfpub.epa.gov/npdes/greeninfrastructure/information.cfm#greenpolicy, accessed October 22, 2011

3.5 **Public Health**

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3.5.1 Context

Urban areas are important drivers of climate change, because of their concentration of business operations and extensive transportation networks. In addition, urban areas are particularly susceptible to climate impacts due to their high population density, concentration of diverse and vulnerable populations, enhanced warming as compared to surrounding areas, and in many cases, proximity to water bodies. The health sector in metropolitan areas is vast and encompasses metropolitan hospitals, local clinics, emergency services, and city agencies. These entities play a crucial role in planning, monitoring, and responding to health impacts of extreme weather events, but also can themselves be vulnerable to service disruption during such events. Rising temperatures, changes in extreme heat and cold weather events, increased intensity of storms and related flooding and storm surge in coastal and low lying urban areas all have the potential to impact public health in urban areas.

Increased demand on emergency systems is likely to contribute additional burden to systems that may already be overstretched. A study in Toronto, Canada found that for every one °C increase in ambient mean temperature, there was a 32 percent increase in ambulance response calls for heat-related illness (Bassil et al., 2011). Emergency medicine will also be impacted by climate change, both because of the populations served and the types of conditions seen. Those who are more vulnerable to the weather extremes – the elderly, the very young, and socioeconomically disadvantaged – rely disproportionately on emergency departments (ED) for medical care (Hess et al., 2009). In addition, many conditions that are particularly sensitive to climate changes are often seen in the ED, such as heat-related illnesses and respiratory diseases (Hess et al., 2009). Therefore, it is likely that the ED will incur increased demand for services as climate-related illnesses increase in the future. Demographic trends in the US will result in a growing proportion of older adults in the next several decades, which will place additional demands on the public health system.

3.5.2 Key Impacts

3.5.2.1 Illness and death due to changes in or extreme temperatures

The global mean temperature is expected to increase by between 1 and 3°C by the year 2100 (Meehl et al., 2007) and perhaps more importantly, the frequency of extreme temperature episodes is projected to rise (Meehl and Tebaldi, 2004). This has important implications for public health because numerous studies have found increased temperature and excessive heat during heat waves are associated with morbidity and mortality (Martiello and Giacchi, 2010). Recently, a national study of heat waves demonstrated that the intensity, duration, and timing of a heat wave are all important factors in the impact on mortality (Anderson and Bell, 2011). In addition, this study found regional differences in the effect of heat waves, which may be explained by a variety of factors including physical acclimatization, different levels of exposure, different community-level responses, and different demographics. In particular, US communities in the Northeast and Midwest had the highest effects of heat waves, underscoring the importance of local adaptation and response. A severe heat wave in Chicago in 1995 led to over 700 deaths, with impacts greatest among people who were poor and/or socially isolated (Klinenberg 2002).

Previous reports have suggested that there may be some decrease in US mortality due to relatively milder winters, although the result in net mortality is not clear because of the complexities and uncertainties associated with expected temperature changes and associated mortality (Ebi et al., 2008). Adaptation to warmer urban temperatures might even lead to greater susceptibility to occasional cold events. With these uncertainties, it is unclear whether cold-related deaths will or will not offset expected increases in heat-related mortality (Medina-Ramon and Schwartz, 2007). Thus, it is important to incorporate preparation for cold-related morbidity and mortality into climate change planning. The potential increase in intensity of winter storms has the potential to both increase personal exposure to cold temperatures and interrupt residential and commercial heating supplies (Conlon et al., 2011).

Studies of seasonality and preterm birth, stillbirth, and low birth weight have reported peaks in winter, summer, or both, leading to the hypothesis that temperature extremes may be important in birth outcomes (Strand et al., 2011). A limited number of studies have specifically looked at ambient temperature and preterm birth or birthweight, but the different populations and methodologies have led to inconsistent findings. A recent paper examining ambient temperature and preterm birth in a cohort of almost 60,000 births in California found an 8.6 percent increase in preterm delivery associated with a 10°F increase in weekly average apparent temperature (Basu et al., 2010).

3.5.2.2 Air quality health impacts due to warming

Rising temperatures are expected to have impacts on air quality, specifically ground-level ozone. Ground-level ozone is a secondary pollutant formed from oxides of nitrogen (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. A recent interim report from the US EPA Global Change Research Program underscored the importance of climate change in regional air quality planning. The report concluded that climate change has the potential to produce significant increases in near-surface O_3 concentrations throughout the United States, as well as the potential to lengthen the O_3 season (Kinney, 2008; U.S. EPA, 2009). It was also noted that climate change could decrease O_3 in remote areas with low levels of NOx (US EPA, 2009). The literature on synergism between heat and ozone effects on human health is limited and it is not clear how much of the mortality in a heat wave is attributable to ozone versus temperature (Doherty et al., 2009). There is an indication that these environmental factors interact, and preliminary evidence indicates that this synergism may be enhanced in cities that are highly populated (Pattenden et al., 2010), although further research is needed. An additional potential air quality and heat synergy was illustrated by the 2010 fire smoke and heat that impacted Moscow. Similar events have the potential to occur in the US, with downwind impacts in urban areas. The impacts of climate change on anthropogenic particulate matter levels is less predictable that is the case for ozone and has been the subject fewer studies to-date.

A recent paper modeling asthma morbidity from increased ground level ozone due to climate change projected a 7.3 percent increase in regional summer ozone-related asthma emergency department visits by 2020 in the New York metropolitan area (Sheffield et al., 2011). This outcome was obtained for the A2 greenhouse gas emission scenario driving the GISS climate model, downscaled using MM5 and linked to the regional scale CMAQ air quality model. While some areas will experience increased dry spells and others will experience increased wet spells, research indicates that changes in climate, such as temperature, humidity, and precipitation, have the potential to alter the concentration and allergenicity of pollen and mold, as well as the length of their seasons (Sheffield et al., 2011). Effects of changing CO2 and climatology on pollen season length and intensity is an issue of importance to allergy sufferers in US urban areas. A recent study by Ziska and colleagues reported changes in pollen season length over time and space in relation to climate variations (Ziska et al., 2011).

3.5.2.3 Storms, floods, water-borne risks

Health impacts of extreme storms depend on the interaction between hazard exposure and characteristics of the affected communities (Keim, 2008). Coastal and other low-lying infrastructure and populations in urban areas can create vulnerabilities related to communications, healthcare delivery, and evacuation. Health impacts include direct effects (eg: death and injury) and indirect, long-term effects on contamination of water and soil, vector-borne diseases, respiratory health and mental health (Gamble et al., 2008). Infectious disease impacts from flooding include creation of breeding sites for vectors and bacterial transmission through contaminated water sources causing gastrointestinal disease. Additionally, chemical toxins can be mobilized from industrial or contaminated sites (Karl et al. 2009). Elevated indoor mold levels associated with flooding of buildings and standing water have been identified as risk factors for cough, wheeze and childhood asthma (Jaakkola, et al., 2005; Bornehag, et al., 2001). Mental health impacts may be among the most common and long-lasting impacts of extreme storms as well as droughts; however to date they have received relatively little study (Berry et al., 2010). Stress of evacuation, property damage, economic loss, and household disruption are some of the triggers that have identified through recent work with populations in the Gulf Coast and Midwest region (Weisler et al., 2006; Gamble et al., 2008).

Waterborne infections may be contracted through consumption of drinking water, by inhalation of aerosols containing bacteria, and by direct contact with recreational or floodwaters. Commonly reported infectious agents in recent US include legionella bacterium, the cryptosporidium parasite, campylobacter, and giardia (CDC 2011). Changes in the temperature and the hydrological cycle can influence the risk of waterborne diseases (Curriero et al. 2001, Greer et al., 2008).

3.5.3 Key Vulnerabilities and Risks

The U.S. Census has estimated that the size of the elderly population is expected to grow substantially, thus the risks to this population sector will also grow. The elderly have often been recognized as a group that is particularly vulnerable to weather changes, specifically temperature-related morbidity and mortality (Basu, 2009). Because elderly people spend approximately 90 percent of their time indoors in the US (USEPA), a recent study in Detroit, MI, examined how outdoor summer temperatures relate to indoor summer temperatures in a sample of 30 residences occupied by persons over the age of 65. During the sample period, average maximum indoor temperature for all locations was 34.85 °C (94.73 °F), 13.8 °C (56.84 °F) higher than average maximum outdoor temperature (White-Newsome et al., 2011). In addition, of the characteristics that were under study, homes that were more sensitive to outdoor temperature and solar radiation were made of asphalt, low rise, and built between 1912 and 1939. The last characteristic is particularly relevant to urban areas, as many of the buildings are of older construction.

Children are especially susceptible to environmental exposures because of their physiology and metabolism, increased absolute and proportionate exposure, and different behaviors. Allergic and non-allergic diseases to which children are susceptible to are expected to be exacerbated by changes in air pollutants and allergens due to climate changes (Sheffield and P. J. Landrigan, 2011).

Individual socioeconomic and medical characteristics may confer additional susceptibility to climate variability and change. There is evidence that socio-demographic characteristics such as age, race, and educational attainment can affect susceptibility to temperature health effects (Anderson and Bell, 2009; Medina-Ramon et al., 2006). Recently, this research has progressed further to examine characteristics within metropolitan areas that confer susceptibility. A study mapping heat vulnerability in the US demonstrated higher vulnerability in the downtowns of metropolitan areas than in those areas outside the city center (Reid et al., 2009). However, this study did not relate the vulnerability characteristics to health outcomes. A recent study of neighborhoods within two US cities, examining certain vulnerability characteristics in relation to heat-related morbidity and mortality found that neighborhoods with more heat exposure (e.g. percent impervious surface), vacant households, and Black, Hispanic, and socially-isolated residents had more heat-distress calls than other neighborhoods in Phoenix, AZ (Uejio et al., 2011). This same study found that in Philadelphia, PA, neighborhoods with lower housing values and a higher proportion of Black residents had more heat-related mortality. These vulnerability factors may work together in certain urban neighborhoods to heighten the burden of climate change (e.g. poor elderly populations) and make it increasingly difficult for such populations to adapt and respond to climate change impacts.

3.5.4 Adaptations

Effective adaptation efforts cross time scales, often involve other sectors, and can have benefits beyond those related to climate change. On shorter time scales, adaptation efforts include infrastructure planning to reduce impacts, such as unimpaired emergency transportation systems and routes, improved sanitation systems, as well effective communication to the most highly vulnerable populations so they will take necessary actions, (i.e., move to cooling centers, evacuate appropriately, boil water, avoid contaminated water bodies).

Weather and seasonal forecasting tools, such as those that predict El Nino conditions and related drought, flooding, wildfires can be used as part of a comprehensive adaptation plan. Adaptation actions include communication through trusted sources—public health officials and weather forecasters (Maibech et al., 2008) - to encourage appropriate outdoor activities and exercise; pre-plan and pre-position emergency or disaster relief resources before the event; improved public health surveillance-to establish baselines as well as detect emerging outbreaks or disease incidence; planning for anticipated changes in mosquito, rodent and tick vectors of disease.

Longer time scales involve urban planning, increasing urban green space, access to low carbon footprint food, improved sanitation systems and sewage infrastructure, access to clean water and reliable food supplies, effective and understood evacuation plans, and accessible transportation for evacuation and access to emergency facilities, improvements in surge capacity for hospitals and emergency departments, training of hospital and medical personnel to deal with multiple emergencies and to detect new or emerging diseases and other health risks before an outbreak.

While air conditioning plays a central role in reducing human exposure to extreme temperatures, it is important to note that this also contributes to climate change through increased greenhouse gas emissions. A comprehensive adaptation plan will balance the risks and benefits of alternative strategies, and attempt to include measures that have a less damaging impact on the environment. Some strategies that might be employed are enhancing green space, particularly in areas that resource poor, installing cool roofs, and devising risk management plans to prevent isolation of elderly and vulnerable residents during heat waves and extreme weather events. Other strategies that have the potential to mitigate climate change and improve air quality and human health should also be considered (Shindell et al., 2012).

3.5.5 Overcoming Barriers and Stimulating Innovations

In many cases the local public health infrastructure is not currently prepared to meet the increased demand that will be brought about by climate change. Links to transportation and sanitation infrastructure are also critical for public health. Orderly and safe evacuation requires that critical transportation routes are open during hazardous events. Significant challenges exist to ensure that urban populations have access to, and use, traditional public health infrastructure--functional hospitals, urgent care facilities, or relief centers--during extreme weather events. In addition, in many cities the sanitation infrastructure is based on Combined Sewage Overflow (CSO) to manage excess water during storm and flood events. Most of the CSO infrastructures were built when urban populations were much smaller, are inadequate to serve current population size, and are in need of repair. This results in contaminate sewage water flowing into the streets and into local water bodies during heavy rainfall events. A survey of directors of local public health departments in the US concluded that a majority of them saw climate change as a public health problem likely to become more serious over the next 20 years, but very few had made climate change a priority in their department (Maibach et al., 2008). Reasons for this include lack of knowledge within the public health community and among key stakeholders in the community, other public health priorities, and a lack of resources. These factors are likely to play an even larger role in smaller metropolitan areas around the country.

Near real-time surveillance systems may be useful innovations in the urban response to climate change. New York City recently developed a syndromic surveillance system for cardiovascular morbidity related to air pollution and other environmental events (Mathes *et al.*, 2011). Such a model can prove useful in detecting city-wide increases in illness due to weather changes or natural disasters related to climate change.

3.6 **Ecosystems and the built environment**

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3.6.1 Context

Cities are recognized for their population and building density as well as the network of hard infrastructure needed to support that density. Many cities, however, also have a rich and complex network of natural systems that play a vital role in enabling cities to function. The built and natural environments in cities will both be impacted by climate change and can be utilized to mitigate some of the anticipated impacts.

How a city is laid out, land is used, property zoned and regulated, and buildings designed and sited play a significant role in community resilience including for adaptation to climate change (Cutter et al 2008). Additionally, the interplay of urban density and form, open space, natural elements (e.g. trees, rivers), and forests, wetlands, and watersheds in the surrounding region also help to determine adaptive capacity (Foster, et al 2011). The degree to which temperature and precipitation including extremes can be effectively regulated and managed via adaptations in built environments, infrastructure, and services is at a crux of urban quality of life in a changing climate. Ecosystem services, green infrastructure design, low impact development, and green innovations are increasingly recognized as a critical element of comprehensive responses to climate change. Ecosystem services are improvements to the environment that directly sustain or enhance human well-being (Brown, 2007).

The Millennium Ecosystem Assessment classifies ecosystem services into four categories: supporting, provisioning, regulating and cultural. *Supporting services* are naturally-occurring processes that organisms perform such as photosynthesis, nutrient cycling and soil formation (WRI MEA, 2005). These functions result in *provisioning services* - or goods - such as food, water, fiber and natural medicines that humans use and for which there are often associated markets (Brown, 2007; WRI MEA, 2005). *Regulating services* are improvements to environmental conditions that result from supporting services and from which humans derive benefit. These include water purification, pest regulation, hazard protection and climatic regulation, among others (Kinzig et. al 2011). For example, a supporting service would be nutrient cycling by soil microorganisms where the soil is the provisioning service and water purification (due to contaminant removal by the organisms through decomposition) is the regulating service. Lastly, *cultural services* provide aesthetic, cultural, educational, spiritual or recreational values (WRI MEA, 2005).

Cities have long used policy, urban design, and ecosystem services to enhance the resilience of public and private buildings, infrastructure, and services to weather extremes and climate variability. Environmental protection and management of urban density have been used for decades as means to change the character of the built environment and infrastructure to achieve environmental goals, improve quality of life, and—while often unacknowledged—help cities to bounce back from weather extremes, natural disasters, and other environmental stresses (Foster, et al 2011; Kooshian et al, 2011). For example, policies encouraging urban tree planting and zoning for open space improve quality of life while also helping slow runoff from rainstorms and lessen the frequency and impact of flooding (Foster, et al 2011). More recently, green infrastructure and ecosystem services practices are increasingly being brought into the mainstream of urban planning, design, and operations (e.g. in localities such as Chicago, New York City, Seattle, Toronto, and Miami Dade County) (ISC 2010). These practices have enhanced the capacity of local urban governments to better assess, plan, prepare for, and manage risks from climate variability and change (floods, droughts, wildfire, sea-level rise, and public health threats, etc.) while also enhancing the local resilience of the built environment and infrastructure to climate impacts (Foster, et al 2011; Lowe et al 2009).

Conventionally local governments and economies have used the most efficient and cost-effective plans and practices as a means to manage weather and climate variability substituting technology and "hard infrastructure" for natural systems. However, cities and urban regions now are recognizing the value of blending traditional "grey infrastructure" methods with green infrastructure practices, ecosystem services, eco-buildings, and innovative urban design, form, and land use to achieve greater environmental sustainability and to adapt to future climate changes. The idea of mimicking the natural environment is catching on not only because of greater potential resilience but also because practices (such as green roofs or urban tree planting) are often more cost effective than "grey" alternatives (e.g. underground storm water storage) and provide multiple benefits regardless of the magnitude and timing of emerging global climate changes (Foster, et al 2011; Hewes and Pitts 2011).

Spatial scale plays a crucial role in how climate change impacts to buildings and infrastructure are experienced and how adaptive "green" solutions are implemented. For example, flooding—anticipated to become more frequent or intense under various climate change scenarios—simultaneously will impact an entire watershed in which a city resides while also effecting neighborhoods and individual property owners. To be effective, green infrastructure solutions need to be implemented by both local governments and landowners broadly enough to achieve economies of scales across jurisdictions. For example, planting one tree to better manage stormwater has little benefit but planting a million across a city or region on public and private lands will have significant aggregate benefit—especially when considering co-benefits, such as pollution abatement, cooling, reducing urban heat island temperatures, fewer combined sewer overflows, and carbon sequestration (Foster, et al 2011). Meanwhile, gray infrastructure for a storm water management derives value more from being sited in a specific location solely at public expense and does not necessarily achieve greater economy of scale if implemented regionally – just increases in cost.

3.6.2 Key Impacts

3.6.2.1 Buildings

The typical American spends 90 percent of their life indoors. Consequently, homes, offices, schools, and other structures provide the context for our lives and mediate our impact on the environment. Buildings reflect many dimensions of culture, technology, and societal values and aspirations. Buildings are usually customized to the specific range of climatic variability expected for a given location; typically based on historic meteorological observations. Climatic information is implicitly embedded throughout a project, including specifications for the envelope, windows, heating and cooling equipment, stormwater management, and landscaping. Climatic assumptions also underpin buildings codes which, typically, strive to balance tradeoffs between the cost and efficiency of individual measures under different circumstances. For example, California's well-known Title 24 building energy codes are customized to 16 historic climate zones across the state. Climatic changes have the potential to alter code requirements based on historic conditions in these areas (Miller at al., 2008).

Changing conditions can invalidate these assumptions and call into question the basis for architectural designs and engineering decisions. This has the potential to contribute to underperformance and, in extreme cases, failure. For example, a commercial office building is typically designed to accommodate a so-called Typical Meteorological Year. These data are designed to reflect specific design-relevant features, such as the distribution of heating and cooling degree days and the severity of heat events. Architects and engineers use this information to specify requirements for insulation, grazing performance, and mechanical systems. Rising average temperatures and changes in temperature extremes might suggest different design and engineering strategies, such as additional shading structures or additional cooling capacity (Wilbanks et al., 2008).

Climate change can also have implications for the health and wellbeing of building occupants (Epstein, 2005). Depending on project circumstances, changing climatic conditions can have implications for air quality and thermal stress. The impacts of these changes are likely to be felt disproportionately by specific sub-populations, such as children, low-income groups, and the elderly (Harlan et al., 2006). Each of these sub-populations has risk factors that increase their sensitivity to environmental exposures and circumstances that reduce the adaptive capacity. Built environments can exacerbate these vulnerabilities with synergistic stressors, such as mold or other indoor contaminants.

3.6.2.2 Ecosystems

In any environment, the quality of ecosystem services is determined by ecosystem health, which can be threatened by many factors. These may include habitat disturbance, non-native species introduction, extraction of natural resources, climate change, modification of rivers, and changes in local land use and land cover (WRI MEA, 2005). In urban areas, ecosystems are impacted by habitat fragmentation caused by changing land use patterns and cover types, high urbanization rates, increased population density, pollution and soil compaction (Depietri et al., 2012).

Changes in climate such as increased temperatures affect species distribution, population sizes, timing of migration and mating events and pest and disease outbreaks (WRI MEA, 2005). Changes in land cover due to urbanization, such as the replacement of pervious with impervious surfaces, may cause lowered groundwater tables, decreased soil moisture content, faster runoff rates and reduced groundwater recharge (Depietri et al., 2012). Extreme weather events like floods may change the natural chemical and physical properties of soil types, thus disturbing organismal activities such as nutrient cycling (Depietri et al., 2012).

All of these factors place stress on natural ecosystems by reducing their ability to perform critical supporting and regulating services. Consequently, as these services become compromised, urban areas may become increasingly vulnerable to impacts from extreme climate events such as floods and heat waves and air pollution (Depietri et al., 2012).

3.6.3 Key Vulnerabilities and Risks

Increasing urban density is imperative if we are to move toward sustainability at a global scale. But one of the problems of increasing urban density is its exacerbation of the urban heat island (UHI) effect. The UHI effect is defined as increased air and surface temperatures in urban areas relative to surrounding suburban and exurban areas (Solecki et al., 2005). Over the last thirty years, our knowledge of UHIs has advanced (Oke, 1973). In metropolitan areas in the United Kingdom, the UHI increased the temperature by as much as 7^{o}C from the surrounding countryside (Wilby, 2003) We now understand that cities and urban areas may contain many dispersed UHIs (Jenerette et al., 2007; Huang et al., 2011, Gaffin et al, 2008). UHIs are not unique to large cities but also exist in smaller cities and towns. Lower-income residents and racial minorities are more likely to live within UHIs (Harlan et al., 2006). UHIs also increase decrease urban air quality by increasing the production of ground-level ozone (Stone, 2004). Climate change will further exacerbate UHI problems, decreasing both residents' interior and exterior thermal comfort during warmer summers and increasing death rates during heat events (Wilby, 2003).

At small scales, the urban built environment creates environmental externalities—a negative impact caused by some practice or activity, but for which there is no penalty when doing so—that generate social costs. These include low albedo (i.e., dark) surfaces like street pavements and rooftops that efficiently capture sunlight and generate extreme summertime surface temperatures. Such impervious surfaces are similarly efficient at capturing rainwater and shunting this into the often combined sewershed-drainage system leading to combined-sewage-overflows (CSOs). Many other ecosystem services are provided by exposed soil systems (Hillel, 2004) - such as water cleansing and cooling, supporting urban vegetation and biodiversity - and are similarly lost by installing an impervious surface. The urban built environment creates 'urban canyons' that have many atmospheric effects and impacts, such as altering winds, additional sunlight trapping or shading and reducing skyview from the ground, which impedes night-time thermal cooling – a major contributor to the urban heat island effect. Developers are free to install low albedo and impervious surfaces and to cover soils on their property but do not pay for the social costs generated by these practices, which accumulate collectively. In the same way that greenhouse gas emissions generate social costs that are currently unvalued.

3.6.4 Adaptations

Enhancing urban ecosystems through “low impact development” (LID) and “green infrastructure” (GI) could mitigate the many of the anticipated impacts of climate change. The terms LID and GI are used interchangeably although they may not always overlap with respect to technologies and systems implied. LID and GI have in common the general goals of increasing onsite retention and stormwater infiltration (Pyke et al, 2011) and, ideally, of restoring pre-development hydrology for the area (e.g., LID Center (2011)), while creating concurrent environmental benefits. To the extent that LID refers to “development” it may be the more inclusive term at larger scales and could include concepts such as ‘smart growth’ with efficient transportation and urban planning, for example.

GI may be distinguished by the fact that it usually implies systems that deliver *multiple environmental benefits* beyond just hydrology, including heat reduction, biodiversity increases and urban amenity value. In this sense GI is also distinct from the term “gray infrastructure,” which is meant to be a ‘hard engineering’ solution to a specific problem, such as a water-retention tank. Green strategies will carry multiple benefits beyond just coastal protection and include ecological and habitat restoration, water pollution prevention, contaminant removal and other natural services.

At neighborhood and city scales, small-scale green infrastructure strategies such as bioswales, rain gardens and green roofs and abundantly healthy soils provide the regulating service of floodwater management (storage, purification and filtration) during storm surges or extreme rain events. At regional and watershed scales, large-scale green infrastructure such as functioning wetlands, forests and waterways also provide these services and their collective impact reduces stress at microscales. In cities like Boston and New York, which have aging infrastructure, Combined Sewer Overflows (CSO) may result from the inability to quickly manage high quantities of stormwater runoff causing contamination of local waterways with toxic sewage. Using natural stormwater treatment systems such as green infrastructure strategies may reduce the load on treatment plants and minimize CSOs.

Cities worldwide are also beginning to develop innovative adaptation plans for reversing altered local climate and hydrology impacts from development. For example, New York City has recently articulated a goal for managing urban imperviousness for 10 percent of its land area by 2030 using a broad array of existing and emerging GI’s (DEC, 2011) Comparable programs are underway elsewhere regionally (Levine, 2011). The notion of reducing or managing runoff for large urban areas represents a prime example of radical new visioning for cities to develop resilience or relatively short time frames (PlaNYC, 2012).

3.6.4.1 Urban forestry and trees

Urban forestry includes planting trees in open spaces such as street trees, but may also include planting in open park spaces as well (Rosenzweig et al, 2009). Improved street tree pit infiltration is an important goal because many urban tree pits are heavily compacted in pedestrian right-of-way areas. Restoring native vegetation is an important strategy because such plant systems are already adapted to the local climate and rainfall. Rainwater capture can take different forms ranging from a humble rain barrel connected to a downspout to more complex retention tanks. Large-scale retention tanks and systems are more inclined to represent gray infrastructure as opposed to green.

Urban vegetation such as street trees, green walls and urban forests can offset the Urban Heat Island Effect (UHI) by providing a cooling effect, thus creating comfortable microclimates for humans to enjoy. This microclimate regulation is a function of evapotranspiration, shade provision and increased albedo (Depietri et al., 2012) and improves thermal comfort, reduces health risks associated with extreme heat, and reduces energy costs. The ability of ecosystems to be resilient to extreme events like heat waves and floods is a function of the hardiness of the local plant selection and the quantity and diversity of species. The greater the diversity, the higher the chance that the overall system will withstand the event and continue to perform regulating services.

Trees also provide the regulating service of improving air quality in cities. Through photosynthesis, plants absorb carbon dioxide (CO_2) and they also reduce concentrations of particulate matter and gases such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and ozone (O_3) (Depietri et al., 2012). The effectiveness of pollutant capture is determined by species type, canopy area and leaf surface area (Depietri et al., 2012). Coniferous trees with pine needles are best for filtering smaller particles while trees with sticky bark or leaf surfaces are best at filtering larger particles. Greater biological diversity collectively creates a more effective ecosystem service.

3.6.4.2 Buildings

Buildings offer more than vulnerabilities. They also offer a range of opportunities to prepare for changing conditions. These opportunities can be found across the life cycle of buildings, from the earliest stages of conceptual design through engineering during operations and in the behavior of occupants.

Several studies have reviewed opportunities for adaptive changes in individual building components, such as roofs, windows, and foundations (Wilson, 2009) Simulations for a variety of buildings types in the United Kingdom show that adaptive design and engineering changes can reduce the thermal responsiveness of structures and improve the indoor thermal comfort of occupants (Hacker et al., 2005).

Research has also shown that adaptive opportunities extend into the operational phase, including facilities management and occupant behavior (Kwok and Rajkovich, 2010). Facilities managers have shown that they can use available controls to reduce the impacts of heat storms and extremes. For example, managers may utilize pre-cooling strategies to reduce peak demand using short-term forecast data or manage the use of outside air to reduce exposure to urban air pollutants.

Some widely-used building engineering standards assume that building occupants are essentially passive receptors of delivered conditions. These guidelines presume that occupants cannot or will not act to increase their comfort. However, researchers have also shown that occupants can and will adapt through individual changes in physical activity, clothing, and personal space conditioning. These strategies make occupants active participants in adaptation at personal scales. Personal behavioral adaptations provide important opportunities; however, it must be recognized that vulnerable sub-populations may have significant limitations.

It is clear that buildings can have sensitivities to changing conditions, and they can provide valuable opportunities to prepare and adapt. The majority of studies-to-date have used a relatively reductionist approach to consider impacts and opportunities as individual decisions. There are significant opportunities to consider impacts and adaptive opportunities on buildings and communities based on their behavior as complex, coupled systems. Such considerations may change the understanding of impacts and potentially identify additional adaptive opportunities. For example, informed site design and landscaping by reduce solar heat loads on a structure and reduce the need for additional energy consuming and emissions producing cooling technologies under future temperature regimes. The net benefit of these measures would ultimately depend on how they are deployed as part of an integrated building system.

3.6.4.3 Cool Roofs

White roofs are a fundamental method for lowering the surface temperatures for large areas of the urban landscape. Albedo is the scientific term for the fraction of incident solar radiation that is reflected by a given surface. A clean white surface can often reflect up to 80 percent or more of such incident light, in contrast to dark asphaltic surfaces that often *absorb* 80 percent or more of such light energy. White roof membranes are increasingly becoming available as single-ply elastomeric or thermoplastic options (Gaffin et al, 2012) and are available at the same cost as traditional dark membranes. They arrive on-site as pre-fabricated sheets that are unrolled and fastened or ballasted to the subsurface. For rooftops with very simple geometries, infrastructure and few penetrations (e.g., big-box stores) such single ply membranes are easily installed and are the norm. For more complex roof geometries and infrastructure, dark asphaltic built-up membranes have been traditionally used, which is one reason for the preponderance of dark roofs in urban areas. The easiest cool roofing retrofit in these cases is white elastomeric acrylic paint as it is cheap, and can be done with minimal technical training. The acrylic paint approach probably represents the fastest technology for rapidly increasing urban albedo significantly (Gaffin et al, 2012).

Dramatically raising rooftop albedo is the clearest 'low-hanging fruit' among technology options for raising urban albedo. Creating effective bright surfaces at grade presents much greater challenges and even acceptance for urban human activity at street levels (e.g., glare, safety). Other rooftop sited technologies such as solar panels, solar thermal, wind power, are green technologies as well and are more thoroughly discussed in studies on green building design.

3.6.4.4 Green Roofs

Vegetated green roofs have experienced a remarkable growth of interest within the United States within the past 10 years. Virtually unknown to the U.S. public at that time, they have since become an increasingly familiar green infrastructure option for cities. The reasons for this include the fact that aggregate urban roof space can range from 10-20 percent of urban land area and as such represents one of the largest untapped areal greening opportunities remaining in cities. Moreover the current roof landscape is not just an unproductive or an untapped resource, but rather an environment negative due to aforementioned low-albedo and impervious effects creating urban heat and runoff pollution. Roof spaces are also relatively unoccupied, safe, secure areas meaning green infrastructure that may be costly in some cases, can be deployed there with reduced risks of human interference and low maintenance (Gaffin et al, 2010).

A distinction should be made between green roofs that are non-agricultural and those that are intended for urban farming. The latter are very unlikely to be installed at anywhere near the scale of sedum-based green roofs. The reasons for this include the need for greater medium depths and hence rooftop loads for farms, the need for much more maintenance and human presence and the need for additional material and water inputs for irrigation and other farming needs.

By contrast, sedum-based green roofs have been shown in many studies to be proven, low maintenance systems that achieve many environmental goals such as heat reduction and distributed stormwater control (Gaffin et al, 2011; Gaffin et al, 2010). Moreover they have been shown to deliver additional ecosystem benefits such as biodiversity and even ecosystem restoration potential (Snodgrass and McIntyre, 2011). System weight can be as little as 12-15 lbs/ft^2 fully saturated meaning such green roofs will be a viable option for many more city rooftops.

Rain barrels, which have been in use for centuries as a method to collect rainwater from rooftops for later use or consumption (Sands and Chapman 2012), can also be used to reduce flooding risks. The applications of rain barrels have recently increased because of the renewed recognition of the relative ease of making downspout connections. Their uses now include lawn and garden watering (usually during a drought) as well as CSO reduction. Recently, cities nationwide such as Milwaukee, Washington D.C., and New York have adopted programs that freely distribute rain barrels to private building owners. For example, last spring the New York City DEP distributed 1,000 rain barrels on a first-come, first-served basis throughout Brooklyn, Queens, Staten Island and the Bronx (Cheeseman, 2011).

3.6.4.5 Urban Heat Island

Efforts to lessen the negative impact of the UHI may be categorized into four categories of adaptation strategies: 1) modifying urban geometry, 2) altering surface thermal and energy balance properties, 3) increasing energy efficiency, and 4) reducing anthropogenic heat. The first category of strategies considers optimal building location, building design and street orientation to reduce prolonged sun exposure and increase natural ventilation. Also within this category of strategies is consideration of how building heights relative to street widths create urban canyons that reduce skyview and impede longwave cooling to the atmosphere (Offerle et al., 2007). Oke et al. (1991) found that canyon geometry and the presence of impermeable surfaces were approximately equal in their contribution to the UHI formation.

The second category of adaptation strategies involves altering impermeable surfaces to i) permeable surfaces, ii) light-colored surfaces, or iii) vegetated surfaces. Large portions of cities are covered with asphalt and concrete surfaces that absorb sunlight during the day and release this heat during the night. Oke at al. (1991) found that canyon geometry and the presence of impermeable surfaces were approximately equal in their contribution to the UHI formation. Light colored or 'cool' surfacing constitutes another category of adaptation strategies (Gaffin et al, 2012). Interestingly, Meyn and Oke (2009) studied seven North American roof materials and assemblages used on both flat and pitched roofs and found the contribution of roofs to the total heat storage was relatively minor compared to the ground surfaces and walls (Meyn and Oke, 2009).

The third category of adaptation strategies calls for increased building energy efficiency (Shahmohamadi et al., 2011). Reliance solely on mechanical cooling to address UHI problems is not desirable from a long-term perspective due to the release of additional emissions, the fragility of the electrical grid, and the problem of poverty utility for our cities' poorest residents. Akbari and Taha (1992) found that the UHI increased the air-conditioning peak electricity demand in 5 US cities between 5 to 10 percent. Therefore, passive ventilation strategies should be prioritized.

The fourth category of UHI adaptation strategies strives to reduce the presence of anthropogenic heat (Shadmohamadi et al., 2011). Some research has indicated that anthropogenic heat increases UHIs by 1 to 3˚C (Fan and Sailor, 2005). Reducing the contributions of air-conditioning units and industrial processes in urban areas would require that planners will actively protect natural ventilation as a resource within urban settings. In many cities, private vehicles generate large amounts of waste heat.

3.6.5 Overcoming Barriers and Stimulating Innovation

When decision-makers evaluate the value of ecosystem services within an urban area, consideration should be given to the trade-offs that often exist among ecosystem services with respect to context, scale, and species diversity.

For example, one study in Britain looked at the relative performance of floodwater management, carbon storage and agricultural production as regulating services under two development scenarios: 1) the expansion of urban areas outward from an existing city in a typical "urban sprawl" fashion and 2) increasing density within the bounds of an existing city. The results showed that floodwater mitigation services were less impacted in scenario 1 compared to scenario 2 but the converse was true for carbon storage and agricultural production (Eigenbrod et al., 2011). Therefore, ecosystems services must be evaluated in relationship to each other and within the context of the urban area.

Furthermore, impacts to ecosystems and the services they provide are felt across local, regional and continental scales (Grimm et al., 2008). For example, urbanization not only affects the availability of provisioning services, such as food, but also the distribution of its beneficiaries, such as people who live in cities but get their food from agricultural lands in rural areas (Eigenbrod et al., 2011). Urbanization trends – whether increasing density within an urban area or expanding urban areas into suburbs – will affect the distribution of ecosystem service supplies and beneficiaries. Due to the tradeoffs among ecosystem services at different scales, smart land-use and planning policies can mitigate ecosystem service loss provided that the value of the service is quantified (Eigenbrod et al., 2011).

Ecosystem services are only as effective as the diversity and health of the species that create them. Consequently, a city's resilience to varying weather conditions is improved by a great diversity of species that can adapt to, if not withstand, those changing conditions (Perrings et al., 2010). Biodiversity of species is critical to withstanding erratic climate patterns not only within the boundaries of a city, but also within smaller environments within that larger ecosystem (Perrings et al., 2010). For example, species that regulate microclimate are different from those that produce food, and a city that has multiple types of species that perform many different regulating services will be more resilient than a city that only has a single type (Perrings et al., 2010). Biological diversity within the group of species that performs a single regulating service is also preferable. For example, in a coastal urban area, vegetative species that withstand flooding as well as saltwater intrusion are preferable to those that only manage stormwater.

3.7 **Coastal Zones**

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3.7.1 Context

Sea level rise would increase exposure of many major U.S. coastal cities to destructive floods, enhanced beach and shore erosion, submergence of salt marshes, and saltwater incursion into estuaries and aquifers, which would cause significant property damage, more frequent transportation and communication disruptions, and permanent land loss. Nearly 3 percent of the total United States population, excluding the Great Lakes, lives within the 100-year flood zone[16] (Crowell et al., 2010). Two U.S. metropolitan areas--New York City-Newark and Miami--rank among the top 20 international ports by population exposed to the 100-year coastal flood now and in the 2070s (Hanson et al., 2011). By the 2070s, Miami, New York City-Newark and New Orleans will rank among the top 20 in exposed assets (e.g., infrastructure, building contents).

Global 20th century rates of sea level rise (0.07 in; 1.7-1.8 mm/yr) increased to ~0.12 in (3 mm/yr) since 1993 (Church and White, 2011; Cazenave and Llovel, 2010). By 2100, sea level could rise at least 7-23 in (18 to 59 cm) (IPCC, 2007), or over 3.3 ft (1 meter) (e.g., Vermeer and Rahmstorf, 2010; Horton et al., 2009; Pfeffer et al., 2008).

However, global models provide minimal guidance for local adaptation, because of wide regional variations in sea level rise due to differential land motions from glacial isostatic adjustments, subsidence, neotectonics, and also changes in ocean circulation (Church et al., 2010). In the United States, rates of relative (i.e., local) sea level rise, measured by tide gauges, range between –17.1 mm/yr (Skagway, AK) and +9.7 mm/yr (Eugene Island, LA) (NOAA, 2009). By the late 21st century, sea level in urban areas could rise up to 2 to 3 feet (0.6- 0.9m) or more (Table 3.7.1). Furthermore, projected shifts in North Atlantic circulation could raise sea level in Boston, New York City, and Washington, D.C. an additional 8 to 20 inches (20 to 50 centimeters) by 2100 (Yin et al., 2009; Hu et al., 2011), although these changes are considered fairly uncertain. Thus, future projections should be based on localized sea level, hydrologic, and topographic data (e.g., Southeast Florida Regional Climate Change Compact Technical Ad Hoc Work Group, 2011).

Table 3.7.1. Projected sea level rise for selected U.S. cities.

City	Sea level rise	Reference

[16] The 100-year (or 1-in-100 year) flood has a likelihood of occurring once a century on average, or a 1 percent probability of occurring in any given year.

New York City	2080s: 12--23 inches (30--58 cm); 2080s: ~41--55 inches (104--140 cm)— Rapid Ice-Melt scenario	Rosenzweig and Solecki, 2010; Rosenzweig et al., 2011a
Boston	2100: 24--39 inches (60--100 cm)	Kirshen et al., 2008
Miami-Dade to Palm Beach	2100: 19--57 inches (48--145 cm) relative to 2010	Southeast Florida Regional Climate Change Compact, 2011
San Francisco Bay area	2100(a): 39.4 in (100 cm) (b): 55.1 in (140 cm)	Heberger et al., 2011; 2009

3.7.2 Key Impacts

As discussed throughout this chapter, sea level rise in urban coastal zones will have numerous impacts, including flooding (both coastal and inland) and permanent land loss, storm surges and waves, shoreline retreat, and saltwater intrusion.

Sections of cities such as New Orleans, LA, Norfolk-Virginia Beach, VA, Miami, FL, New York City, and Oakland, CA located on low-lying barrier islands, estuaries, deltas, and inter-tidal wetlands are at high risk to episodic flooding and land loss. An estimated 3.7 million people within the contiguous U.S. live within one meter (3.3 feet) of local high tide (Strauss et al., 2012). Twelve coastal U.S. cities with population over 300,000 have elevations of 3.3 ft (1 meter) or less (Weiss et al., 2011). For example, in New Orleans, 91 percent of the land is 3.3 ft (1 meter) or lower; corresponding figures for Miami and New York City are 18 percent and 7 percent, respectively (Weiss et al., 2011; Overpeck and Weiss, 2009). In Miami-Dade County, a 0.9 meter (3 ft) sea level rise could inundate up to 18 percent of the county and 33.6 percent of the eastern two-thirds urban land area (Southeast Florida Regional Climate Change Compact, 2011, 2012).

Even at present, both tropical and non-tropical coastal storms produce flooding, beach erosion, and other damage (Table 3.7.2). Rising sea level will cause more frequent coastal flooding, even with no changes in storm frequency or intensity (e.g., Table 3.7.2).

Table 3.7.2. Recent hurricanes and strong coastal storms (2008-2011)

Storm event	Cities, states most affected	Main impacts
H. Gustav 9/1/08 cat 2	Baton Rouge, New Orleans, LA	Strong winds, heavy rain

H. Ike	9/13/08 cat 2	Galveston; Houston, TX; LA	High storm surge and coastal flooding; 3rd costliest in 110 years[17]
Nor'Ida	11/13-14/09	Norfolk, VA; Ocean City, MD; DE; NJ	Surge, coastal erosion, heavy rain, flooding[18]
The 2009-2010 el NiZo		San Francisco, Ventura, CA; OR; WA	High waves, coastal erosion[19]
H. Irene	8/22-29/11 cat 2	NC; VA; NJ; NY; CT; VT	Severe inland flooding, strong winds, coastal erosion
T.S. Lee 9/4-8/11		southern LA; Binghamton, NY; Wilkes-Barre, Harrisburg, PA	Heavy rain, severe inland Flooding

Heavy rainfall accompanying coastal storms (Table 3.7.2) have also produced severe inland flooding. Cities along tidal rivers (e.g., New Orleans, New York City, Wilmington, Philadelphia, Washington, D.C., and New Haven) face flooding from both high surges and overflowing rivers.

High waves and/or water levels during intense storms lead to beach erosion and shoreline retreat. Wave heights and storm intensity have increased in the Pacific Northwest in recent decades. Extreme waves during the 2009-2010 El NiZo caused greater shoreline retreat than during the record 1997-98 El NiZo, especially in northern California, including the Pacific shoreline near San Francisco (Barnard et al., 2011). Other recent storms producing extensive coastal erosion include Hurricane Ike, Nor'Ida, and Hurricane Irene (Table 3.7.2). Sea level rise is likely to exacerbate beach erosion. For example, a 1 to 2m sea level rise by 2100 could cause 108 to 220 ft (33-67m) of shoreline retreat at Ocean City, San Francisco (King et al., 2011).

Current and future exposure to flooding and storm damage depends on various factors, including topography, elevation of structures, changes in sea level, storm surge, wave height, and duration. The latter two variables, especially for nor'easters, exert a major effect on shoreline erosion (Herrington and Miller, 2010).

Another consequence of sea level rise is saltwater intrusion upstream and into coastal aquifers, potentially jeopardizing urban drinking water supplies (Karl et al., 2009). Miami, Fort Lauderdale, and West Palm Beach, southeast Florida, and also the greater San Francisco Bay area are especially vulnerable, because of their low topography and unconsolidated, porous subsurface geology. For example, an extensive network of pumps and drainage canals in Miami-Dade, Broward, and Palm Beach Counties currently maintain the water table within a few meters of the surface to minimize saltwater intrusion (Florida Oceans and Coastal Council, 2010, Appendix IIIA). A sea level rise of only 6 inches (15 cm) would cut the operating capacity of

[17] Blake, E.S., et al. 2011.
[18] USGS, 2011. Coastal Erosion Hazards: Hurricanes and Extreme Storms--Nor'Ida. http://coastal.er.usgs.gov/hurricanes.norida (accessed Nov. 22, 2011).
[19] Barnard, P.L., et al., 2011.

the coastal flood (and salinity) control structures by 43 percent and 12 inches (30.5 cm) by 72 percent (Heimlich et al., 2009). The increase in water level of canals and ponds with sea level rise plus torrential downpours (e.g., during hurricanes) would imperil the storm water drainage system and flood control structures and create extensive inland flooding in southeast Florida. Sea level rise would likely exacerbate saltwater intrusion during the dry winter/spring season or droughts.

3.7.3 Key Vulnerabilities and Risks

Vulnerability of people and property depends not only on changes in the magnitude of the hazard (i.e., sea level rise and/or coastal storms), but also on various socioeconomic factors such as current and projected population density, income distribution, land use and housing density, property values, critical infrastructure, transportation routes, and ecological resources within the present or future flood zones.

3.7.3.1 Populations and assets at risk

In the United States, 8.42 million people, excluding the Great Lakes, live within the current FEMA 100-year coastal flood zone, largely in Florida, Louisiana, New Jersey, and New York (Crowell et al., 2010). Over 1.4 million people live on barrier islands (Zhang and Leatherman, 2011). The cities of Miami Beach, Fort Lauderdale, Palm Beach, Daytona Beach, Atlantic City, and Long Beach, NY are built entirely, or in part, on barrier islands.

Urban populations more vulnerable to the combined impacts of coastal flooding with sea level rise include the poor, the aged, and disabled. These groups may not have adequately fortified their property, or lack transportation or quick access to nearby evacuation routes during emergencies. Whereas diverse income groups share a similar exposure to coastal flood hazards in New York City and Long Beach, NY, their ability to cope with disaster differs markedly (Buonaiuto, et al., 2011). Even in a predominantly middle class community, such as Long Beach, NY, neighborhood clusters of high-risk populations will be less able to respond to emergencies.
In the San Francisco Bay area, sea level rise will disproportionately affect minority groups (Heberger et al., 2009). Over half the population in San Francisco County within the 100-year flood zone for a 55.1 in (1.4 m) sea level rise by 2100 (Table 3.7.1) are members of minority groups; 41 percent are renters; and 19 percent earn less than $45,000 (Heberger et al., 2009). However, unlike New Orleans, only 7 percent lack vehicles. On the other hand, many recent immigrants speak little English and may have difficulty responding to emergency warnings.

A different equity issue is subsidization of coastal residents by U.S. taxpayers through programs like FEMA's National Flood Insurance Program (NFIP) or the U. S. Army Corps of Engineers beach replenishment programs. By reimbursing flood losses (often repeatedly) or providing shoreline protection, these programs encourage new development in inherently hazardous areas. Furthermore, NFIP insurance premiums do not always accurately reflect actual risks and, in some communities, may be based on outdated flood-hazard maps (Boetzen and Aerts, 2011). FEMA, however, is currently updating its flood hazard maps to provide more accurate elevation and actuarial data (FEMA, 2010). Yet, these revised maps do not address future changes in flood hazards due to climate change.

Major U.S. coastal cities often locate valuable assets along the waterfront or within the 100-year flood zone. This is especially true of major seaports such as Los Angeles-Long Beach, San Francisco, Seattle, New York City, Boston, Miami, and New Orleans. In addition to port facilities, other types of critical infrastructure potentially at risk include schools, hospitals, transportation routes, oil tanks and refineries, power stations, and wastewater treatment plants. The latter (including some pump stations) are commonly located near the shore in order to use gravity to drain their sewer systems and discharge treated wastewater into the harbor. The ability of structures to withstand severe storms depends on various factors, such as elevation above sea level, building construction type and age, zoning regulations and building codes, and existing protective structures, such as seawalls, breakwaters, and revetments.

Several cities are already taking action to reduce their vulnerability. Norfolk, Virginia's second largest city with a population of over 240,000 is surrounded by water on three sides--James River, Elizabeth River, and the Chesapeake Bay. The rate of relative (i.e., local, sea level rise (0.18 in/yr; 4.44mm/yr [1926-2006]) is the highest along the U.S. East Coast (NOAA, 2009), of which one-third to one-half is attributed to land subsidence[20]. Inundation due to sea level rise will become a major issue. Around 9 percent of the city lies at or below 3.3 ft (1 m) of present sea level (Overpeck and Weiss, 2009). Sea level rise would threaten major transportation arteries, such as the Hampton Roads Bridge Tunnel. Frequency of storm surges has already increased noticeably: five of the seven highest storm surges since 1930 have occurred within the last 13 years (Dorfman and Mehta, 2011).

Because of tidal flooding, the city of Norfolk has raised several roads and a number of vulnerable structures (Dorfman and Mehta, 2011). The city now requires the ground floor of new structures to be at least 1 foot (30.5 cm) above the 100-year flood level. The city will consider sea level rise adaptation in its overall plaNorfolk 2030 and has hired a Dutch engineering firm to prepare a flood forecast analysis and recommend economically feasible coastal defenses.

3.7.3.2 Coastal ecosystems at risk

Natural habitats perform multiple ecological services. For example, coastal wetlands protect against storm surges and wave action, and also provide important habitat for migrating birds, fish, and other aquatic life, recreation (e.g., fishing, boating, hiking, birding), and filtration of water pollution. Extensive wetlands remain in the Mississippi Delta, Chesapeake Bay, Delaware, New Jersey, and southern Florida. While most salt marshes can keep up with present sea level rise, they are unlikely to survive rates much above 0.4 in/yr (10 mm/yr), except where rates of sediment or organic deposition are high (Cahoon et al., 2009). However, many urban marshes have deteriorated for decades due to anthropogenic stresses (e.g., Jamaica Bay, New York City, Hartig et al., 2002). Under projected rates of sea level rise, many marshes, already partially submerging, will not remain intact without sediment replacement and re-vegetation to elevate the

[20] Due to a combination of sediment loading, glacial bulge collapse, groundwater extraction, a buried impact crater, and crustal downwarping. http://pubs.usgs/fs_fs_102-98/; http://www.ngs.noaa.gov/GRD/GPS/Projects/CB/SUBSIDENCE/subsidence.html; http://marine.usgs.gov/fact-sheets/fs49-98/

marsh surface (already underway in places like Chesapeake Bay; U.S. Army Corps of Engineers, 2008a,b).

New York City, in partnership with the State and U.S. Army Corps of Engineers, is working to restore salt marshes in Jamaica Bay, which provides a diverse and unique habitat for birds, small reptiles, amphibians, fish, shellfish, and various flora in the midst of the city. Past marsh loss has been extensive. Excluding dredge and fill activity, from 1951 to 2008, 66 percent by area of the vegetated island salt marshes in the bay have converted to subtidal and intertidal mudflats with 323 ha remaining (Christiano and Mellander, 2012, personal communication). Annual rates of loss from 2003 to 2008 exceeded 2 percent per year, averaging 7.7 ha yr^{-1}. While the exact cause of the losses still remains uncertain, multiple stressors, including high nutrient loading, shoreline armoring, navigation dredging, boat wakes and sea level rise may be involved.

Although current marsh sediment accumulation rates exceed historic sea level rise at the Battery, New York (2.77 mm y^{-1}), this may not suffice to compensate for shallow compaction and projected sea level rise (Don Cahoon, 2012, personal communication). Inasmuch as urban infrastructure limits opportunity for landward migration of fringing marshes (August et al., 2011; Connelly et al., 2009), losses may be compensated by ongoing sediment nourishment projects that will approximate the 1974 marsh extent. Between 2006 and 2010, 80 acres (32.4 ha) were restored at Elders Point marshes, using dredged material from nearby harbor deepening projects (USACE, 2012) followed by re-planting with *Spartina alterniflora* (Fig.3.7.1). The restored marsh plant productivity matched that of a reference site after two growing seasons (Rafferty et al. 2011). An additional 94 acres (38 ha) of marsh restoration is scheduled for 2012 at three more Jamaica Bay islands, including 42 acres (17 ha) at Yellow Bar Hassock.

Figure 3.7.1. Native grasses being transplanted by hand, Elders Point—West, Jamaica Bay, New York. Source: Galvin Brothers, Inc.
http://chl.erdc.usace.mil/Articles/7/5/4/JamaicaBay.Grasses.jpg

3.7.4 Adaptations

Adapting to sea level rise generally involves implementing measures to minimize inundation risks. Specific adaptation actions can follow three basic pathways: 1) shoreline protection, 2) accommodation, and 3) managed relocation (retreat).

Several cities are utilizing a mix of these actions to respond to rising sea levels. In the San Francisco Bay area, approximately 180,000 acres (72,900 ha) are vulnerable to flooding following a 16 inch (40 cm) sea level rise, and over 213,000 acres (86,300 ha) to a 55 in (140 cm) sea level rise (BCDC, 2011, Appendix A) (Figure 3.7.2). Without coastal protection, 270,000 people could be at risk to a 55 inch sea level rise (Heberger et al., 2009). Assets at risk total an estimated $62 billion.

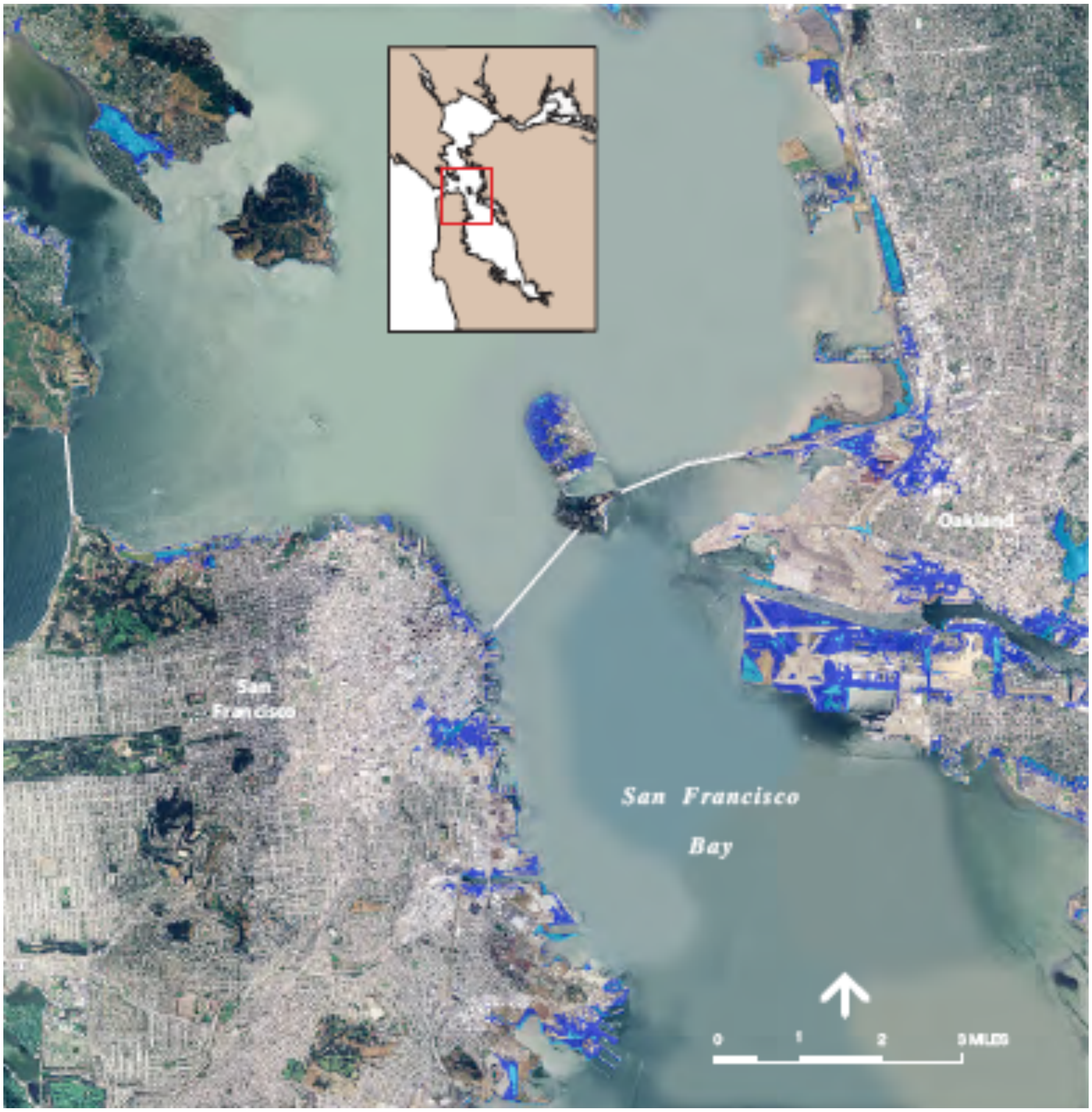

Figure 3.7.2. Sea level rise in San Francisco Bay. Source: San Francisco Bay Conservation and Development Commission (BCDC), 2011.

The San Francisco Conservation and Development Commission (BCDC) regulates development and permits for dredging and filling in Bay waters, salt ponds, managed wetlands, and land within 100 meters of the shoreline, according to guidelines in its San Francisco Plan, amended in October, 2011 to account for climate change and adaptation to sea level rise (BCDC, 2011). The amended Plan recognizes the need for restoration of wetlands, creation of buffer zones to allow for erosion losses, landward migration of saltmarshes with sea level rise, and upgrading of shoreline protection. It recommends that planning be based on the most current science, tailored to regionally specific projections of future sea level rise. New development should follow policies that accommodate sea level rise over a specific planning horizon (i.e., adaptive management strategies). Finding the optimum mix of adaptive solutions entails a comprehensive regional adaptation strategy, involving local, regional, state and federal agencies and relevant stakeholders. However, until a region-wide sea level rise adaptation strategy is completed, the

BCDC suggests that each proposed project be evaluated individually as to its public benefits, flood resilience, and adaptive capacity.

3.7.4.1 Shoreline Protection
Seawalls, bulkheads, revetments, groins, jetties, and breakwaters protect against wave action and erosion. Unless properly designed, these "hard defenses", or shoreline armoring, may exacerbate downdrift erosion, or undermine embankments. Other protective structures include dikes and levees (e.g., Mississippi River, the Netherlands), tidal gates or barriers (e.g., Maeslant barrier, the Netherlands, Thames Barrier, London, Bowman et al., 2004).

"Soft" protection strategies attempt to restore the shoreline to a more natural condition. Beach nourishment and widening buffers against storm surge and also provides recreational opportunities. In New York City, a a $12 million project t Orchard Beach in the Bronx completed in January, 2011 entailed beachfill replacement, offshore regrading, and groin rehabilitation (Bocamazo, 2100; U.S. Army Corps of Engineers, 2011). In addition to preserving valuable ecological resources, saltmarsh restoration, such as underway in Jamaica Bay (section IIIi.3), or Chesapeake Bay (U.S. Army Corps of Engineers, 2008a,b), will help protect nearby urban areas such as Brooklyn and Queens, New York City, and Baltimore, Annapolis, and Cambridge, Maryland.

The city of New Orleans together, following the devastation of Hurricane Katrina in 2005, has adopted a multi-pronged approach that combines restoration of coastal wetlands as a protective buffer, with construction of new flood gates and levees, reinforcement of existing protective structures, raised structures, and improved storm flood management, including "blueways" (i.e., canals for drainage, boating), expanded green infrastructure (parks, tree planting, and rain gardens; e.g. Kazmierczak and Carter, 2010; New Orleans, 2010). A key feature of the city's master plan is the notable shift to green infrastructure in order to increase coastal resilience.

3.7.4.1 Accommodation
Damage from storm surges can be minimized in various ways. Buildings can be raised above the FEMA 100-year flood level (Fig. 3.7.3). Houses can be built on stilts, or the ground floor used for non-residential activities, such as commercial, parking space, recreation (as in the Lower Ninth Ward, New Orleans, Törnqvist and Meffert, 2008). Another accommodation is use of "floating" buildings and houseboats (e.g., Sausolito, Seattle, Amsterdam, Hong Kong, and Bangkok. Other innovative approaches involve building canals and slips and artificial offshore islands (Nordensen et al., 2010; Aerts and Botzen, 2011).

Figure 3.7.3. Left: Unprotected house destroyed by a storm, Long Island, NY. (Photo: Michael Bruno, Stevens Institute, Hoboken, NJ). Right: Schematic sketch of minimum NFIP A-zone requirements. BFE = FEMA's base flood elevation, equivalent to the 100-year flood height, plus wave crest. Source: FEMA, Coastal Construction Manual, v. I [FEMA-55, Chap. 6, p. 6-11].

Raising structures represents another adaptive strategy. The Port of Miami recommends raising its property on Dodge Island from 7.5 to 10 feet (0.23-0.30 m) relative to NGVD[21], which is the FEMA base flood elevation (Miami-Dade County, 2010). Currently, Miami-Dade County in partnership with the City of Miami and the Florida Department of Transportation is constructing a highway tunnel that connects the Port of Miami, an island, with the mainland, in accordance with 10 foot minimum elevation requirements (Miami-Dade County, 2010).

Urban water management needs to encompass both inland and coastal flooding, inasmuch as river cresting ultimately reaches the coast. Green infrastucture, including green roofs, expanded park space, and curbside tree plantings increase soil infiltration, which in turn reduces runoff and urban flooding. Creating a "soft edge" shoreline, as at Brooklyn Bridge Park, New York City, reduces the seaward gradient. A re-planted salt marsh there dampens ship wakes, reduces wave energy and surge impacts, and also provides new wildlife habitat (Fig. 3.7.4, NYC-DCP, 2011).

[21] NGVD = National Geodetic Vertical Datum (1929)

Figure 3.7.4. Creating a soft edge shoreline, Brooklyn Bridge Park, New York City. Source: Department of City Planning, City of New York City, 2011.

3.7.4.2 Managed relocation

The increased frequency and severity of flood damages associated with sea level rise may eventually necessitate relocation further inland. The relocation can be phased in over time through buyout programs, erosion setbacks that account for sea level rise, rolling easements, relocation of individual structures inland, land use zoning, and acquisition of open land. The latter can act as a buffer zone against storm surges and provide new sites for public infrastructure facilities otherwise vulnerable to sea level rise.

Existing regulations vary by state and locality, and are often weakly enforced (Titus, 2009). Because of the high value of beachfront property and general resistance of coastal landowners, managed relocation is not widely practiced in the U.S. Yet, in some sites vulnerable to repeated hurricane damage or cliff retreat, moving further inland may be the only feasible option. In California, for instance, managed relocation strategies are ongoing in San Mateo County and at Surfer's Point, Ventura County, and under consideration in Santa Barbara County (King et al., 2011).

3.7.5 Overcoming Barriers and Stimulating Innovations

Close interconnections exist between the coast and interior, through climatic and geomorphological processes and human interactions—commerce, governance, travel--that extend far inland. Thus, the impacts of climate change that affect coastal cities (i.e., sea level rise, storm surges, saltwater intrusion) can have ripple effects way beyond this fairly narrow zone. Impacts of major coastal storms and rising sea level will affect many communities and therefore larger-scale coastal zone management becomes important.

However, the highly localized jurisdictional level of urban decision-making has hampered comprehensive coastal zone management. Another issue is the widely varying definitions of "coastal zone". In the U.S. Coastal Zone Management Act, 1972, the coastal zone encompasses coastal waters (including submerged land) and adjacent shorelands, islands, intertidal areas, salt marshes, wetlands and beaches. In many cases, arbitrary land or seaward boundaries are defined as being a certain distance from physical references (e.g., Mean Low Water Mark (MLWM) or Mean High Water Mark (MHWM). Each state has its own definition. For example, in New Jersey, the landward boundary is 30 m to 30 km, depending on urban area; the seaward boundary is tidal, bay and ocean state waters. In Rhode Island, the landward boundary is 200 feet from the shore, while the seaward boundary is the territorial limit (i.e., 3 miles).

Stakeholders' responses to perceived or anticipated impacts of sea level rise have been strongly influenced by their often conflicting needs and interests. However, many cities, states, or regions have begun to develop climate change assessments, including coastal initiatives, some of which are listed in Appendix 3A. Yet the need exists for even greater exchange of scientific information and coordination of planning and policies extending beyond the municipality level, to include state and federal government agencies, the private sector, and other affected stakeholders. Developing a resilient strategy to cope with rising sea level may require a much longer planning horizon than usual, since the greatest effects will not be felt until decades hence.

As a first step, local governments and regional agencies can begin shoreline risk assessments and prepare coastal inundation maps. The maps should delineate the 100-year flood elevations, including best estimates of future sea level rise. The planning process should prioritize areas needing the greatest flood protection. Development planning that avoids the highest risk areas will ultimately spare future expenses. Flood management should ideally work closely with natural processes, e.g., by restoring wetlands, or building green infrastructure. Flexibility should be incorporated into the system to allow for updated and improved climate change projections. Some of these principles are outlined more fully in the San Francisco Conservation and Development Commission (BCDC)'s report.

Appendix A. State and regional adaptation reports

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Heberger M., Cooley H., Herrera P., Gleick P.H., Moore E. May 2009. *The Impacts of Sea-Level Rise on the California Coast,* California Climate Change Center CEC-500-2009-024-F, p. 101, http://www.pacinst.org/reports/sea_level_rise/report.pdf.

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Miami-Dade County, 2010. *Port of Miami 2035 Master Plan*, http://www.miamidade.gov/portofmiami/2035-master-plan.asp

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4 Critical Dimensions of Adaptation Planning

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4.1 Introduction

The climate system is warming, resulting in changes in average climate conditions and extreme events (IPCC, 2011; IPCC, 2007). Earlier chapters demonstrate the particular ways in which cities are or may be affected by climate change. Such effects could have wide ranging implications for physical, social and economic costs for urban areas across different sectors and regions (CCSP, 2008; McEvoy, 2007; Wilbanks et al., 2007; Wilby, 2007; Bigio, 2003).

Cities are first-hand observers of climate change impacts, and are motivated to respond because of their investments in and commitment to the quality of life of their citizens and the systems that support them (CCSP, 2008). There are several key ways that cities can effectively address potential impacts. These approaches include: government regulations and policies that provide guidelines and incentives, adaptation plans and planning processes; and multi-stakeholder partnerships and participatory measures that facilitate the exchange of ideas and information. The private sector has the potential to play new roles in supporting and sustaining adaptation. In addition, effective adaptation requires sound economic and fiscal planning. As addressed in the sections that follow, these measures can facilitate adaptation. At the same time, cities face challenges in managing uncertain risks associated with climate change, in assessing the economic costs, benefits, distributional effects of adaptation, and in ensuring that outcomes are equitable.

Scientific uncertainties remain about how climate change will affect specific cities, and measures and protocols are still being explored and tested by cities. However, numerous gains have been made. Therefore, this chapter summarizes the research that has emerged on critical aspects of adaptation planning and highlights strides cities are making to advance adaptation. One trend that is emerging and shows promise for supporting urban adaptation is the role of the private sector as partners in adaptation. The private sector is often overlooked as partners, but can contribute resources, tools, and data, including risk management approaches, financial instruments, and smart systems. In addition, multi-jurisdictional and multi-scalar coordination and collaboration are integral to adaptation efforts since they recognize the interdependence of adaptation and promote capacity through joint learning, planning, and implementation.

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4.2 Government Institutions

4.2.1 Policy and Regulation

4.2.1.1 Allocation of Legal Authority

In the absence of comprehensive federal climate legislation, responsibility for adaptation to climate change is dispersed among every level of government. For this reason there are wide variations in how government organizations affect the substantive actions cities take. This section describes the federal, regional, state and municipal legal authorities that enable or limit local governments' capabilities to address climate change impacts. Currently, primary mechanisms cities may use include land use planning, provisions to protect infrastructure, regulations related to the design and construction of buildings, and emergency preparation, response and recovery (Grannis, 2011). Recommendations are provided for how these legal authorities can be improved to better facilitate adaptation.

4.2.1.1.1 Federal

In the United States there are no federal statutes that explicitly and comprehensively deal with climate change adaptation. Numerous federal agencies undertake planning activities focused on adaptation of their own lands and facilities to climate change: the U.S. Department of the Interior, which manages most federal lands, is especially active in this regard (U.S. Department of Interior, 2009). Federal agencies involved in the construction, operation or oversight of infrastructure such as the US Army Corps of Engineers (Olsen, 2010) and the Federal Highway Administration (Wlaschin, 2010) also have adopted their own adaptation procedures.

In 2009 President Obama issued Executive Order No. 13514, Federal Leadership in Environmental, Energy and Economic Performance, which among other things requires federal agencies to participate in the Interagency Climate Change Adaptation Task Force. This Task Force has issued an interim progress report that sets forth "recommended actions" to support a national climate adaptation strategy, including the following: all federal agencies implement adaptation planning, improve water resource management, protect human health by addressing climate change in public health activities, and build resilience to climate change in communities (specifically ensure relevant Federal regulations, policies and guidance demonstrate leadership on community adaptation and integrate adaptation considerations into Federal programs that affect communities). These recommendations – if implemented fully – will reach down to the municipal level and affect municipalities' readiness for and ability to adapt to climate change.

For example, this strategy could eventually lead to EPA changing the Stormwater Rule to require municipalities to incorporate climate change impacts into their stormwater control plans.

Despite the lack of a comprehensive statute, listed below are a number of ways the federal government could affect municipalities' ability to adapt, some of which have been implemented.

- *Requirement to consider climate impacts in the environmental impact assessment process.* The National Environmental Policy Act (NEPA) requires that federal agencies prepare environmental impact statements (EISs) for major federal actions that may significantly affect the environment. Its implementation is overseen by the U.S. Council on Environmental Quality (CEQ). In February 2010 CEQ issued draft guidance that would require federal agencies to consider adaptation issues in EISs (CEQ, 2010). The guidance has not been made final, but an increasing number of EISs do discuss adaptation issues, though without any uniform methodology. Examples include the environmental impact statements for the relicensing of the Seabrook Station nuclear power plant (USNRC, 2011) and the Mississippi River Gulf Outlet.[iii] Federal actions (including actions directly undertaken, funded or permitted by a federal agency) in cities may thus be subject to this requirement. Examples can include federally-funded highways, mass transit and airport projects; projects funded by the American Recovery and Reinvestment Act; and projects involving landfill or waterfront structures requiring Corps of Engineers permits.

- *Incorporation of climate change considerations into the distribution of State and local grants for infrastructure activities (and the determination of what rules to use to allocate those monies).* Little progress has been made on the use of these potential tools beyond the above-noted limited consideration of climate adaptation matters under NEPA, but many federal grant programs exist that could be used (e.g., highway and mass transit grants, construction grants, Drinking Water and Clean Water State Revolving Fund grants).

- *Consideration of future climate impacts in funding for rebuilding.* The Federal Emergency Management Agency (FEMA) is charged with responsibility for coordinating responses to major disasters, as set forth in the Robert L. Stafford Disaster Relief and Emergency Assistance Act. FEMA also runs the National Flood Insurance Program (NFIP) that is designed to identify locations that are especially vulnerable to flooding and to discourage vulnerable construction in those areas. This program has been criticized as not seriously affecting development patterns or even as being maladaptive by allowing development in areas subject to coastal hazards. One reason for this criticism may be because their maps do not incorporate rising sea levels caused by climate change and the consequent changes in flood plain areas. However, in response to a GAO report (GAO, 2007), studies are underway to estimate those effects, potentially leading to changes in the designation of the 100-year flood lines and affecting existing and new development in flood-prone zones.

- *Actual adaptation on Federally owned land and waters within or adjacent to municipalities.* In 2009 the Secretary of the Interior issued Order No. 3289 to establish a coordinated approach to dealing with the impacts of climate change. The National Park Service,[iv] the Fish and Wildlife Service (U.S. Fish and Wildlife Service, 2010), the Bureau of Land Management,[v] and the Bureau of Reclamation (U.S. Department of the Interior, 2011) have developed or are preparing adaptation plans for the resources they manage, as are agencies outside of Interior, most notably the National Forest Service (US Department of Agriculture, 2010). There are numerous examples of national parks within or overlapping large cities, including Gateway National Recreation Area in New York City; Golden Gate National Recreation Area in San Francisco; Rock Creek Park in Washington, D.C.; Santa Monica Mountains National Recreation Area in Los Angeles; Cuyahoga Valley National Park connecting Cleveland and Akron, Ohio; Boston Harbor Islands National Recreation Area; and the Indiana Dunes National Lakeshore connecting Chicago with Gary and Michigan City, Indiana. Adaptation actions to protect and preserve these areas would also provide benefits to the urban centers they are in or near.

- *Voluntary programs to assist municipalities in adaptation activities.* Among the federal government's voluntary programs to help cities adapt to climate change are the EPA Climate Ready Estuaries Program and the Climate Ready Water Utilities Program, the HUD-DOT-EPA Partnership for Sustainable Communities, and the Federal Highway Administration's adaptation conceptual model pilots. SAFETEA-LU (the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users of 2005) provides a framework that can be used for regional adaptation planning for transportation infrastructure, but it has not been used much for that purpose.

- *Guidance to states and municipalities on adaptation.* There are several federal efforts to work with and provide guidance to municipalities and others on climate adaptation. For example, the U.S. Fish and Wildlife Service is working with federal, state, tribal and local governments, private landowners, and others to develop a National Fish and Wildlife Climate Adaptation Strategy (USFS, NOAA, AFWA, 2012). Another example is the Coastal Zone Management Act (CZMA), a federal statute that establishes a framework for considering the effect of human activities on coastal areas. Amendments adopted in 1990 explicitly reference potential sea level rise as a factor that states should anticipate and plan for. To help implement the CZMA, many municipalities have developed local waterfront management plans. Increasingly these plans are reflecting anticipated climate impacts.[vi]

The measures described above do not represent a comprehensive federal approach for helping municipalities adapt to climate change; they are rather an assortment of loosely coordinated efforts. An organizational framework for providing assistance across institutional lines, with sufficient funding for staff support would be a first step toward a coordinated and comprehensive federal approach (Farber, 2009).

One limitation faced by the federal government is that traditional mechanisms of environmental governance tend to be fixed and static. They have fixed pollution standards (such as for air and water quality), that aim to return conditions or systems to their natural state or to historic baselines and that often require elaborate and lengthy processes to change. Such rigid processes can make it difficult to cope with rapidly changing conditions, where every few years there is a "new normal." This rigidity especially arises in the context of the Endangered Species Act, with its elaborate and time-consuming processes for adding species to or dropping species from the lists requiring special protection. There are decision making approaches that seek to be responsive to changing conditions, primary among them being adaptive management. Adaptive management promotes flexible decision-making on the basis that adjustments will be made as the outcomes of actions and events are better understood. This method supports taking action today using best available information while also providing the possibility of ongoing future refinements through an iterative learning process. This approach, when applied consistently and appropriately, is well suited to decisions with a high degree of uncertainty and therefore promising, if able to be implemented fully by the relevant federal programs.

4.2.1.1.2 Regional

Climate change has and will continue to manifest itself differently across regions of the country in terms of changes in temperature and precipitation patterns, and extreme events (IPCC, 2011). Regional organizations that represent groupings of municipalities, or at least closely coordinated efforts (e.g., Western Governors Association, Interstate Commission on the Potomac River Basin), could facilitate rational planning for and implementation of adaptation measures. For example, some cities (such as New York) draw their drinking water from watersheds located tens or hundreds of miles away. Coastlines typically run along multiple municipalities, and actions in one, such as construction of seawalls or groins, can affect conditions (such as beach health) down the coast. Linear infrastructure that may cover miles of countryside -- such as highways, rail lines, pipelines, water delivery systems, and electric transmission lines -- is particularly vulnerable to disruptions at any point in the system. A disruption at one spot can impair operations of the entire system. It is difficult, however, for regional planning bodies like Metropolitan Planning Organizations to address such vulnerabilities since they rarely have their own regulatory or land use powers, though they do have considerable influence in allocation of federal transportation and housing assistance. However, several exceptions exist, such as regional entities that build and operate mass transit systems for several metropolitan areas, and regional entities (typically encompassing several states) that operate electrical transmission systems for several parts of the country.

Examples of some regional government agencies created by the federal government are the Tennessee Valley Authority and the Appalachian Regional Commission. Another type of regional organization is one created by interstate compact, such as the Port Authority of New York and New Jersey. Among the regional entities created by states and cities are the Atlanta Regional Commission, the Denver Regional Council of Governments, the Minnesota Twin Cities' Metropolitan Council, and the Puget Sound Regional Council in the Seattle, Washington area.

The structures and mandates of these regional entities vary widely. Few of them have taken on climate change adaptation as one of their major focuses, but were they to do so, they would have a broader array of adaptation approaches available because of their larger geographic scope. They also have considerable potential to harmonize city and suburban adaptation efforts and reduce conflicts over shared resources such as water. The politics of every region vary; the relationships between neighboring cities, between the central city and its suburbs, and between the metropolitan area and its state(s) vary widely, so one-size-fits-all solutions are not available, but it is evident from the regional nature of many climate issues that regional efforts are often warranted.

4.2.1.1.3 States

The states are sovereign entities with broad powers. Every state has its own laws and system of environmental regulation. The states also implement many of the federal environmental statutes. With a few exceptions, states are free to adopt environmental rules that are more stringent than those of the federal government, but they cannot have less stringent laws.

Most states follow a legal doctrine known as Dillon's Rule, under which the state is the sovereign entity; cities, counties, and all other political subdivisions derive their authority from grants from the state, and state permission is required before a subdivision may adopt any laws other than those specifically allowed. Other states are "home rule states," meaning that under the state constitution, political subdivisions may adopt rules on their own governance. Several states have a hybrid of the two. Municipalities in Dillon's Rule states sometimes claim that the rule inhibits them from adapting their land use laws to new conditions, though that effect may be exaggerated (Richardson et al., 2003).

One activity that can directly affect municipalities is how states build and operate state and federal highways and other infrastructure. The way in which they do that can have considerable influence on municipal resilience to climate change. For example, the capacity of the drainage systems in state-built highways greatly affects a city's ability to withstand heavy precipitation events. To a large extent, states are aware of the effect their policies can have on cities. In fact, as of July 2011, fifteen states created, or are in the process of creating, adaptation plans that, while they vary widely in their content, all deal with adaptation of infrastructure to climate change as well as public health (Arroyo and Cruce, 2012)[vii].

Several states have enacted their own laws that require EISs for state and local actions. Some of these states have begun issuing guidelines directing that climate change be discussed in EISs. The leader here, California, requires lead agencies to analyze greenhouse gas emissions as well as potentially significant impacts associated with placing projects in hazardous locations, including locations potentially affected by climate change, as part of the California Environmental Quality Act (CEQA) process. However, in November 2011 the California Court of Appeal ruled that the environment's effects on a proposed project—such as perils caused by sea level rise—do not have to be analyzed under CEQA (Ballona Wetlands Land Trust v. City of Los Angeles). As this is written in February 2012, an appeal to the California Supreme Court is being pursued. The outcome of this litigation may have considerable influence on the use of CEQA, and perhaps other state-level environmental impact laws, in analyzing[viii] efforts in and by municipalities to adapt to climate change.

A few cities have their own environmental impact review procedures (usually to implement state laws). New York City's procedures now require disclosure of GHG emissions; they do not explicitly require a discussion of adaptation issues, but they do provide that "where appropriate, the potential for a proposed project to result in a significant adverse impact to the environment as a result of the anticipated effects of climate change may be qualitatively discussed in environmental review (City of New York, 2010). The example given to illustrate their point is the storage of hazardous materials in a floodplain.

Several states have taken actions to assist the adaptation efforts of local governments. For example, the Virginia Coastal Zone Management program has given grants to help coastal communities plan for climate change impacts.[ix] The Massachusetts Office of Coastal Management created a "StormSmart Coasts" website to help local governments prepare for storms, floods, sea level rise, and climate change.[x] The Oregon Coastal Management Program is helping municipalities prepare adaptation plans (Oregon Department of Land Conservation and Development, 2009). California has created a web-based service, Cal-Adapt, that synthesizes existing data about temperature, sea-level rise, snowpack, wildfires, and other factors, and through a GIS interface allows local officials and others to reflect climate vulnerabilities in their planning.

These efforts are, for the most part, scattered and partial. No standard methodology has emerged, and in an area with tight governmental budgets, the resources available to implement plan recommendations are quite limited.

4.2.1.1.4 Municipalities

Municipalities have long been the principal decision-makers on land use matters. They derive their power from the states, but most states long ago conferred on cities (or, in some states, counties) the power to divide the land within their boundaries into zones, to designate permissible uses in each zone, to establish parks and buffer areas, and to enact building codes. Municipalities build and operate most local infrastructure projects such as water lines, sewers, and streets, and they are also in charge of the police and fire departments and other first responders. These are the primary authorities cities may use to adapt to the impacts of climate change and are discussed in more detail below.

A few of the largest cities have established small staffs devoted to climate adaptation. For example, in New York, the Mayor's Office of Long Term Planning and Sustainability has a professional staff devoted to climate adaptation. The City also created a Climate Change Adaptation Task Force and a New York City Panel on Climate Change, which together are devoted to assessing the likely impacts of climate change on the city and to identifying adaptation measures, with a focus on infrastructure protection. The panel produced a major report in 2010 presenting its initial findings (Rosenzweig and Solecki, 2010). Chicago created a Climate Change Task Force that produced the Chicago Climate Action Plan (City of Chicago, 2008). One of its components is a set of adaptation strategies: manage heat, pursue innovative cooling, protect air quality, manage stormwater, implement green urban design, preserve our trees and plants, engage the public, engage businesses, and plan for the future. In most municipalities, however, consideration of these issues is a small part of the work they are responsible for accomplishing.

4.2.1.2 Municipal Legal Authorities and Limitations for Key Functions Related to Adaptation

4.2.1.2.1 Land Use Planning

Vulnerability and resilience to climate change are heavily influenced by land use patterns. Most cities have broad land use planning authority, with extensive discretion in determining which kinds of uses are allowable in various locations within their boundaries. Typically land use plans and implementing ordinances, such as zoning, are adopted by the municipal legislature (such as a city council) and implemented by professional staff in city planning and building departments. However, this planning is often subject to a number of constraints. First, the planning body can prevent new construction, but has much less ability to compel the removal, closure or relocation of existing buildings and other uses. Second, if land use restrictions prevent all reasonable economic use of property, the landowners may be entitled to compensation for a governmental "taking." Third, property owners, neighbors, interest groups and others are entitled to comment on and sometimes participate in the decision-making process; obtaining such input is essential to developing adaptation plans, but the process can become quite protracted. Fourth, much planning related to hazard mitigation is based on historic conditions, such as flood heights, that may not reflect evolving realities. Fifth, few cities have the budgets to allow for comprehensive looks at how changing climate conditions may affect the kind and location of uses that are appropriate. Last, cities can only plan land uses within their borders, and not in the broader metropolitan areas. Some regional planning takes place through metropolitan planning organizations.

Despite having land use planning authority, few cities or states have adopted coherent policies on whether their development patterns should be modified to retreat from vulnerable coastal areas, or should defend against sea level rise and other conditions through such devices as sea walls and beach nourishment. The California Coastal Commission has a policy of discouraging armoring measures (20 Cal. Pub. Res. Code §§ 30235, 30607). Rhode Island has adopted a requirement that public agencies considering land use applications accommodate a base rate of expected 3-5 foot sea level rise by 2100 (6-2-1 RI Code R. §145). A comprehensive approach might systematically discourage land use development in areas that are especially vulnerable to coastal hazards and other climate change impacts, and that might go so far as to prevent the reconstruction of structures in vulnerable areas (see for example CCSP, 2009).

4.2.1.2.2 Providing and Protecting Infrastructure

Most coastal cities -- those that have the greatest vulnerability to sea level rise -- have mature infrastructure systems that are maintained or expanded on an incremental basis. Their sewers, drinking water systems, highways, mass transit networks, ports and airports have been in place for decades. The same applies to most large inland cities that are finding they are quite vulnerable to extreme flooding events that can overwhelm their infrastructure. Moving these systems is all but impossible (at least without multi-billion-dollar investments) and even retrofitting them is enormously expensive. Few metropolitan areas have regional taxing authorities that allow multiple municipalities to share in the costs of improving the infrastructure of the core city, though special financing mechanisms have been developed for such regional facilities as airports. Examples include the Regional Airports Improvement Corporation in Los Angeles and the three airports operated by the Port Authority of New York and New Jersey.

The opportunity to build infrastructure that is resilient to anticipated climate conditions primarily arises when the developed areas of municipalities are expanding, or when existing infrastructure is being fundamentally upgraded for mostly non-climate reasons. Such large-scale work has traditionally relied heavily on federal financial assistance, but that kind of assistance is increasingly constrained. Where a large-scale project does take place, it is often guided by a locally-developed public works capital improvement plan, a master plan for major facilities such as ports and airports, and a hazard mitigation plan. Such locally developed plans for new or upgraded infrastructure present an opportunity to incorporate consideration of projected climate change impacts.

The infrastructure for handling stormwater is especially vulnerable to climate change and the extreme precipitation events that it may cause. The principal constraints here are financial; finding the money to protect against low-probability or remote events is challenging in an era of great fiscal restraint. EPA has developed an elaborate program of permitting stormwater discharges, but it is primarily aimed at regulating contaminants in the discharges rather than ensuring that the pipes and other devices can handle extreme precipitation. More recently, however, EPA has been encouraging "green infrastructure" as a way of helping to adapt to extreme events (USEPA, 2008). This includes, for example, permeable pavements, rain gardens, green roofs, removal of impervious cover, cisterns and rain barrels, trees and expanded tree boxes, and reforestation. The Energy Independence and Security Act of 2007 requires that the sponsor of any development or redevelopment project involving a federal facility with a footprint that exceeds 5,000 square feet "shall use site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to temperature, rate, volume, and duration of flow" (Sec. 438).

Many municipalities have made special efforts to require green infrastructure for stormwater control. For example, Portland, Oregon's city code requires on-site stormwater management for new development and re-development. It also subsidizes a program for the disconnection of downspouts, and it builds vegetated curb extensions that can help protect local basements from flooding (USEPA, 2010).

4.2.1.2.3 Regulating Design and Construction of Buildings

Building codes are in use throughout the United States to ensure building safety and to meet other objectives. Some states adopt state building codes; in other states, each city may adopt its own. Most cities are responsible for implementing the adopted building codes. In California, cities may establish more restrictive building standards than those contained in the California Building Standards Code if the amendments are reasonably necessary because of local climatic, geological, or topographical conditions.[xi] Cities additionally have broad authority to adopt and implement building design and site planning requirements such as standards for height, architecture, landscape and parking. However, some states constrain their cities' authority to vary certain technical requirements (such as electrical codes). Another constraint can arise from political pressure exerted on cities by parties with an interest in the outcome of changes to building codes (for example, the real estate industry that may see changes as increasing building costs).

As with infrastructure, it is far easier to require new buildings to meet the latest standards than it is to retrofit existing ones. Thus the rate of turnover of building stock is a major determinant of the pace of incorporation of new adaptation features or technologies. However, turnover rates are typically low, and many of the building standards that would help adapt to climate change are so highly technical and rapidly changing that many municipalities cannot keep up with them. The Greater London Authority has demonstrated one way to deal with this problem. The London region currently has a housing stock of more than 9 million homes, the majority of which are expected to be in existence by 2050 when the region is expected to experience a climate very different than the current climate. Given the expected that the housing stock turnover rate is expected to be 1 percent per year, they are providing information to homeowners about how existing buildings can be retrofitted and adapted to increase their resilience to changes in the climate. The focus is on cost effective measure to address flooding, water stress and overheating. (Three Regions Climate Change Group, 2008).

Some of the building standards that have been developed to facilitate adaptation to climate change include requirements for basement flood proofing; roofs and windows that would withstand high winds; and provisions for passive cooling in the event power is lost. The National Flood Insurance Program has adopted performance standards for buildings in hazard areas that address the elevation of the lowest floor, the means by which a building's foundation is elevated to or above the base flood elevation, and the materials used below that elevation (44 C.F.R. part 60).

4.2.1.2.4 Emergency Preparation, Response and Recovery

There are several resources that have been developed to help organizations plan for or respond to disasters. One example is the National Response Framework issued by the Department of Homeland Security pursuant to the Homeland Security Act of 2002. It is a framework to assist government, NGO and private sector organizations in planning for and responding to disasters. Another example is the Emergency Management Assistance Compact to help state governments respond to disasters. All fifty states have signed on to this Compact, which provides for deployment of emergency response resources to where they are needed.

Almost all municipalities have broad legal authority to respond when life-threatening emergencies occur. They can order evacuations, restrict access, impose quarantines, and procure emergency equipment. Governors may call out the National Guard, and in the most extreme circumstances, the federal government may make the military available. Despite such resources, municipalities vary a great deal in their preparations for emergency situations. The principal constraints on advance planning, and on the exercise of these emergency powers tend to be economic and political, not legal.

On the other hand, recovery from emergencies may be constrained by legal requirements. Where an area has suffered extensive damage, doing anything beyond rebuilding what was there before may be subject to elaborate planning requirements, such as those under a state-level environmental review law. However, that is not to say that such laws are the principal cause of delay in rebuilding; often the municipality takes quite a bit of time to achieve consensus on its own post-disaster form, and the environmental and planning laws establish the process in which the local debates are conducted and decisions are made. Moreover, many municipalities that have suffered grievous injury (whether from fire, extreme weather events, or terrorism) find that the federal assistance that is promised in the immediate aftermath of the disaster is not coming in nearly the quantities expected, or is far short of what is actually needed.

4.2.2 Policy Incentives

Use of incentives rather than mandatory measures by municipal authorities has benefits both for municipalities and for individuals, businesses, and institutions that have opportunities to respond to them. For example, municipalities can offer incentives to real-estate developers, such as expedited permitting, greater height-to-area ratios, or other relaxations of zoning code requirements, and direct or indirect financial subsidies, in exchange for voluntary adaptation measures, which themselves may provide substantial economic benefits.[xii] As suggested by the example of Boston's LEED initiative, this includes municipalities offering development opportunities linked to energy savings or other requirements (see Box 4.1: LEED Initiatives in Boston).

Box 4.1: LEED Initiatives in Boston

In spring 2011, the City of Boston, through its planning and economic development agency, the Boston Redevelopment Authority, and the Department of Neighborhood Development, offered private developers the opportunity to purchase three City-owned lots for development of 1-4 residential units on each lot. The opportunity took the form of a design/build proposal competition. Proposed developments were required to be energy-positive (E+; that is, over a year, producing more energy than they consumed) and LEED Platinum, with the purpose of "advanc[ing] industry practice and public awareness of energy efficient green buildings." (The "stretch" energy code adopted by the City of Boston currently requires new residential units to achieve a HERS (Home Energy Rating System) score of 70 or lower; E+ homes will have a negative score.) Additional incentives provided by the City and its partners included: monetary design-innovation awards, utility support and rebates, affordable-housing subsidies, and preferred lending from a partner bank. Fourteen developer/designer teams submitted proposals for three sites. After a public display of all proposals, the City announced the winning teams in September 2011. Construction is expected to be completed before the end of 2012.[xiii]

An often-overlooked incentive that cities can provide is recognition through awards and other means. Recognition provides incentives for individuals and organizations to favor environmentally beneficial alternatives, and perhaps use such recognition in their marketing materials.[xiv] Another indirect benefit comes from the enhancement of a property's value due to measures taken to adapt to climate change. For example, many cities are developing expansive tree-planting programs, which have adaptation and mitigation benefits. While property owners must supply land, labor and water, often the trees are provided at a reduced cost or for free.[xv] In addition to reducing energy costs for close-by buildings, the presence of trees usually raises a property's value (Donovan and Butry, 2009).

Incentive programs often hold benefits for municipal authorities. Benefits include easier implementation and less opposition since they do not generally require enactment through a legal or regulatory process, and are not a requirement. Incentive programs often allow experimentation that opens the door to better solutions (the other side of the flexibility favored by developers) and can provide the conditions for innovative ideas to become conventional (City of Boston, 2011). These same programs also serve to introduce city officials themselves to such ideas, and give them a low-risk approach to addressing the problems of climate change while gaining knowledge about their cities' specific vulnerabilities. The flexibility that incentives often allow, such as open-ended choices of means for reaching specified goals, may also lower the costs of adaptation and can sometimes be crafted into regulatory requirements. (For example, the requirement that many municipalities have that new construction meet LEED standards.)

Incentive programs may also have disadvantages, depending on how they are designed and implemented. Too much flexibility might lead to a counterproductive lack of uniformity: property owners taking not only different measures, but measures that may counteract each other. It may also produce uncertainty for property owners about program requirements and uncertainty for government officials over what constitutes fulfillment of requirements. Different types of property owners (for example, residential/ commercial/ institutional, new buildings/existing buildings, large/small) also respond to different types of incentives, so it may be difficult to structure programs that equitably provide opportunities for all segments of the community. Finally, such incentives may divert actions away from systemic adaptation. For example, incentives may focus work on individual properties when what is needed are larger-scale, systemic projects that address community-wide vulnerabilities.

4.3 Governance Measures

4.3.1 Adaptation Plans and Planning

Many communities around the United States are initiating efforts to build local resilience towards climate change. Much of this work is centered on adaptation planning–a relatively nascent practice that produces a strategy for how a local government will prepare for weather and climate impacts (Cruce, 2009; Agrawal, 2009). This section explores the types of plans and planning processes that local governments in the US are undertaking in order to promote climate adaptation.

4.3.1.1 Drivers of Adaptation Planning

In today's society, local governments are faced with a cadre of concerns ranging from maintaining a balanced budget to ensuring the health and safety of citizens, to maintaining critical services that allow local communities to thrive economically, socially, and environmentally. In light of these pressing concerns, climate change continues to rank as a low national priority (Leiserowitz et al., 2011). Nonetheless, many cities throughout the U.S. are thinking about or taking action on climate change. Based on a recent survey, 58 percent of cities in the U.S. reported that they are moving forward on climate adaptation planning, although 48percent are still in the preliminary stages of planning (Carmin et al., 2012). Among the main reasons cities around the world cite for initiating planning are: 1) previous experience with a hazardous event; 2) perception of a future weather related threat; 3) interest in demonstrating community leadership; and 4) acknowledgement that climate change could inhibit a community's ability to meet their existing goals (Anguelovski and Carmin, 2011).

4.3.1.2 Adaptation Plans and Plan Development

Three approaches are commonly associated with adaptation plans in US cities. The first is a standalone action plan. Keene, New Hampshire and Punta Gorda, Florida are two cities that leveraged their success with climate mitigation to create plans focused exclusively on adaptation. The second type of approach is to integrate adaptation into community plans, mainly climate action and sustainability plans (Zimmerman and Faris, 2011). Seattle, Portland, New York City, Chicago, Berkeley, and Homer, Alaska, are examples of cities where climate adaptation was integrated into climate action or sustainability plans.

A third approach is to integrate adaptation into sectoral plans (Fussel, 2007). Common areas for integration include hazard mitigation, coastal zone development, water resource, wetlands conservation, and economic development plans. These approaches have proven fruitful in places like Lewes, DE and the City of Phoenix, AZ where adaptation has been integrated into hazard mitigation and water resource plans, respectively. Planning efforts being led by the Water Utility Climate Alliance (WUCA) and statewide coastal zone management offices are contributing to the integration of weather and climate considerations into water planning and coastal zone management planning around the country (Means et al., 2010). In addition, communities such as Boston, New York, and Philadelphia are accounting for climate change in their public health planning in order to better account for impacts on human health, such as the spread of diseases, incidence of heat-health hospitalizations, and changes in malnutrition (Maibach et al., 2008; Cooney, 2011).

Local governments throughout the U.S. are pursuing each of these three types of planning, and in some cases, a combination of these approaches. However, current trends suggest that communities engaged in planning are favoring the development of strategic adaptation plans over the creation of sectoral plans (Carmin et al., 2012). An integrated adaptation planning process requires commitment and coordination across local government departments. To address this, many communities in the early phases of planning focus on information sharing and the engagement of departments in the adaptation planning process (Moser and Ekstrom, 2001). In places such as Keene, New Hampshire, Tucson, Arizona, and Lee County, Florida, adaptation efforts initially focused on how the local governments could enhance the resilience of internal government operations to climate change impacts (ICLEI, 2010). Internally driven efforts such as these tend to have representation from a majority if not all of the departments within the local government as well as external support from experts such as academics and state agencies.

Building internal support is essential for establishing a foundation for adaptation. In many cities, the formal adaptation planning process often is initiated by compiling historic and future climate-related data. These data are then used to conduct a climate vulnerability or risk assessment (ICLEI, 2010; Bierbaum, 2010; Lowe et al., 2009; Fussel, 2007). The results of the assessment then can be used to identify priorities and, in turn, to develop strategies to help build local resilience. The process by which recommended strategies are selected varies among communities. In and Lewes, DE for instance, a matrix was established that allowed stakeholders to rank each potential action based on a set of pre-agreed upon criteria. Those actions that received the highest score were evaluated for feasibility and then selected for inclusion in the

City's Climate Change Adaptation Strategies list. Alternatively, in Homer, AK, potential strategies for enhancing resilience were identified and then ranked based on cost. Those that were no cost or no regrets strategies were prioritized for implementation (see Box 4.2: Strategic Planning in Chula Vista, CA, for another illustration of this approach).

Many cities in the U.S. are still in the earliest stages of adaptation planning, such as holding meetings, exploring options, and looking into the feasibility of moving forward with planning (Carmin et al., 2012). Whether they are just beginning the process or have one underway, most cities report that they are encountering numerous challenges. Resources are a top-ranked challenge, with most cities noting that they are having difficulty obtaining funds to support adaptation efforts. Cities in the U.S. also find that often it is difficult to allocate staff time to adaptation (Carmin et al., 2012).

Gaining the commitment and support of local elected officials for adaptation is a challenge in about 25 percent of US cities, with just under 20 percent indicating that commitment is very low. Despite efforts to engage departments, cities note that they are still struggling with generating commitment in this arena as well. The situation is further compounded given that 36 percent of cities in the US believe that national government agencies and representatives do not appreciate the challenges they face or understand the types of support they need in adaptation planning (Carmin et al., 2012).

Box 4.2: Strategic Planning in Chula Vista, CA

The City of Chula Vista, California prepared its *Climate Change Adaptation Strategy* through a rapid, low-cost process that reflected local needs and resource availability. Located near the US-Mexico border in San Diego County, Chula Vista is representative of a broad segment of American communities that are small- to medium-sized and resource-constrained during the down economy. The City has long been a leader in climate mitigation at the local level, and in October 2009 the City Council directed staff to address climate adaptation in a manner that would have little impact on the City's General Fund. To meet these parameters, the City designed a process that leveraged local partners and the City's Climate Change Working Group (CCWG), a volunteer stakeholder group comprised of representatives from development companies, business associations, energy and water utilities, environmental organizations, and education institutions. The group held 11 publicly announced meetings and two public workshops between December 2009 and August 2010 to review potential impacts and identify over 180 opportunities to reduce these risks. The CCWG was further supported by representatives from ICLEI, regional experts, climate scientists, and staff members from multiple municipal departments. In October 2010, the City Council adopted 11 adaptation strategies to address climate change vulnerabilities and solutions related to energy and water supplies, public health, wildfires, biodiversity, coastal resources, and the local economy.

Chula Vista's process was successful in generating tangible actions for building local resilience in a way that minimized costs by leveraging local partners and community volunteers. Project costs were also reduced by minimizing the scope of vulnerability and risk analyses to only what was needed to inform the City's initial adaptation strategies, many of which were "low-regrets" approaches that did not entail significant new investments and that had co-benefits contributing to other community goals. The City viewed the project as a first step in an ongoing process of climate adaptation, identifying key strategies to begin implementing while building on its climate leadership in a way that could make the City more competitive in pursuing adaptation-related funding in the future.

4.3.1.3 Government Capacity and Governmental Coordination

Localities across the United States are pursuing diverse and innovative institutional arrangements catered toward increasing the adaptation capacity and coordination functions of city governments. Cities are critical bodies for provision of services, investment opportunities, and development planning (Kahn, 2009; Selin and VanDeveer, 2007; Dierwechter, 2010); given these responsibilities, plans, policies, and strategies addressing the projected effects of climate change have been proliferating among cities across the country (Wheeler, 2008; Rabe, 2009; Anguelovski and Carmin, 2011). At the same time, many localities are beginning to uncover critical institutional barriers to adaptation planning and implementation, such as issues of government capacity-building and inter-governmental coordination both within and across scales of state authority and territorial regulation (Dierwechter, 2010).

Many adaptation initiatives are enabled through strong relationships among different actors–e.g., individuals and organizations with stakes in the policy domain–and institutions, which in this context, refers to formal and informal rules that determine how actors interrelate (North, 1990). In the case of the San Francisco Bay Region, California, relevant actors not only include the nine counties and 101 cities representing the locality, but it also include state-level departments, special districts, sector-specific regional departments, and various voluntary councils. The institutional context within which these actors operate includes the California state regulatory context and the region's existing natural resources. In this case, San Francisco Bay's adaptation program involves all local, regional, and state level interests and policy instruments. The combined capacity of these actors, working within existing institutional frameworks, greatly affects the city authorities' capacity to respond to project climate effects. (See Box 4.3: Coordination in the San Francisco Bay Region, for further discussion of the complexities of planning in the Bay area.)

Government-led adaptation can fall into two general action categories. First, governments can enact direct interventions aimed at exerting formalized influence (Kooiman, 2003). Direct structural and non-structural projects such as reinforcing river embankments, promoting urban greenery, and enacting information and education campaigns all fall into this category. Increasingly, though, many governments are seeking out other partners. In some instances these take the form of horizontal interactions that promote dialogue across sectors across government (Kooiman, 2003). The creation of adaptation task forces, working groups, and panels, such as the California Joint Policy Committee (JPC) (see Box 4.3) and Boston's Community Advisory Committee on Climate Action (see Box 4.4) fall are examples of how institutions are seeking not only to channel vertical authorities from state and local governments, but are also seeking to enhance horizontal dialogue between actors within government.

The decentralization of governmental action on climate change adaptation has greatly increased the number and type of actors and institutions involved in the planning and policymaking process. Formal and informal institutions, state and non-state actors, and associating markets and networks are now all involved in adaptation planning and policymaking (Pahl-Wostl, 2009). Decentralization of governance in the United States, unlike in Europe (Hooghe and Marks, 2003; Pahl-Wostl, 2009; Piattoni, 2009), has followed a path of federalism (Frug and Barron, 2008; Rabe, 2009), which envisions a division of powers among the national government, the states, and localities. The dispersion of authority away from the central state (Pahl-Wostl, 2009) and toward localities is both indicative of (1) a general recognition of the intrinsic value of civic participation and engagement (Frug and Barron, 2008) and (2) the importance of localities as centers of innovative ideas (Frug and Barron, 2008; Wheeler, 2008; Anguelovski and Carmin, 2011) and as nodes of multilevel political systems (Betsill and Bulkeley, 2006; Simon, 2007).

Most research on multilevel governance of climate change originates in Europe and focuses on mitigation rather than adaptation. Still, one can draw important lessons that are applicable to adaptation planning in the United States. The inherent socioeconomic diversity of localities is a key rationale for a decentralized, multilevel approach to planning and governance (Andonova et al., 2009; Hodson and Marvin, 2010). Two general typologies of multilevel governance have been identified: one that refers specifically to the multiple tiers in which governance processes take place and a second that highlights the myriad of actors and institutions that act within and across these levels (Betsill and Bulkeley, 2006; Bulkeley, 2009; Betsill, 2007; Betsill and Bulkeley, 2007; Hooghe and Marks, 2003). For example, in the case of San Diego, California, multilevel adaptation planning occurs simultaneously (and occasionally, independently) on the city, county, and state levels. Each governing level enjoys unique authorities and responsibilities within their purview. Similarly, adaptation planning in San Diego involves local and regional actors such as the City of San Diego, the Port of San Diego, the San Diego Regional Airport Authority, and others that work among and across all levels of governance (see Box 4.5).

The different actors within a multilevel adaptation planning context are associated with each other, either vertically or horizontally. The different actors involved create nested and overlapping regimes that provide opportunities for adaptations to spread horizontally and vertically through communication networks, top-down support, or capacity and practice transfer (Pelling, 2010).Vertical relationships relate to the role of municipalities defined by central or regional governments and is delegated to local authorities (Urwin and Jordan, 2008; Bulkeley, 2010). The relationship between the State of California and the cities of San Francisco and San Diego is one such example. Vertically directed adaptation projects are usually required by law, regulation, or mandate through national or state governments. Horizontal relationships, on the other hand, refer to partnerships and networks (Elander, 2002; Bulkeley, 2005; Bulkeley, 2010; Anguelovski and Carmin, 2011) that transcend fixed territorial spaces and hierarchical scales of governance (Bulkeley, 2005). Examples of networks include: ICLEI-Local Governments for Sustainability's Cities for Climate Protection Program (CCP), which links a number of municipalities across the United States; interstate compacts; ecosystem-based programs; and other regional/inter-urban partnerships (Rabe, 2009; Anguelovski and Carmin, 2011). Chula Vista, California's City's Climate Change Working Group (CCWG) is one such example of horizontal relationships being developed within one urban setting (see Box 4.2).

Effective and comprehensive adaptation planning in the United States requires intra and inter-organizational strengthening and reform. Currently, issues of coordination and capacity building inhibit implementation of many adaptation projects. For example, one key capacity and coordination challenge is the inherent temporal and scalar mismatches between urban political cycles and the long-term decision-making processes required for adaptation (Bai et al., 2010). Similarly, issues of unclear jurisdictional authorities and widespread capacity differences between governments affect the ability of adjoining localities to cooperate (Bai et al., 2010). Lastly, partnerships and networks within and across cities maybe restricted due to local socioeconomic conditions or limits imposed by higher levels of government (Wolman and Goldsmith, 1992).

Box 4.3: Coordination in the San Francisco Bay Region

The San Francisco Bay region has a population of over seven million people. The responsibility for planning the future of the region and achieving this planned future is shared by a host of government agencies. Nine counties and 101 cities have the primary authority over land use decisions. Five agencies, two of them State of California Departments, two state-created special districts, and local government association, control Bay protection, water quality, air quality, transportation funding, and housing allocation. Hundreds of special districts deal with a broad range of issues ranging from fire and flood protection to water supply and parks.

In an effort to coordinate the principal regional planning initiatives, California law created a Joint Policy Committee (JPC) and charged it with coordinating the activities of four regional agencies, each of which is responsible for achieving its own unique set of responsibilities. The Metropolitan Transportation Commission (MTC) is the transportation planning, coordinating and financing agency for the region. The Association of Bay Area Governments (ABAG) is a voluntary council of local governments that provides regional planning and other services. Pursuant to state and federal law, the Bay Area Air Quality Management District (BAAQMD) regulates stationary sources of air pollution. The San Francisco Bay Conservation and Development Commission (BCDC), which is the federally-designated state coastal management agency for the Bay Area, uses the enforceable policies in the San Francisco Bay Plan to regulate activities and development in and around the Bay to achieve the goal of protecting Bay resources.

All four agencies have committed themselves to working together to enhance the Bay Area public's quality of life, to protect the region's natural environment, to improve social and economic equity, and to advance the current and future economic prosperity of the metropolitan area. These efforts are being advanced under the banner of "One Bay Area," an initiative that is aimed at advancing an overarching recognition that the region is more than the sum of the mosaic of the hundreds of agencies that are responsible for various components of governance in the region. In order to achieve the goals of One Bay Area, the four regional agencies will need to reach agreement on a single "Plan Bay Area," which embodies integrated regional policies.

Despite the agencies' commitment to these regional goals, it is challenging for each agency to administer its legally required individual responsibilities in a manner that advances the objectives and responsibilities of the other three agencies. Pursuant to state law, MTC and ABAG are responsible for formulating a Sustainable Communities Strategy that will reduce GHG emissions by reducing vehicle miles traveled (VM). Fairly or not, MTC and ABAG have been accused of largely ignoring climate change adaptation, and particularly sea level rise, in order to assure that the initial SCS will be completed by the 2013 deadline mandated by state law. BAAQMD has adopted CEQA guidelines to specify how to assess and mitigate the impacts of air emissions in development projects near transportation corridors. BAAQMD's stated purpose in formulating these guidelines is to streamline the approval of transit-oriented development (TOD), one of the key elements of the SCS, by introducing more certainty into the CEQA process. However, fairly or not, BAAQMD's CEQA guidelines have been accused of making the approval of TOD more difficult. BCDC has mapped areas around the Bay that may be vulnerable to flooding from future sea level rise and storms brought about by global climate change. Fairly or not, BCDC has been accused of making infill development, another of the key elements of the SCS, more difficult by introducing a new factor—flooding danger—that can be used in CEQA challenges to infill projects. Finally, the scope of the present Plan Bay Area is currently limited to the SCS being developed by MTC and ABAG.

The executive staffs of the four agencies have been largely successful in dealing with both the perception and the reality of these challenges, and over the next two years the JPC is embarking on a number of interlocking initiatives that seek to boost regional economic development, create jobs and build the Bay Area's resilience to the impacts of climate change.

Box 4.4: Coordinating City and State Initiatives in Massachusetts

Starting in the spring of 2009, the City of Boston and the Commonwealth of Massachusetts undertook extensive public processes that led to new climate action plans and reports addressing both mitigation and adaptation for both entities (City of Boston, 2010; City of Boston, 2011; Commonwealth of Massachusetts, 2010; Commonwealth of Massachusetts, 2011). Although the individual entities were not formally coordinated, they were effectively linked by several institutional, personal, and technical factors.

The first factor was the existence of overlapping public committees. The City of Boston formed two committees, a task force appointed by the mayor and a community advisory committee that addressed mitigation and adaptation formed through open nominations. The Commonwealth of Massachusetts, in compliance with climate legislation, created two separate advisory committees for mitigation and adaptation. Each of the state-level committees included an official from the City of Boston as a formal member. Two individuals served on both a state committee and the mayor's task force, and two organizations were represented on both city and state committees. Furthermore, several members of the state committees provided scientific and technical advice to the City.

The second factor was overlapping working groups. The work of the public committees at both state and city level was supported by a large number of working groups, which welcomed participation beyond the formal committee members. City staff participated in the Commonwealth's working groups, and vice versa, and important non-governmental participants contributed to both efforts.

Third, extensive staff consultation occurred. As the two parallel efforts proceeded, committee staffs at both levels of government were keenly aware of each other's work. In many instances, there were concerted efforts to ensure that, to the greatest extent possible, assumptions and methods of calculation were the same; and where they were not, to recognize why. Because Boston is the largest city in Massachusetts, participants and staff at both levels recognized that it would make no sense if the city and state plans were not consistent with each other.

Fourth, mediation was provided by regional planning bodies. The interaction between the City and the Commonwealth often is mediated by regional planning bodies on which both groups rely. Regional entities (political subdivisions of the Commonwealth) control the water supply and waste treatment facility and the public transportation system, with Boston being the largest member in both cases. (Boston, by law, has seats on the water authority board, though not on the transportation authority board.) Furthermore, natural hazards mitigation planning, an important part of emergency preparedness, is conducted for the City by a regional planning council. These three areas–water supply, waste treatment, and public transportation—are particularly important for climate adaptation planning, and the regional bodies participated in these areas for both the state and city planning processes.

The fifth factor was the existence of a common understanding among the different levels of government, facilitated by common sources of information. This fundamental element permitted coordination of climate policy between the two levels of government and consisted of a common understanding of the likely effects of climate change and of local vulnerabilities. Scientists from local universities and research institutions participated in both sets of processes to establish the foundations for policy discussions, and staff at both levels compared their understanding of this information. Lastly, strong leadership was provided. Both the Governor and the Mayor made clear that climate action was an important part of their governing agendas and set high expectations for results.

4.3.1.4 Adaptation Planning and Uncertainty

Adaptation planning requires making decisions under conditions of uncertainty because of having to anticipate future changes in a number of interacting factors. Some of these factors include future changes in population and demographics, technology and innovation, the economy and governance, and the magnitude and timing of climate change impacts. Understanding the important and relevant uncertainties for decision making as well as approaches for managing uncertainties are keys to effective decision making. Uncertainties relevant to decisions are those that, when reduced through the provision of more information, would substantively change the decision.

Approaches or frameworks for making decisions under uncertainty include structured decision-making, sensitivity analysis, risk management approaches (e.g., such as transferring the risk, avoiding / reducing the negative effect or probability of the risk, or accepting some or all of the potential or actual consequences of a particular risk), robust decision making, scenario-based planning and portfolio approaches, adaptive management, "real options", and flexible infrastructure, (National Academy of Sciences, 2011; Matthews, 2011; Brown, 2010; Means, 2010). In its report *America's Climate Choices* (2011), the National Research Council of the

National Academy of Sciences highlighted the role of iterating using risk management strategies. The report recommends that decision makers should "implement an iterative risk management strategy" that is based on best available information and assessments that are reviewed and "revised in light of new information, experience and stakeholder input."This approach is similar to adaptive management, another flexible decision-making method that emphasizes periodic adjustments as outcomes of management actions and events become better understood.

New York City provides one example of adaptation planning that "flexible adaptation pathways" to enable adaptation strategies to evolve over time as new information becomes available (National Academy of Sciences, 2011). Seattle Public Utilities, the regional water provider for the Seattle region, identified and evaluated adaptation options that were flexible and reversible, or "no regrets" strategies, for offsetting some of the projected losses in supply due to climate change. The Thames Estuary 2100 project focused on achieving flexibility by sequencing implementation of adaptation measures over time while leaving open options to address uncertain climate futures (Reeder and Ranger, 2011).

In "Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning", Means et al. (2010) explore several methods that have been or could be used to address climate change uncertainties and thus enable the development of appropriate adaptation options. The following are three methods described in the paper: Robust decision making (RDM), "real options", and portfolio planning. RDM is an approach that assists in identifying those water management strategies that are most responsive to a wide range of plausible future conditions. "Real options" emphasizes flexible investment strategies that incorporate delaying and phasing of projects to manage uncertainties, while portfolio planning borrows from the financial sector to compose a mix of assets or strategies that collectively minimize exposure. Portfolio planning has been used extensively in the electric utility industry (Means et al., 2010).

"The End of Reliability" (Brown, 2010) echoes the notion of robustness embedded in robust decision making but also introduces a concept from computing, on demand infrastructure, infrastructure that would be "called upon only when needed" and which "might not be needed often (or ever)." Brown also emphasizes the need to meet infrastructure services by transcending traditional infrastructure approaches and incorporating structural and non-structural approaches, including "incorporating innovations in communications, IT and the application of economic mechanisms." *Climate Change and Forests of the Future* (Millar et al., 2007) also emphasizes the importance of incrementalism, portfolio approaches and ongoing learning tied to adaptive decision making while also emphasizing the importance of being able to reverse or change decisions as new information merits.

Seattle Public Utilities (SPU) provides an example of how a city can incorporate ICT approaches as well as reversible and incremental approaches to developing adaptation strategies. SPU partnered with the University of Washington Atmospheric Sciences Department to develop Seattle RainWatch, a precipitation early warning system that utilizes real time data from SPU's rain gages and radar data from the National Weather Service to provide spatially and temporally extrapolated precipitation forecasts and precipitation accumulation information for Seattle. SPU has established thresholds for accumulations and forecasts and when those thresholds are exceeded, email alerts go out to key decision makers in SPU's drainage operations. SPU's work on assessing the climate impacts on water supply provides an example of incremental and reversible adaptation options. Through its assessment effort, SPU used three plausible, GCM-derived climate scenarios that projected losses in Seattle's future water supply due to climate change. To offset those reductions, SPU analyzed a suite of "no regrets" adaptation options, emphasizing low cost, operational, reversible and flexible options that fully offset the reductions in supply in two of the three climate scenarios (EPA, 2011).

4.3.1.5 Participation and Partnerships

Engaging stakeholders offers a means to enhance adaptation planning. For instance, stakeholders can identify challenges that may not be immediately apparent to decision-makers. They also can help identify and implement solutions. While important, it is useful to distinguish between various forms of public participation and stakeholder engagement in adaptation planning (Adger et al., 2009; Carmin et al., 2011; United Nations Human Settlement Programme, 2011).

Some efforts, like those under the banner of *community-based adaptation* (CBA) aim to mobilize citizens directly in bottom-up efforts. CBA involves helping communities, and marginalized groups in particular, to define their needs and address vulnerabilities that exacerbate the risks associated with climate change (Reid et al., 2009). CBA assumes that communities have the skills, experience and local knowledge to implement risk reduction activities that increase resilience to a range of factors, including climate change, and that they are best situated to act (Dodman and Mitlin, 2011). The CBA approach has largely been implemented in rural areas in developing countries, although there are urban examples, like a project to engage favela dwellers in Rio de Janeiro in tree planting to control erosion and prevent landslides (UNFCCC, 2012). CBA may be useful when working with vulnerable groups in the United States to increase their resilience. San Francisco's adaptation efforts have paid particular attention to environmental justice concerns, and to increasing the resilience of the city's most vulnerable (Lowe et al., 2009). Furthermore, some of the techniques associated with the CBA approach, like community mapping and modelling, and alternative means of communication, like theatre and music, may be useful for engaging segments of the population often ignored in more formal planning processes (Reid et al., 2009).

CBA puts a great deal of agency in the hands of citizens, assuming that they can effectively manage the risks associated with climate change by addressing existing vulnerabilities via bottom-up action. At the other end of the scale of stakeholder engagement processes are those that promote cooperation among experts across sectoral boundaries, but do not involve laypersons and sometimes even exclude practitioners. The New York City Panel on Climate Change brings together experts from various academic disciplines and related analytical fields, like insurance and risk management, to consider how the region's critical infrastructure will be impacted by and can be protected from future climate change (Rosenzweig et al., 2010; Rosenzweig et al., 2011). The implicit assumption is that long-term adaptation planning is a technical problem requiring expert analysis. Similar efforts bring together infrastructure managers for both intra- and inter-municipality and agency planning and coordination (OECD 2010). For example, five multi-departmental Adaptation Work Groups, focusing on specific areas like 'extreme heat' and 'buildings, infrastructure and equipment' are implementing Chicago's Climate Action Plan (Coffee et al. 2010). In some cases these efforts are coordinated by standalone offices, like the Adaptation Division of the Environmental Affairs Department in Los Angeles (Lowe et al., 2009).

In practice, many municipal adaptation efforts engage city staff; technical experts; agency staff from other levels of government; and citizens and non-expert stakeholders either together or in concurrent processes, adopting a portfolio approach. New York City's efforts extend far beyond the more academically oriented Panel on Climate Change, with a comprehensive web of various committees and engagement processes that interrelate and involve the gamut of stakeholders (Lowe et al., 2009). The Climate Change Adaptation Task Force, which is part of the broader PlaNYC effort and the key client for the Panel on Climate Change's outputs, brings together leaders from across city government, relevant state agencies and industry (Rosenzweig et al., 2010). The Task Force will release a comprehensive report in the coming months. Outreach efforts, including many at the neighbourhood-level, have also been initiated through PlaNYC to engage citizens directly in assessing their vulnerabilities to climate change and initiating or proposing responses (City of New York, 2011). Efforts are happening at the sectoral level too. For example, there is a comprehensive standalone climate change program to assess and prepare for the potential impacts on the city's water supply, stormwater and wastewater management systems (New York City of Environmental Protection, 2008). This effort brings together Department staff and external experts. Boston's adaptation effort was steered by a Leadership Committee comprised of city planners and decision-makers, academics, business and non-profit leaders and representatives of the general public (Carmin et al., 2011). Similarly, the Chicago Climate Action Planning effort is coordinated at the top by a 'blue ribbon' task force comprised of community leaders, supported by external experts and city staff and engaging other stakeholders in numerous ways (City of Chicago, 2008; Coffee et al., 2010). Given the multiple dimensions of adaptation planning, a portfolio approach that engages different stakeholders and fosters partnerships across sectoral boundaries via different, yet coordinated, processes seems appropriate.

Many cities that engage the general citizenry do so late in the game via public meetings to at best vet and at worst defend their plans. This tends to engender opposition and recriminations of hubris and bias, and leads to plans that are not as well informed as they could be. Those that attend these meetings are typically either the 'usual suspects' or driven by narrow self-interest; it is not clear that the broader range of interests in the community are well represented. There are various alternatives that may produce more legitimate and productive outcomes. The Cambridge Climate Emergency Congress loosely adopted a *deliberative polling* approach, selecting a group of delegates that represented the demographic diversity of the community to deliberate, craft recommendations for the City and other key players, and express their preferences (City of Cambridge, 2010; Fishkin, 1991). In addition to engaging the general public, Quito Ecuador is involving representatives from various civil society groups in the planning and implementation of their climate change strategy (Carmin et al., 2011). These groups can provide additional implementation capacity, valuable feedback from the grassroots and added legitimacy in the eyes of their respective constituencies. As noted previously, many communities have created 'blue ribbon' commissions to lead their adaptation efforts (City of Chicago, 2008; Rosenzweig et al., 2010). The community leaders involved can provide insight, legitimacy and political cover to administrations interested in taking bold steps.

Many adaptation efforts feature committees or work groups that involve extensive collaboration across traditional departmental and agency boundaries, and among external experts and other stakeholder representatives. Participants are often unfamiliar with each other's approaches and perspectives, and are unclear on what is expected of them. Effective process techniques and the creation of useful boundary objects can help parties to make their collaborations more effective (Cash et al*.,* 2003; Susskind and Paul, 2010). Role-play simulation exercises have proven useful in this regard, introducing parties to the various dimensions of the adaptation-related challenges they face and to how they might work together to address them. They have been used at various scales, in various sectors and towards different ends. One series of exercises is being used to introduce Massachusetts towns to the risks associated with climate change and some of the tools they may use to address them, like scenario planning (MIT Science Impact Collaborative, 2012). A role-play simulation was run with high-level energy sector officials in Ghana to instigate reflection on how they might respond to new, yet still very uncertain, information on how climate change could impact hydroelectricity projects (World Resources Institute, 2011).

While providing many benefits, engaging stakeholders in adaptation planning also has its costs and potential pitfalls. In addition to the concerns inherent to any participatory process – particularly the resource and time requirements, and challenge of providing procedural equity – the long-term, complex, uncertain and contextual nature of climate change makes public participation particularly difficult (Few et al., 2007). Government agencies may find it all too easy to advance their own ambitions with participatory processes serving merely as 'window dressing', leading to friction later. Furthermore, it is hard to balance the relatively diffuse interests of an uncertain yet looming future against the clear and current interests of groups that may lose today if adaptive measures are taken. Planners and decision-makers need to be honest and up-front about the scope and limitations of participatory processes, and do what they can to support the legitimate representation of the various interests at stake (Few et al., 2007). This requires, among other things, attention to how information is generated and presented (United Nations Human Settlement Programme, 2011).

Box 4.5: San Diego Climate Change Sea Level Rise Strategy

A recent adaptation planning project in the San Diego region is a good example of effective stakeholder engagement to address climate vulnerabilities. The *San Diego Bay Sea Level Rise Adaptation Strategy* was prepared through an intensive regional process driven by stakeholders from a diverse cross-section of interests and sectors. The goal of the project was to develop a vulnerability assessment and provide adaptation policy recommendations for a Steering Committee comprised of local and regional jurisdictions on San Diego Bay, including the City of San Diego, the Port of San Diego, and the San Diego Regional Airport Authority. The Steering Committee directed the technical and stakeholder engagement work, which was supported by The San Diego Foundation and performed by ICLEI, in partnership with NOAA's National Estuarine Research Reserve-Coastal Training Program and the New School of Architecture in San Diego. This core group represented an unprecedented collaboration of multi-jurisdictional and multi-sectoral partners that each brought specific expertise and resources to the initiative.

A broad set of stakeholders were engaged through the Stakeholders Working Group and Technical Advisory Committees, and participated in workshops at each milestone of the project.

The Stakeholders Working Group was comprised of 30 organizations with direct interests in the future of the Bay. Organizations included regulatory agencies, natural resource management agencies, the US Navy, and representatives of business and environmental interests. Through workshops held over the course of a year, these stakeholders came to understand climate science and adaptation concepts, worked through difficult issues, and emerged with consensus-based recommendations for building resilience in the region. They were informed throughout by technical advisory committees consisting of researchers from Scripps Institution of Oceanography and a variety of local practitioners. Project partners attribute the project's success largely to a clearly defined process of stakeholder participation from public agencies, the private sector, academia, philanthropy, and other non-profit organizations.

Box 4.6: Community Engagement in the San Francisco Bay Region

The San Francisco Planning and Urban Research Association (SPUR), a member-supported nonprofit organization, was founded in 1910 by a group of young city leaders who came together to improve the quality of housing after the 1906 earthquake and fire. That group, the San Francisco Housing Association, authored a hard-hitting report that led to the State Tenement House Act of 1911. Over the next century, in a city dominated by single-interest politics, SPUR has played the crucial role of uniting citizens to jointly craft solutions to common problems. More recently SPUR has expanded its role to encompass research, education and advocacy that promotes good planning and good government throughout the nine-county San Francisco Bay Area.

In 2009, SPUR, supported by grants from the Urban Land Institute, the Richard and Rhoda Goldman Fund and San Francisco Foundation, began work on an in-depth study on how to adapt to warming temperatures and changing weather patterns, including reduced snow-pack in the Sierra Nevada and rising sea levels on the edges of the Bay. In February 2011, they published "Climate Change Hits Home"[xvi] a document that describes the impacts of climate change and recommends more than 30 adaptation strategies for local and regional agencies to respond to the impacts and begin minimizing the region's vulnerabilities to long-term, but potentially catastrophic, effects of climate change.

Box 4.7: City Hall Partnerships with the Boston Community

In spring 2009, Mayor Thomas M. Menino created a Climate Action Leadership Committee to develop recommendations for updating of Boston's 2007 climate action plan. Among the Leadership Committee's tasks was to "[e]valuate the risks to Boston from sea-level rise and other consequences of climate change, and recommend actions to reduce these risks." Under the Leadership Committee's guidance, the year long process developed an extensive public consultation apparatus. Five working groups, including one focused on adaptation, sought the participation of additional academic, institutional, business, and community partners. A Community Advisory Committee on Climate Action, comprising 30 members selected through an open nomination process, met in parallel with the Leadership Committee. After draft recommendations were available in all areas, five community workshops—three-hour meetings held in various neighborhoods of the city and attended by about 500 people in all—discussed

Boston's climate vulnerabilities and appropriate responses. The committees delivered their mitigation and adaptation recommendations to the Mayor on Earth Day 2010.

The City of Boston's formal efforts around community involvement have been supplemented by independent efforts. In 2009-2010, Dr. Paul Kirshen, Dr. Ellen Douglas, and colleagues, with funding from NOAA, conducted a series of adaptation workshops in East Boston, a primarily residential neighborhood of Boston that sits on Boston Harbor and next to Logan Airport (Douglas et al., forthcoming). Working with the non-profit organization Neighborhood of Affordable Housing, they held three workshops with neighborhood residents, including a sizable contingent of teenagers, that worked progressively through the causes and consequences of climate change, the specific vulnerabilities of East Boston, and possible adaptation actions, the last supported by some engineering analysis. Participants, including City Hall staff, discussed the advantages and disadvantages of various proposals from a wide variety of perspectives. Kirshen and Douglas expect to initiate a new round of neighborhood meetings in 2012 to develop more specific community-backed adaptation strategies.

A major outreach to the Boston business and real-estate development community occurred at a public forum under the auspices of The Boston Harbor Association (TBHA), again with City Hall staff as part of the planning committee and as speakers at the forum. TBHA, an NGO with a 20-year record of working to protect Boston Harbor, commissioned new maps showing projections of sea level rise-related funding in the Boston area and organized an evening presentation on the science of climate change and a following daytime forum on adaptation proposals and policies. The forum was marked by the significant involvement of leading business representatives and City Hall planners and an extended discussion of the economic consequences of climate change and adaptation. As a follow-up to the forum, the TBHA held two well-attended neighborhood adaptation workshops.

The newest, visible manifestation of partnership between City Hall and the community is Boston's Green Ribbon Commission, a self-organized group of business, educational, and institutional leaders committed to assisting the City in implementing climate action. The Mayor serves as a member ex officio, and the Commission, working with City Hall staff, has developed an extensive array of working groups, including one on adaptation, that reach beyond the membership of the Commission.

4.3.2 Communication

Municipalities face an uphill battle to engage citizens in supporting and responding to the complex, long-term, uncertain issue of climate change. Despite familiarity with the issue, many Americans lack a sense of personal connection (Leiserowitz, 2007), and perceive it as a much lower priority in the near term than other issues, such as unemployment and the economy. Communication is one tool that local governments can use to both engender support for climate adaptation policies and motivate adaptive responses by organizations and individuals within their own spheres of influence.

While climate change is a complex problem, local governments have experience dealing with and communicating complex issues to their constituents. They also have substantial experience communicating with their constituents about important issues. For example, a local government will routinely test public safety measures, educate citizens on what to do during a natural disaster, and ensure that effective lines of communication are available to inform citizens of changes in public services. As climate variability and change continue to affect localities, governments will need to combine their understanding of their communities with the latest methods, tools and knowledge about communicating uncertain, complex risks that are often also politically charged to constituents in ways that will elicit support for change (Ockwell et al., 2002).

4.3.2.1 Framing Climate Change

Recent studies have shown that using alternative frames for messaging might be more effective than strictly framing issues in terms of climate change (Nisbet et al., 2011; Roser-Renouf and Maibach, 2010; Nisbet, 2009; Asim and Todd, 2010). Using alternative framing has the advantage of aligning climate change with other higher priority issues that have greater appeal to members of the public. Some suggested frames are public safety, national security, and economic stability (Moran, 2011; Asim and Todd, 2010; Leiserowitz et al., 2010; Nisbet 2009; Center for Research on Environmental Decisions, 2009; Busby, 2007). While these may be influential, public health, local wellbeing, and resilience are frames that have resonated with communities (Leiserowitz et al., 2011; Roser-Renouf, 2010; Maibach, 2010; Center for Research on Environmental Decision, 2010; Lindseth, 2004; ICLEI USA, 2011). Several studies that show Americans who view climate change as being harmful to their local community are more likely to support climate policy responses (Maibach, 2010; Cash et al., 2002; Leiserowitz et al., 2011). Resilience framing emphasizes how actions can maintain or build on a community's resources and adaptive capacities to enable a community's positive response to change. In contrast to doom and gloom scenarios of what our world will look like without action, positive frames such as resilience are gaining support as a more effective way to engage and inspire residents to support climate change action (Center for Research on Environmental Decision, 2010; Beattie, 2011).

4.3.2.2 Innovation in Communication

Local governments are responsible for communicating with a diverse, dynamic, and constantly evolving set of stakeholders. From high school students to retirees, local governments need to find ways of communicating the complex issue of climate change to stakeholders using the most appropriate types of medium – recognizing that multiple types of medium will likely be necessary (Moser, 2006). In the case of climate communication in the City of New York, dozens of mediums are used to reach out to constituents about climate adaptation and climate mitigation efforts – such as websites, television, billboards, flyers to homes and businesses translated into multiple languages, twitter and Facebook, and the use of a mascot (see PlaNYC). The City of Medford, Massachusetts utilized friendly competition and television as tools to encourage residents to reduce their energy consumption. Known as the Energy Smackdown, the program was so well received that a second season brought together teams of households from three different communities in Massachusetts – Arlington, Cambridge, and Medford – to see which community could make the biggest energy reduction over 12 months. The competition was aired on public television and viewed by thousands (Center for Research on Environmental Decision, 2010).

As illustrated by the previous example, the use of visualization can be a strong tool for securing public support and motivating individuals to respond. As an example, the Bay Conservation and Development Commission in California hosted a "Rising Tides" competition in 2010 (see below). The competition encouraged stakeholders to project what the Bay would look like with a sea level rise of 1-meter. Research from CRED identifies that "messages should: have vivid imagery, in the form of film footage, metaphors, personal accounts, real-world analogies, and concrete comparisons; messages designed to create, recall, and highlight relevant personal experience and to elicit an emotional response" (Center for Research on Environmental Decision, 2010).

Box 4.8: Building Awareness of Climate Change in California

Convincing a skeptical public that climate change is a real issue that needs immediate attention is proving difficult throughout the nation. This is true even in the San Francisco Bay region, where educational levels are high, and where future sea level rise makes 330 square miles of low-lying land surrounding San Francisco Bay vulnerable to future flooding (San Francisco Bay Conservation and Development Commission, 2011).

According to the Pacific Institute, along the California coastline, property and structures with a replacement value of $100 billion are vulnerable to sea level rise induced flooding. About $60 billion worth of that property is around the San Francisco Bay, where many of the affected communities are lower-income and ethnic minorities.[xvii] Record budget deficits and high unemployment in California compound the challenge of gaining public support to address sea level rise. However, two low-cost initiatives have brought this issue to the public's attention and have inspired ideas and personal actions for dealing with the problem.

In 2009, the San Francisco Bay Conservation and Development Commission (BCDC) held an open international design competition for ideas on potential responses to sea level rise in San Francisco Bay and beyond. The competition invited participants to rethink how to: build new communities in areas susceptible to future inundation; retrofit valuable public shoreline infrastructure; protect existing communities from flooding; protect wetlands; and anticipate changing shoreline configurations. About 130 entries from 18 nations were submitted. On July 13, 2009, all submissions were evaluated by a five-member, multidisciplinary, international jury. Although asked to choose one grand prizewinner, the Jury selected six winners to share a total prize of $25,000. The Judges determined that the submissions by these additional winners were needed to thoroughly address the complex problems surrounding the Bay and sea level rise. The Rising Tides design competition gained international media attention, has inspired similar exhibits elsewhere and has generated a rich collection of ideas that are undergoing further research and feasibility analysis.[xviii]

An even lower cost and more inclusive effort was launched in California in late 2010. The 2011 California King Tides Photo Initiative had two main objectives: to identify and catalog coastal areas currently vulnerable to tidal inundation, and to gather compelling images that can be used by anyone to promote awareness of the potential impacts of sea level rise. The King Tides event[xix] chronicled the extreme high tide events that occur when the sun and moon's gravitational forces reinforce one another. These king tides tend to be more dramatic in the winter when storms cause increased wind and wave activity along the coast. The idea for a King Tide event began in 2009 in Australia, and was followed by similar events in Washington and British Colombia. Participants submitted hundreds of photos of high tides in their neighborhood and uploaded them to Flickr, a photo sharing website. The photos were geo-tagged to note the locations where the photos were taken in order to give a sense of the areas covered by the Initiative. The California King Tides Initiative brought in pictures from as far north as Humboldt Bay to San Diego, showing a variety of effects from the higher water (e.g., waves overtopping levees, flooded roads, inundated natural areas). The images also depicted the diversity of shoreline types that will require protection, restoration, retreat or rebuilding strategies as sea level rise occurs and other hazards become more frequent.

4.4 Private Industry and Risk Management

4.4.1 Insurance

The insurance industry, comprised of principally (re)insurance companies, is in the business of managing risk. The industry transfers risk from individual policyholders to a larger risk sharing community, diversifies risk across differing classes of business and spreads risk globally through reinsurance markets. Premiums are calculated using actuarial principles; for example, homeowners on East Coast barrier islands pay a higher premium than those who reside inland due to the increased probability of wind-related losses (flood related losses are covered by the National Flood Insurance Program). The industry aims to be equitable and cost effective to customers while maintaining solvency and shareholder value for the company.

The stakes are high regarding successful management of natural catastrophe risks. According to a report by AIR entitled *The Coastline at Risk: 2008 Update to Estimated Insured Values of U.S. Coastal Properties* (2008), the value of insured coastal properties along the US Gulf and East coasts rose to almost $8.9 trillion in 2007. Figure 4.1 below shows losses greater than 1 billion or with 50 or more fatalities. As the figure illustrates the total economic losses from significant natural catastrophes in the US (hurricanes, floods, wildfires, droughts, tornadoes, winter storms, etc.) regularly exceed $50 billion, and the private insurance industry covers a significant portion of the total economic losses. According to a 2011 Lloyd's white paper, these losses have grown in the past two decades as a result of population growth and increased value of properties in highly exposed regions, increased new development in catastrophe prone areas and increase in frequency of natural hazard events, some of which is attributable to climate change (see Figure 4.1) (Lloyd's Insurance Market, 2011).

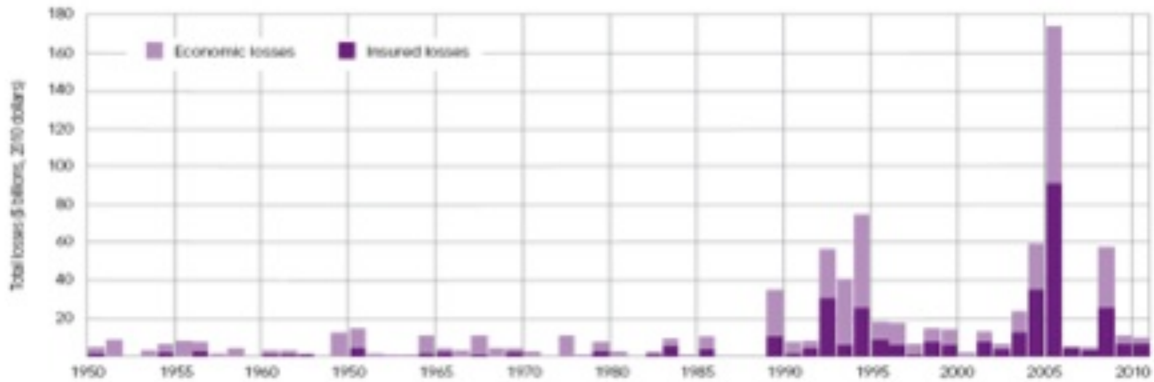

Figure 4.1: Significant US Catastrophe Losses (1950-2010). Source: MunichRe NatCat Service, 2010.

The insurance industry must remain stable and sustainable so that private companies are capable of paying all incurred losses to policyholders without becoming financially insolvent. Risk-based pricing is one of the tools that ensure continuing financial competence. It calculates premiums using objective actuarial principles, resulting in higher premium charges when risks are located in regions prone to natural disasters or when buildings and infrastructure are poorly constructed. Conversely, lower premiums are charged when risks are in areas not exposed to natural catastrophes or when buildings are well-constructed and fortified against potential damage. This pricing approach, coupled with portfolio diversification, allows insurers to retain enough capital to pay even when severe losses affect their books of business.

Direct competition between government subsidized programs (such as Florida's Citizens Property Insurance Corporation, the Florida Hurricane Catastrophe Fund and the National Flood Insurance Program [NFIP]), and private (re)insurers creates problems because government subsidized programs do not charge based on actuarially-derived rates. Therefore, these programs are not sustainable. When such publically sponsored insurers offer "affordable" insurance at rates below the actuarially sound rates of the private market, they undermine the insured's incentive to mitigate risk in order to obtain a lower premium.

Additionally, the government subsidized insurer or reinsurer is frequently undercapitalized due to these low, inadequate premiums and undiversified portfolios. A single, significant natural hazard can affect many insurance policies and has the potential to render undercapitalized government-sponsored entities insolvent, which in turn will likely burden tax payers at large, many of whom do not have at-risk properties. Two examples (the NFIP and Florida's Citizens') are discussed briefly below (see Box 4.9).

Box 4.9: Losing a Private Market for Insurance

A 2011 US Government Accounting Office (GAO) report states that the NFIP is approximately $17.8 billion in debt and concluded that the NFIP is "not actuarially sound" (GAO, 2011). The report re-states previously identified public policy goals, which include "charging premium rates that fully reflect risks" and "encouraging private markets to provide flood insurance."

A 2010 report by New York University (NYU) Law School concludes that the NFIP is at odds with climate change adaptation and that the program's deficit is "**likely dwarfed by the ecological damages that the program encourages" (NYU Law Institute for Policy Integrity, 2010).** The report goes on to say that "The current price of flood insurance both subsidizes new development in flood zones and subsidizes risk for those who already built in flood zones. The costs of the subsidies will likely be borne generally by taxpayers. But where there is a subsidy, there is a benefit. The benefits of the NFIP appear to accrue largely to wealthy households concentrated in a few highly-exposed states."

Similarly, Florida's Citizens charges policyholders premiums below those of private companies. Its CFO testified in early 2011 that Citizens' rates for covered homeowners' would need to be raised 55 percent to make the company "actuarially sound" (Binnun, 2011).

4.4.1.1 How the Insurance Industry Helps with Climate Change Adaptation

The insurance industry, through partnerships with federal and local governments, customers and other stakeholders, can assist with climate change adaptation to build resilient communities (see Table 1, for examples of insurance related incentives and support for risk mitigation). One area the insurance industry can assist with is supporting basic research related to managing and adapting to weather related risks. The Willis Research Network, a collaboration of insurance industry companies, academic institutions and government, focuses on the key issues related to climate and weather risks, including storms, floods and other extremes. Any research conclusions are designed to help identify and quantify exposure to extreme events, and assist in the risk management decision-making process.

European reinsurer Munich Re funded a collaborative study with the London School of Economics to investigate the risks and economic impacts of anthropogenic climate change. Global re(insurers) such as Swiss Re, Zurich, Allianz and Lloyd's have conducted or collaborated on research on the economic impacts of climate change and adaptation options. For example, Swiss Re contributed its expertise in a 2010 report supported and sponsored by America's Energy Coast, America's Wetlands Foundation and Entergy. The report includes a cost-benefit analysis of adaptation measures on the US Gulf Coast.[xx] Lloyd's released a 2011 white paper (Lloyd's Insurance Market, 2011), with a focus on climate change adaptation entitled "Managing the Escalating Risks of Natural Catastrophes in the United States" (Lloyd's Insurance Market, 2011).

Furthermore, the insurance industry can help to develop, encourage, and incentivize risk mitigation measures. Risk based pricing of insurance premiums, at the core of delivery of sustainable private insurance, provides incentives for risk mitigation measures. High-risk property owners will either pay increased premiums or find premium costs prohibitive and remain uninsured. When risk is mitigated through retrofits, stricter building codes or changes to zoning ordinances, premiums decrease or insurance becomes available.

One example of risk mitigation, cited in Section 4.2.1, describes the choice to use community financing to repair levees in Illinois because it was less costly than requiring individuals to buy flood insurance. Another example is the program developed by the non-profit Institute for

Business and Home Safety that promotes code plus building standards and retrofits for specific hazards and building types. Members, primarily property and casualty insurance companies, are encouraged to offer insurance discounts to customers who implement these measures.

SaferSmarter.org is a national coalition including nine US insurance industry companies or associations, united in favor of environmentally responsible, fiscally sound approaches to natural catastrophe policy. Coalition members support measures that encourage and assist homeowners in taking steps to protect their homes against natural disaster and they support a Federal government role in helping homeowners to undertake mitigation efforts.

Table 4.1: Insurance Related Measures for Risk Mitigation. Source: Entergy, America's Energy Coast, and America's Wetlands Foundation, 2010.

Type of Incentive or Measure	Example
Risk based premium pricing	Rates decline if property is in area less prone to weather risks or built to a higher standard
Strengthen Ecosystems	Strengthening ecosystems to reduce risks of natural hazards (e.g. Tokyo Marine's planting of mangroves, enhancing wetlands and forests for risk mitigation)
Require or encourage use of safer building codes, retrofits and other risk mitigation measures that result in lower premiums	Use of storm shutters on coasts; Institute for Business and Home Safety's promotion of risk mitigating building codes and retrofits; fire-proofing of homes in forests
Community risk mitigation measures can be less costly than individual insurance premium increases	Levee rebuilding in Illinois
Insurance policies with higher deductibles and lower premiums	Insurers use savings from lower premiums to pay for risk mitigation

The insurance industry can also encourage better data collection, hazard maps and improvements to climate models. (Re)Insurers have a vested interest in understanding the impacts of climate change on extreme weather events. Like adaptation planners, (re)insurers need high quality geophysical data and observational tools, such as LIDAR and flood maps. The insurance industry has lobbied for improvements in data collection and evaluation tools, for example in efforts to reform the NFIP. For the first time since its inception, the Intergovernmental Panel on Climate Change (IPCC) is in the process of releasing a report which strongly implies a causal connection between anthropogenic emissions and frequency shifts in extreme weather events (IPCC, 2011) Shifts in extreme event frequency alter the risk landscape and expose (re)insurers to previously unforeseen losses. Therefore, in order to maximize future portfolio management and risk capital allocation, (re)insurers must consider the potential impact of climate change in addition to historical loss patterns.

Although it is important to consider future climate changes in portfolio management and risk capital allocation, actually doing so can be quite difficult. Climate change projections are produced by highly sophisticated global coupled ocean-atmosphere general circulation models (GCMs). The computational intensity of developing climate change scenarios for the whole globe results in temporally and geographically coarse output which insufficiently captures individual weather events. Useful downscaling techniques have been applied to develop finer spatial scale projections of climate change, including changes in the variability of extreme events such as hurricanes. However, many of the underlying population, technology, energy, economic, and other assumptions used to generate climate scenarios, along with the parameters within the climate models themselves remain highly uncertain and require more research before model output is sufficiently useful for natural catastrophe modeling.

With the caveat above, the insurance industry can still develop innovative and useful applications of the industry catastrophe models. Catastrophe models, used by underwriters to price natural catastrophe risk, can be applied to determine the potential economic and financial impacts of climate change. Catastrophe models are computer models which combine scientific, engineering, economic and financial principles to provide insurers with projections of loss severity and loss frequency. The models contain hazard sets, which are hundreds of thousands of physically plausible but non-historical events, such as earthquakes, hurricanes, floods, blizzards and tornadoes, and an associated probability of occurrence. The input is a portfolio which contains information about the location, construction and value of each individual risk, and the output gives expected loss values across various return periods and the annual average loss.

Models can be tweaked to account for climate change by altering the frequency or the severity of different simulated events. Output then reflects losses expected in a new climate regime. A handful of studies have already employed catastrophe models to gain a perspective on the changes in potential losses in a new climate regime and the costs that can be offset by mitigation efforts; one such example is *Shaping Climate-Resilient Development*, a report released in 2009 by the Economics of Climate Adaptation Working Group, a partnership between the Global Environment Facility, McKinsey & Company, Swiss Re, the Rockefeller Foundation, ClimateWorks Foundation, the European Commission, and Standard Chartered Bank (McKinsey and Company, 2009). One section of the study focuses on South Florida, namely Palm Beach, Broward and Miami-Dade Counties. Under certain assumptions about a changed climate, the potential annual loss from more frequent major hurricanes in the three counties is $30 billion, which is approximately 10 percent of the area's gross domestic product. However, through simple mitigation strategies such as beach nourishment, building-code improvements and vegetation management, almost half of this additional loss could be offset.

Lastly, the insurance industry can help to develop index-based weather coverage. In the near term, states and municipalities can offset year-to-year budget fluctuations caused by weather variability by purchasing index-based weather cover. Transparent and parametric, a product based on a weather index (temperature, precipitation, snow fall, hurricane wind speed, etc.) allows states and municipalities to quickly receive funds to finance various aspects of post-event response. Such activities would include snow removal, salt purchases, branch removal, and flood cleanup.

The State Insurance Fund of Alabama is one such government entity that has entered into a parametric weather transaction (see Box 4.10 below).[xxi] In 2010, Alabama and reinsurer Swiss Re signed a three-year contract whereby Swiss Re makes a payment to the state of Alabama if a hurricane of a given intensity or higher makes landfall along the state's Gulf Coast. The transaction was novel; marking the first time a state government used an alternative risk transfer solution to shift its financial risk to the private market.

While the Alabama-Swiss Re transaction was the first of its type in the United States, several other alternative risk transfer agreements have occurred between governments and the private sector. Multi-Cat Mexico is a series of multi-peril bonds offered by the Mexican government which are tied to earthquakes, Atlantic hurricanes and Pacific hurricanes.[xxii] The Caribbean Catastrophe Risk Insurance Facility (CCRIF)[xxiii] is a risk-pooling facility that offers parametric insurance products to Caribbean governments, providing short-term financing immediately after any natural catastrophe in the region. CCRIF is a successful program to date, making payments to various governments after Hurricane Ike and the Haiti earthquake.

Box 4.10: Swiss Re and the State Insurance Fund of Alabama

The transaction between Swiss Re and the State Insurance Fund (SIF) of Alabama is the first of its type between a United States government entity and a private reinsurer. Signed in 2010, the three-year deal protects the SIF against catastrophic hurricane losses. The structure of the coverage is not a typical excess of loss catastrophe program, but rather a parametric cover based on the physical characteristics of the event. In the case of the Swiss Re – Alabama program, the SIF will receive a payout whenever a hurricane of a specified intensity or higher makes landfall in the region.

The benefits of a parametric cover are multiple: transparent, objective and easily settled. The entity experiencing the loss does not have to endure the claims-filing process and the trigger is transparent, allowing funds to be received quickly. Furthermore, because typical underwriting techniques are not applied to pricing a parametric cover, this particular type of risk transfer mechanism can insure non-traditional risks outside the scope of conventional insurance. These characteristics can make parametric insurance covers particularly beneficial for state and federal entities, allowing budget offices to more efficiently manage administrative costs, overtime salaries and other incurred costs as a direct result of extreme weather events.

4.4.2 Private Sector Opportunities

4.4.2.1 Current Role of the Private Sector in Urban Decision-Making

Municipal governments engage in decision-making around the physical and social infrastructure in their areas. Businesses that provide services such as waste management, water and energy delivery, transportation, and telecommunications are an important part of the decision-making process in many cities that have privatized these services. These businesses are often intimately involved in the day-to-day operations of cities and so are in key positions to be able to contribute information, techniques, and best practices to the urban planning process. Since urban physical infrastructure may experience significant shocks and challenges due to climate change, many of these businesses are already planning for adaptation. Cities can take advantage of the work the private sector has already done in assessing the risk of climate change to their business services by partnering with them to use the information in their own adaptation planning. Two examples of businesses that are providing services to cities and are engaged in climate adaptation are Arup and CH2M HILL.

Arup is a global consulting company based in London, UK, that provides infrastructure and building engineering and planning services for global urban areas, including cities in the United States (Arup, 2011). One of their recent US projects was a plan for the sustainable redevelopment of Treasure Island in San Francisco Bay (Arup, 2011). Arup was also asked by the C40, the former Large Cities Climate Leadership Group, to co-author a 2011 report on the actions 40 global megacities are taking in response to climate change. CH2M HILL provides engineering and construction services for cities world-wide, and is based in Colorado. They collaborated with the City of Alexandria, VA to develop a storm sewer infrastructure plan based on the projected impacts of flooding and storms due to climate change (van der Tak et al., 2010).

Box 4.11: Community Risk Mitigation in Illinois

One Illinois community found a way to fix its levee when it was determined to be insufficient. Levees along a 75-mile stretch of the Mississippi River were deemed to be inadequate and, as a consequence, a 174 square mile area was to be included in a special flood hazard area. Within this area, residents and businesses would be required to purchase flood insurance. Other options were available, and the community found that some of those options for mitigating risks were more cost effective than purchasing insurance. Local officials filed suit to halt the reclassification and at the same time exercised one of their options -- a $180 million project to bring the levees up to an adequate protection level. The project is in progress and the money was obtained through a 0.25percent sales tax increase.[xxiv]

4.4.2.2 Private Sector Urban Data

Private sector companies working in cities are collecting vast amounts of data from their systems that can be useful for urban decision-makers. Businesses providing infrastructure services collect data on many immediate urban variables such as energy and water usage, communication networks, and transit ridership. While there are many applications of these data in models of urban systems, these data can also be used to assess vulnerability and resilience in those systems to best inform adaptation strategies. Businesses that provide these urban services may be collecting data that no one else in the city is gathering, especially if a business is the main contractor for a particular service. Since urban consultants are often focused on a specialized aspect of the city, the data these businesses gather are often collected frequently and can be highly detailed. National and multi-national urban contractors who provide services to many cities have these data available to understand how different cities adapt to similar infrastructure challenges.

Government agencies from the municipal to federal level are also gathering and analyzing urban data, and most businesses providing infrastructure services to cities cooperate with these departments and agencies to share data and participate in planning. While the private sector usually shares some of their data with cities as part of their agreements, many companies keep their raw data or methodology proprietary. Businesses may also have future plans and working scenarios for ways to adapt to external changes such as economic decline or environmental impacts that might be useful to urban planning processes. However, private sector data may not be accessible for researchers at universities, NGOs, or the city itself to analyze. Lack of access to data can hinder full understanding of urban systems and how to best adapt these systems for climate change. There are approaches cities can use to access their private sector partners' raw data and methods while allowing the businesses to retain their competitive advantage. Two examples of private-sector initiatives focused on sharing data and methodologies useful to climate change adaptation are The Sustainability Consortium and Waste Management's recycling initiative in Phoenix, Arizona.

The Sustainability Consortium is an organization with a membership composed of businesses, NGOs, and universities. Their goal is to develop sustainability metrics to evaluate consumer products and the producers of products (Dooley et al., 2011). There are approximately 75 businesses involved, including Wal-Mart, Tesco, and Cargill. Academic and NGO partners are conducting research and life cycle assessments of products and suppliers to develop sustainability measurements and a reporting system. While this effort is still in progress, this cross-sector collaboration is expected to produce an academically rigorous open source system to evaluate products and suppliers on environmental and social impacts, while protecting private-sector intellectual property. The Sustainability Consortium provides an example of how the private-sector can be effectively engaged in an effort to develop open methodologies that use their data to inform public decision-making. In this case, sustainability metrics of products and suppliers can be used by cities when making decisions on contracts for supplies and materials. The choice of contracts for goods and materials can be based on reducing the vulnerability of their environment and population to a variety of risks as they implement adaptation strategies.[xxv]

To assess recycling participation rates, Waste Management (WM) is piloting a project with the cities of the Phoenix, Arizona metro area to weigh their trucks before and after they pick up waste along each route. WM is gathering weights of waste generated along different routes and as well as socioeconomic variables (neighborhood income and education levels, weather, home ownership) that Arizona State University researchers will use to see which factors influence recycling (Fink, 2011). These behavioral patterns can be used by cities to develop policies most likely to encourage recycling and help cities make use of available resources as part of their adaptation plans.

4.4.2.3 Engineering and Government Contracting

Urban climate change adaptation will require extensive engineering efforts as cities build infrastructure to accommodate rising sea levels, more severe weather events, intensified heat waves, and other climatic changes (Royal Academy of Engineering, 2011). Roads, bridges, seawalls, reservoirs, electrical grids, and other critical infrastructure will need to be assessed and improved based on projected changes. Many cities will contract their infrastructure adaptation projects to private sector engineering firms. Multi-national engineering firms are currently working with cities around the world on adaptation plans. These companies are in a key position to develop strategies that can be ported and implemented across cities based on similar risks. As engineers design infrastructure for climate change adaptation, mitigation is often included. For example, a new office building may be built to be energy efficient and also strong enough to withstand future severe weather. In practice, urban engineers generally consider both adaptation and mitigation in their designs (UK Trade and Investment, 2011).

Box 4.12: Engineering Consulting Example – Abu Dhabi

One of the most ambitious examples of an urban engineering project is Masdar City, 20 miles outside of Abu Dhabi. This "sustainable" planned city is being developed as a low-carbon city that will contain a 40-60 megawatt solar plant, wind farms, and solar-powered desalinization plant (Ouroussoff, 2010). Engineering is being provided to the Masdar initiative of the Government of Abu Dhabi by several multinational companies, such as Siemens, CH2M HILL, and Conergy. While Masdar City is still a work in progress and has many critics, it is an end-member of the use of government contracting to build, develop, and run a city. This extreme example of building an entirely new city as an adaptation to climate change highlights the speed of innovation and scope that private sector engineers can bring to new challenges (Nader, 2009). The engineering firms that are working to create Masdar City are approaching these infrastructure projects in ways similar to how they approach adaptation plans with established cities. Masdar City is a test bed for methods that other cities may use in their adaptation strategies.

4.4.2.4 Warning Systems

Disaster risk reduction and climate change adaptation communities have much in common in the area of reducing vulnerability to natural disasters, and can learn much from each other (Thomalla et al., 2006). Climate change adaptation approaches and disaster risk reduction both are based on risk management. Disaster risk reduction is typically focused on the local-scale and is community-based whereas climate change adaptation may be focused on a number of different spatial scales (Thomalla et al., 2006). These two communities are working together more than they have in the past, particularly at the urban level. There are now significant opportunities for cities to engage the disaster risk reduction community to help inform adaptation plans for vulnerability to the impacts of climate change. Cities can especially benefit from the experience in the disaster risk reduction community on developing hazard forecasting and early warning systems. The USGS urban warning systems for earthquake and volcano hazards and NOAA's tsunami warning systems for cities are good examples of experts partnering with decision makers and the public around disaster risk. These systems are based on the science of natural disasters and the ways people respond to threats and risks.

Box 4.13: Early Warning Systems in Miami

Greater Miami is one of the most vulnerable metropolitan regions in the world to threats from both climate change and hurricane activity. The area exhibits a unique confluence of factors which contribute to its unparalleled susceptibility. The factors include; the extremely low-lying topography of Southern Florida, location in the Atlantic hurricane belt, an increasing metropolitan population in excess of 5 million people, and hundreds of billions dollars in at-risk coastal property. Centuries of tropical cyclonic impacts has resulted in an ingraining of hurricane knowledge and warning systems in the general populace and municipal governance. However, knowledge of climate-change impacts, particularly sea-level rise and the correlation with future hurricane impacts is not nearly as developed. Cities in the metro-region such as the City of Miami along with neighboring municipalities, state and federal government agencies, academia and the private sector, will play an increasingly important role in education, communication and preparation for future hurricane impacts amplified by projected sea-level rises.

The City of Miami has a comprehensive Hurricane Plan with specific preparation and response procedures for 5 days prior to expected landfall of a storm, through 96 hours post-landfall. Along with the mobilization of personnel and equipment, liaising with governmental emergency agencies and officials, and activation of other emergency protocol, the Hurricane Plan's effectiveness relies heavily on its communication and information dissemination procedures. These communication procedures include: disseminating preparedness information via broadcast and print media and activating the public information phone center including TDD, 5 days before projected landfall; issuing public information "watch" systems 72-48 hours before projected landfall to citizens, businesses, grocers, construction companies, hotels and nursing homes to initiate specific emergency readiness actions; and, issuing evacuation orders for areas vulnerable to life threatening conditions and activating the emergency alert system and City weather channel with 36 hours of less to projected landfall.

With landfall of a hurricane imminent (less than 12 hours) the City of Miami's communications includes notifying the homeless population service providers of an evacuation order, releasing the Emergency Alert System (EAS) Message, issuing public information statements announcing cessation of evacuations and opening of "Refuges of Last Resort". Upon onset of a Hurricane the City must continuously assess public information and media capabilities. Throughout the entire pre and post hurricane emergency period, the City regularly conducts media briefings, releases and interviews as well as conference calls with county and other governmental agencies to ensure a reliable stream of reliable information and communications. The City ensures effective dissemination of information by accounting for the multi-cultural cosmopolitan nature of greater Miami, with its public broadcasts available in English, Spanish and Creole.

Though not without challenges, knowledge and warning systems for hurricanes have been generally well developed and received due to the area's familiarity with these storms. Communicating the urgency of climate-change sea-level rise has met considerably more challenges. The area has seen a steady rise of sea level (in, how much, from when). And while some estimates project sea level rises to be as much as 6 feet by the end of the century, even more conservative estimates of just 6-8 inches will result in catastrophic impacts especially when hurricanes are considered. Significant sea level rises will dramatically reduce the amount of developed area above high tide, contaminate drinking water, damage crops and ecosystems via salt water intrusion inland, and flood the barrier islands such as Miami Beach (home to large population and billions of dollars worth of property itself) thereby reducing protection from storm surge to the south Florida mainland. Notwithstanding the possible effect that warming sea temperatures (evidence) around South Florida may have on the intensity of Hurricanes themselves, the impacts of these storms will be catastrophic with even a modest predicated rise in sea level. The effects of such storms are further amplified by an increasing population, particularly in the coastal urban core. Consider that the City's poverty statistics including *having the 3rd lowest median income and the 6th highest percentage of residents living below the poverty line in the nation*, and it becomes increasingly difficult to educate a population about the urgency of climate-change when their economic and social concerns are often more basic and immediate in nature. Moreover, balancing the need for economic development with adaptation for climate change through policy development will not be an easy reconciliation. Additionally, with the cosmopolitan nature of greater Miami and in particular with over half of the region's population born outside of the U.S. and also a significant number of its U.S. born population originating from somewhere else in the nation, there has not been a long-term social dynamic and connectivity in place to address climate change issues with the same importance afforded to hurricanes which are seen as more immediate concerns.

Many of the unique factors that result in greater Miami being one of the most vulnerable metro regions to climate change, hurricanes, and the amplified impacts via a combination of both, ironically also renders it one of the more challenging regions within which to develop climate change knowledge and warning systems for the general populace and the private and public sectors. The City of Miami and several other neighboring municipalities have developed general climate change adaptation and mitigation programs. However, economic and political realities have reduced the capabilities of many of these Cities to implement climate change programs and to enact adaptation-focused policy. With the Miami metro region's unique vulnerability to sea-level rises and hurricane impacts from climate change, enhancing knowledge and warning systems to address the phenomenon will continue to be difficult by even more necessary.

4.4.2.5 Urban Knowledge Systems

The private sector has been involved in developing urban knowledge systems to aggregate data for urban decision-makers, the public, and their own interests. Most of these applications are focused on the concept of "big data", or the analysis of very large volumes of data in relational databases and on parallel servers for trends and patterns. The scale of data available to analyze has grown exponentially in large part because of data now accessible through nontraditional new sources, such as telecommunications networks, wireless technology, and social media. In order to develop adaptation strategies that best account for vulnerability and resilience of urban populations, cities can take advantage of these data to find where climate change will most affect their communities and how they can most efficiently spend their resources. However, cities often do not have the resources to create knowledge systems on this scale, and so the private sector often has the opportunity to showcase its technology and draw municipal governments and the public to use their services (Hoornweg et al., 2007).

Cisco's project, Connected Urban Development, has a goal of reducing carbon emissions in cities by making them function more efficiently through improvements in information and communications technology (Villa and Mitchell, 2009). The project focuses on residential services, transportation, and real estate. This program started in three pilot cities: San Francisco, Amsterdam, and Seoul in 2006 and has since expanded to others cities. The CUD project is now run by The Climate Group, an NGO working with the private sector and cities on collaborative initiatives.

As an example of an individual city partnering closely with the private sector around a knowledge system, the city of Dubuque, Iowa is partnering with the IBM Smarter Cities project (IBM, 2009). The goal of the collaboration is to create a system to inform decision-makers about the efficiency of urban infrastructure (e.g., energy and water management, and transportation), and to give the public feedback on their own consumption of resources. This partnership is the beginning of an IBM initiative to develop sustainability models for smaller cities of under 200,000 people.

Currently urban knowledge and warning systems used by a particular city are not easily extendable to other cities. While regional and national level datasets and methodologies may be similar, local datasets and policies can differ dramatically, even between cities in the same state. Cities collect data in different ways for different purposes, and because of these differences, it can be difficult to compare cities in areas such as management, quality of life, sustainability, and adaptation. Cities, both nationally and globally, could benefit from quantitative comparisons to best decide what strategies to employ in the face of challenges, especially in the area of climate change adaptation. Having a common baseline across cities for recommendations on urban adaptation would be useful. There is currently no consensus on urban indicators or metrics to use that would allow a rigorous comparison across cities to develop recommendations, however there are a number of initiatives that are beginning to develop comparable urban indicators (Munda, 2006). One example of an urban comparison initiative is the Global City Indicator Facility (GCIF).

GCIF, based at the University of Toronto, was started by the World Bank (WB), in collaboration with UN Habitat, the Japanese Trust Fund, and the Canadian Government. GCIF organized a four-year consultative process with representatives from nine large cities: Toronto, Montreal, Vancouver, Sao Paulo, Bogota, Cali, Belo Horizonte, Porto Alegre, and King County, WA to identify common indicators that cities would be willing to collect and report on a regular basis (GCIF Report, 2011). These environmental and sustainability-related indicators are intended to be standardized, consistent, and comparable over time. The GCIF envisions this data system being used to help elected officials, city managers, and the public to monitor city performance, facilitate comparisons across cities, and provide enhanced government accountability (GCIF Report, 2011).

4.5 Economics and Finance

4.5.1 Economic Costs Associated with Impacts, Vulnerabilities and Adaptation

The literature on the economic dimensions of climate change impacts and adaptation is growing rapidly. While much of this work is either global or national in scope (e.g., Stern, 2007; Parry et al., 2009; Agrawala and Fankhouser, 2008), there has been a recent dramatic expansion of work on the economic consequences of climate change for cities and urbanized regions (c.f., Hunt and Watkiss, 2011; Hallegatte et al., 2011). Issues raised in this work include: the value of properties and infrastructure assets at risk from sea level rise and storm surge; the effect of extreme climate events such as hurricanes on wages and housing values; the factors that make cities more or less resilient to climatic shocks and stresses; and the types of costs that are associated with adaptation in cities (Leichenko and Thomas, 2011; Leichenko, 2011). This section explores these and other issues addressed in recent work on the economic dimensions of climate change impacts and adaptation in cities and urban areas.

4.5.1.1 Costs Associated with Climate Change for Businesses and Livelihoods

Studies of the economic impact of climate change emphasize documentation of the potential consequences of climate change, estimation of costs associated with these consequences, and identification of adaptation options and costs associated with those options (Leichenko and Thomas, 2011). While early studies typically examined the economic impacts of changes in mean temperature and precipitation under a range of climate change scenarios, attention in recent years has been directed toward the economic impacts of changes in climate extremes, such as droughts, heat waves, hurricanes and floods (IPCC 2011). Studies in this vein draw from a broader literature on the economic costs of natural disasters (c.f., Cavello and Noy, 2010; Greenberg et al., 2007), as well as from the literature on the economic impacts of climate change (c.f., Hallegatte et al., 2011; Tol, 2009; Agrawala and Fankhauser, 2008).

Among the studies of U.S. urban areas, attention is primarily directed to coastal areas and to the potential direct and indirect costs of hurricanes and other extreme coastal storms. Direct costs include those to public infrastructure (such as damage to roads, property, capital assets and inventories), as well damage to natural assets (such as beaches and freshwater marshes). Indirect costs may include those associated with business interruption (such as lost wages, lost revenue, loss of livelihoods), and reduction of ecosystem services (such as flood control).

A number of studies have evaluated the direct and indirect economic impacts of recent hurricanes for regions located in the U.S. Atlantic and Gulf Coast regions. These studies consider the impact of storms using economic indicators such as number of affected business establishments (Jarmin and Miranda, 2009), changes in taxable sales (Baade et al., 2007), production and employment (Hallegatte and Ghil, 2008), and housing prices and wages (Vigdor, 2008), and loss of natural assets (Costanza et al., 2008). For regions that have not been hit by a recent storm, analogs from past hurricane events allow researchers to consider the types of impacts that might be expected if a similar event were to occur in the present. For example, LeBlanc and Linkin (2010) assess the potential present day economic impacts on the New York metro area of storms similar to the 1938 hurricane, known locally as the "Long Island Express." The study estimates that insured property losses from such a storm would be as high as $110 billion (roughly triple the damage of Hurricane Katrina), and losses to the New York metro area economy as a result of secondary impacts due to business interruption would exceed $200 billion.

In addition to studies focused on specific storms or analog events, a number of studies draw from larger cross-sectional or panel data sets to quantify whether hurricane-related losses are changing over time and to assess how hurricanes affect local and regional economies over the short and long term. Pielke et al. (2008) examine normalized hurricane losses in the United States over the period from 1900 to 2005, and conclude that growing hurricane costs through 2005 are largely a function of increased wealth and coastal development rather than increased magnitude and frequency of hurricane events. Although climate change is expected to bring increases in intensity, duration, and frequency of these types of storm events, this work underscores the importance of urban development patterns and population growth in accounting for storm-related damages.

Beyond the direct and indirect costs associated with specific events, there is also concern with how damage will affect housing markets and urban economies more generally in both the short and long term. For example, new flooding patterns may alter the desirability of particular properties or neighborhoods. Murphy and Strobl (2011) explore these issues in a study of the impacts of hurricanes on housing prices in U.S. coastal counties in the North Atlantic Basin, a region that extends from coastal Maine to the Gulf Coast of Texas. Their results indicate that, over the period from 1988 to 2005, hurricane strikes were associated with higher prices for housing in the affected region for several years following the event, largely due to damage to the housing stock.

Among studies focused on the effects of hurricane damage on local employment, earnings, and income, findings typically show modest negative impacts in the short term (i.e., over one or two years), but little effect over the long term (i.e., over three or more years) (c.f., Cavallo and Noy, 2010 and Hallegate and Dumas, 2009). Belasen and Polachek (2008), for example, investigate the effects of hurricanes on earnings and employment in Florida counties, based on data from the 19 hurricanes that made landfall in Florida during the period from 1988 to 2005. Their findings suggest that hurricanes have a modest negative impact on employment in affected counties but a positive impact on earnings, and that both types of effects dissipate over time (Belasen and Polachek, 2008). By contrast, in an examination of the economic effects of hurricane strikes on local economic growth rates in the United States, as measured by changes in per capita income, Strobl (2011) finds significant negative impacts on net economic growth patterns, particularly at the county level, but little detectable effect at the national level. These findings of minimal aggregate effects of climate change, but significant local economic effects, suggest that additional work is needed to identify which urbanized areas are most vulnerable and to identify options for adaptation (Leichenko and Thomas, 2011).

4.5.2 Costs of Climate Change for Cities and Urban Economies

Risk-based studies focus on the quantification of assets at risk due to climate change. While many facets of climate change may post risks to cities, infrastructure, and population, the vast majority of studies emphasize the potential costs of damage from sea level rise and heightened storm surge (e.g., Titus et al., 2009; Paterson et al., 2010). Although there is some overlap between risk-based studies and economic impact studies discussed above, risk studies concentrate largely on assets at risk to *future* scenarios of climate change while impact studies examine effects of *past* events. While the terminology of "vulnerability" is sometimes used in risk studies, emphasis is placed on, for example, physical exposure to sea level rise, identification of property, assets, population and infrastructure at risk to damage or destruction, and assessment of adaptation options and costs (Leichenko and Thomas, 2011).

As mentioned above, one focus within the risk based literature is assessment of urban populations and economic value at risk to future sea level rise (e.g. Hanson et al., 2011; Weiss et al., 2011; McGranahan et al., 2007). These studies rely on projections of growth of population, economic assets and infrastructure in coastal regions and calculate risk based on anticipated sea level rise and density of development. A recent study by Hanson et al. (2011), for example, ranks port cities worldwide based on population and assets exposed to sea level rise (see Table 4.2). Other studies also provide rankings of cities and regions and find that while sea level rise leads to increased exposure, the increase in density of population and assets in coastal areas is also a major contributor to future risk (Nicholls et al., 2008; McGranahan et al., 2007). City specific studies use this same methodology of quantifying exposed population and assets to provide an assessment of future economic risk to sea level rise (Hallegate et al., 2011, Genovese et al., 2011).

Table 4.2: Top 20 cities ranked based on assets expected to be exposed to coastal flooding in the 2070s (including both climate change and socioeconomic change) and showing present-day exposure. Source: Hanson et al. 2011.

Rank	Country	City/Urban Agglomeration	Exposed Assets current ($Billions)	Exposed Assets-future ($Billions)
1	USA	Miami	416.29	3513.04
2	China	Guangzhou	84.17	3357.72
3	USA	New York-Newark	320.20	2,147.35
4	India	Kolkata (Calcutta)	31.99	1,961.44
5	China	Shanghai	72.86	1,771.17
6	India	Mumbai	46.20	1,598.05
7	China	Tianjin	29.62	1,231.48
8	Japan	Tokyo	174.29	1,207.07
9	China	Hong Kong	35.94	1,163.89
10	Thailand	Bangkok	38.72	1,117.54
11	China	Ningbo	9.26	1,073.93
12	USA	New Orleans	233.69	1,013.45
13	Japan	Osaka-Kobe	215.62	968.96
14	Netherlands	Amsterdam	128.33	843.70
15	Netherlands	Rotterdam	114.89	825.68
16	Vietnam	Ho Chi Minh City	26.86	652.82
17	Japan	Nagoya	109.22	623.42
18	China	Qingdao	2.72	601.59
19	USA	Virginia Beach	84.64	581.69
20	Egypt	Alexandria	28.46	563.28

While the majority of these studies explore economic exposure to future sea level rise without considering protection measures, many develop the argument that adaptation is imperative to abate extensive economic losses (Leichenko and Thomas, 2011). For example, in a case study of Metro Boston by Kirshen et al. (2008), they estimate total costs of sea level rise to be the sum of damage to infrastructure and the price of implementing adaptation measures for a variety of scenarios. In this study, the cost of adaptation measures includes construction of seawalls, flood proofing of infrastructure, and prohibition of development in flood-prone areas. They demonstrate that a combination of adaptation measures results in significantly lower total costs than taking no adaptation action (Kirshen et al., 2008). Neumann et al. (2010a; 2010b) adopt a similar approach, developing a model to estimate the total costs of property value losses as the result of climate change in coastal areas, assuming that a range of different adaptation actions will be taken. These adaptations, each of which has different costs, include 1) protection via construction of hard structures such as flood walls and soft responses such as beach nourishment; 2) accommodation via elevation of buildings and land-use changes; or 3) planned retreat from a coastal area via development restrictions and abandonment of existing structures.

4.5.2.1 Costs Associated with Making Cities Resilient

To some extent, economic costs associated with climate change depend not only on the degree of exposure to climate change that cities will experience, but also on each city's response to the multitude of climate and other stresses and pressures they will face. This "response", or ability to maintain socioeconomic structures and systems under climate change stresses, referred to here as resilience, is gaining increasing prominence within the literature on cities and climate change. Terms used within this work, such as "climate resilient," "climate-proofing," and the "resilient city," emphasize the idea that cities, urban systems, and urban constituencies need to be able to withstand or quickly return to normal function from climate-related shocks and stresses (Leichenko, 2011). Thus, enhancement of resilience is widely cited as a key goal for both adaptation and mitigation efforts in cities and urban regions (Crichton, 2007; Muller, 2007; Sánchez-Rodríguez, 2009). Many of the costs associated with adaptation to climate change entail measures that are intended to enhance the resilience of cities.

Because climate change-related shocks typically occur in combination with other environmental, economic, and political stresses (Wilbanks and Kates, 2010; Leichenko and O'Brien, 2008; Maru, 2010; Ernstson, 2010; Pike et al., 2010), promotion of urban resilience to climate change requires that cities become resilient to a wider range of overlapping and interacting shocks and stresses (Leichenko, 2011).

Studies that are specifically concerned with economic resilience of cities to climate change explore topics such as the ability of infrastructure systems, urban firms and industries, and urban communities to quickly and effectively recover from extreme climate events and other types of hazards. Some examples of recent work in this area include studies that explore ways to quantify economic resilience to hazards (Rose, 2007), evaluate resilience of infrastructure systems and urban built environments (McDaniels et al., 2008), and, investigate how cities recover following disaster events, with particular emphasis on community resilience in New Orleans following Hurricane Katrina (Campanella, 2006; Colten et al., 2008; Pais and Elliot, 2008). Other hazard resilience studies develop models of community resilience based on a wide range of quantitative indicators (Cutter et al., 2008) or measure variations in resilience of towns within specific regions based on characteristics of households (Zhou et al., 2010). Recent studies also identify mechanisms and strategies to increase hazard resilience of poor urban communities in developing world cities (Chatterjee, 2010; Satterthwaite et al., 2007).

Paralleling the growing interest in economic measurements of resilience (Rose, 2007) is an emerging body of literature on the resilience of urban economies. This literature, which rooted in urban planning and economic geography, applies ideas and terminology from ecological resilience theory such as complexity, diversity, and self-organizing systems, to study the evolution of urban and regional economic and industrial systems (e.g., Martin and Sunley, 2007;

Pendall et al., 2010; Pike et al., 2010). These studies, which explicitly recognize that climate change is one of many types of shocks and stresses that urban and regional economies face (Pike et al., 2010) are particularly concerned with factors that explain why resilience is uneven across places and locations (Pike et al., 2010), and examine linkages between resilience and long-term growth and/or decline of cities and regions (Simmie and Martin, 2010).

One important, yet relatively little studied issue, concerns how cities can pay for resilience efforts, and who may benefit or lose out from efforts to promote resilience. The ability to pay for efforts to promote resilience of, for example, urban infrastructure, varies widely across cities, as does implementation capacity. Ayers (2009) draws attention to the need for international sources of funds to build and promote resilience in low and middle income countries. As discussed later in this section, sources of outside funding are also likely to be needed for adaptation in smaller or less affluence U.S. cities. Yet institutional and governance literatures, as discussed in an earlier section, recommend caution about putting programs into place from top down, without buy in and cooperation from affected communities, firms and industries (O'Brien et al., 2009). There is also a need to put mechanisms in place to ensure that external financial incentives that are intended to promote resilience do not inadvertently undermine self-sufficiency of local communities.

Further attention needs to be devoted to the distributional consequences of actions intended to promote urban resilience, including identification of which social groups, industries, and urban neighborhoods will benefit from or bear the cost of resilience efforts (Leichenko, 2011). Some recent studies identify situations where promotion of resilience for some locations may come at the expense of others (Pike et al., 2010), or enhancement of resilience at one scale, such as the level of the community may reduce resilience at another scale, such as the household or individual (Sapountzaki, 2007). Other studies raise questions about the relationship between resilience and poverty and recommend more attention to inequalities that may arise with application of resilience approaches (Boyd et al., 2008; O'Brien et al., 2009). Additional work is needed in order to identify ways that efforts to promote urban resilience to climate change can take into account the unintended consequences of these actions, both across space and at different analytical scales, in order to ensure that these efforts do not reinforce existing inequalities or create new ones (Leichenko, 2011).

4.5.3 Economic Opportunities for Cities, Businesses, and Livelihoods

Much has been made of the economic opportunities that arise from efforts to address climate change. Many studies emphasize potential economic gains associated with efforts to mitigate greenhouse gas emissions, arguing that transition to clean or renewable energy sources and efforts to promote energy conservation and efficiency can result in significant new forms of economic activity (c.f. UNEP, 2008; Wei et al., 2010; Sastresa et al., 2010; Carley et al., 2011). Increasingly, however, studies have also noted the potential opportunities made available from efforts to adapt to climate change (Alliance for Water Efficiency, 2008). Because climate change impacts will manifest themselves in different ways depending on the locale, these gains may take several forms, such as job creation related to the deployment of green infrastructure strategies that moderate temperature increases or address potential flooding from extreme weather events.

Other economic opportunities may arise from strategies that increase the resiliency of key infrastructure, such as highways and public transit systems, energy infrastructure, water supply or treatment facilities, and buildings in flood-prone areas (c.f. Rosenzweig et al., 2011a; Rosenzweig et al., 2011b)

Quantifying the benefits of climate adaptation policies or investments can be challenging. Economic growth is traditionally measured in terms of changes in gross domestic product (GDP) or other metrics that compare changes in the total level of economic activity in a region over specific time scales (Hammer et al., 2011). Whether climate change adaptation investments will rise to a level that they are noticeable in GDP reports is unclear, as they may be masked by other significant macroeconomic trends. The use of GDP as a key metric may also be problematic given that city GDP data are not readily available for all cities (PwC, 2009). Moreover, although there may be a short term economic bump related to some type of adaptation-related investment or policy change, the true benefit – calculated in terms of avoided losses – may not be observable until the climate-related hazard finally manifests itself. Estimating the value of loss avoidance may be very difficult because such calculations presume to quantify what losses would amount to had these investments or policies not been pursued.

Other studies quantify economic impacts by projecting changes in employment levels using computable general equilibrium models that forecast the impacts of policy or program changes (Pollin et al., 2009, Schrock and Sundquist, 2009). A key challenge in estimating employment level changes related to climate change is the limited availability of baseline employment level data in many key job categories that can be used to populate these models. Most sectoral employment studies rely on data from firms that have self-reported their NAICS (North American Industry Classification System) job category, but such notations may not fully reflect current business activities. These tracking systems are also limited by the job or business sector categories employed in their model. For example, the US Department of Commerce (2010) designated 87 green products and 647 green services in a recent report on the green economy. Despite this breadth, however, it is still difficult to differentiate engineering or landscape design firms specializing in large-scale green infrastructure projects from companies with no particular expertise in that area; whether one qualifies may simply be a matter of personal opinion. As a result, using this categorization system, it would be difficult to assess whether local plans promoting green infrastructure (c.f. Chicago Wilderness, 2004) have successfully expanded job levels in a specialty sector closely linked to climate change adaptation work.

The US Bureau of Labor Statistics is in the process of developing a new job categorization system designed to more accurately gauge green job levels around the US; data collection using this new system is expected to begin in 2011 with the first data published in 2012 (Bureau of Labor Statistics, 2010). It is still unclear, however, how granular the coding system will be and whether it will allow researchers and policymakers to fully discern changes in jobs associated with climate change adaptation. Until that system is in place, some studies have sought to gauge changes in green job levels. For example, the Bureau of Labor Statistics (2010) concluded that depending on the definition used, green products and services comprised 1 percent -2 percent of the total private business economy in 2007; in job terms, this amounts to between 1.5-2.0 percent of private sector employment. Another study estimated that roughly 2 percent of all jobs in the US were part of the clean economy (Muro et al., 2011).

The latter study breaks the clean economy into five broad categories and 39 specific employment segments. Data are presented on a state-by-state basis, and by metropolitan (MSA) and Micropolitan (μSA) statistical area. Overall, Muro et al. found that the green economy increased by 37 percent between 2003-2010, with wide variation by employment segment and geographic region. For example, as seen Figure 4.2, the metropolitan regions with the highest employment levels in several market segments closely related to climate change mitigation and adaptation experienced dramatic shifts in these job levels during this time period. Most market segments experienced increases, although some regions did lose jobs in selected clean economy categories.

Clean economy category and # of jobs in US (2010)	Relationship to climate change mitigation (m) or adaptation (a)	Top 3 metro regions in category		
		MSA	*# of jobs in 2010*	*% change from 2003-2010*
Conservation (314,983 jobs)	Jobs related to development or maintenance of natural areas for use as floodplains (a) or that help ameliorate rising temperature levels associated with climate change (m + a)	Washington-Arlington-Alexandria, DC-VA-MD-WV	18194	104%
		Sacramento-Arden-Arcade-Roseville, CA	15914	75%
		Tallahassee, FL	12671	305%
Public mass transit (350,547 jobs)	Jobs linked to system providing GHG emission reduction benefits (m)	New York-Northern New Jersey-Long Island, NY-NJ-PA	57487	53%
		Chicago-Joliet-Naperville, IL-IN-WI	20664	58%
		Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	14556	13%
HVAC and building control systems (73,600 jobs)	Increases control of energy-using equipment and systems in buildings, allowing efficiency improvements (m) and ability to participate in demand response programs during extreme heat events (a)	Memphis, TN-MS-AR	3909	91%
		San Francisco-Oakland-Fremont, CA	3459	477%
		New York-Northern New Jersey-Long Island, NY-NJ-PA	3217	52%
Smart Grid (15,987 jobs)	Allows increased use of distributed energy technology, reducing GHG emissions (m) and allowing greater control of energy-using equipment in buildings during extreme heat heat events (a)	San Francisco-Oakland-Fremont, CA	2861	5622%
		Kansas City, MO-KS	2552	13%
		Atlanta-Sandy Springs-Marietta, GA	2511	10%
Water efficient products (13,066 jobs)	Promotes water conservation, supporting efforts to address climate change-related drought conditions (a). Also reduces energy demand associated with water extraction, distribution, and wastewater treatment (m).	Los Angeles-Long Beach-Santa Ana, CA	1753	4%
		Milwaukee-Waukesha-West Allis, WI	1167	9%
		Atlanta-Sandy Springs-Marietta, GA	925	53%
Solar photovoltaics (24,152 jobs)	Solar power displaces fossil fuel use, reducing GHG emissions (m). Can also reduce peak load levels during extreme heat events, reducing the risk electric grid system breakdown (a).	San Jose-Sunnyvale-Santa Clara, CA	1988	102%
		St. Louis, MO-IL	1800	-21%
		Los Angeles-Long Beach-Santa Ana, CA	1585	71%

Figure 4.2: Size of the Clean Economy in Job Sectors Closely Related to Mitigation and Adaptation. Source: extrapolated from data provided by Muro et al 2011.

Assessing the root cause of any changes in employment levels in different clean economic sectors can be challenging because of the difficulty of disaggregating the impacts of a specific policy change or investment from larger macro-economic changes occurring in a city, region, or country. Many studies examining the employment changes of different environmental or climate policies are structured as ex-post analyses; it is rare to find ex-ante studies that can clearly correlate job level growth or decline to specific policy changes.

Another key consideration is the geographic scale at which we seek to discern impacts. Given that climate change vulnerabilities are very localized in nature, certain impacts may accrue only to specific physical assets, neighborhoods, or regions. As noted above, policy actions–or the failure to take action–can thus result in measurable financial gains or losses. The use of green infrastructure strategies (i.e., the use of parks or other natural areas as flood plains or the creation of swales or earthen berms to direct rain or flood waters away from developed areas) may actually increase property or asset values, as these natural areas can also serve as a community amenity. In some cases, green infrastructure of this type can have a citywide impact, increasing the 'livability' of a city, which in turn makes it more attractive from a business development or retention perspective (Hammer et al., 2011).

4.5.4 Financing Adaptation

4.5.4.1 Challenges for Urban Climate Adaptation Finance

As mentioned in the previous sections, while there is an increasingly rich literature on climate impacts and potential adaptation strategies, comparatively little analysis has been done on the costs associated with adaptation, particularly where it concerns urban areas, let alone those in the developed world. Yet, it is those cost estimates that guide adaptation finance flows.

Recent analyses by the World Bank (2010) suggest that for a limited set of sectors in developing countries costs of adapting to an approximately 2 degree warmer world by 2050 would range from $70 billi*on to $100 billion per year between 2010 and 2050.* Others found that "removing the housing and infrastructure deficit in low- and middle-income countries will cost around $315 billion per year (in today's figures) over 20 years; while adapting this upgraded infrastructure specifically to meet the challenge of climate change will cost an additional $16–63 billion per year" (Parry et al., 2009, p. 12). While these numbers are by no means representative of the adaptation costs that urban areas in the US may face, the cost estimates do highlight the magnitude of capital required even in places where standards of living, urbanization rates and the total value of assets at risk are comparatively low. For example, agencies in England and Wales responsible for flood management have estimated a need to spend (due to climate change) an additional $30 million in 2011 to address flooding due to climate change growing to $720 million annually by 2035 (Environment Agency, 2009).

Many challenges plague efforts to estimate adaptation cost, and as a consequence affect the development of institutions and instruments that can help finance the costs. The discussion that follows summarizes some of those challenges.

- First, given that the current state of infrastructures and institutions may not be optimal with respect to their abilities to provide services – even without climate change – it may not be appropriate to classify all costs of improvements, when done with the goal of reducing climate vulnerability, as climate adaptation costs.

- Second, and closely related, maintenance and upgrades of infrastructures, as well as investments in institutions, are ongoing. How much actual adaptation costs are incurred above these baseline expenditures can rarely be separated out after the fact (Brown et al., 2010).

- Third, many of the costs incurred when adaptation takes place cannot be readily monetized. This is particularly apparent in the case of adaptation actions by individuals changing their behaviors. Where costs of behavioral changes can, in principle, be imputed – such as when commuters take circuitous routes to avoid risks of flooded roads – considerable biases may creep into the analysis. Biases occur when, for example, the burden of longer commuting falls predominantly on the poor, while others may be able to work from home or otherwise cope with climate impacts and risks.

- Fourth, projections of future adaptation costs will hinge on the choice of climate scenarios and their underlying uncertainties, as well as on baseline assumptions about demographics, changes in economic activity, and land use decisions that place assets at risk.

- Fifth, since it is not likely that any assessment of adaptation costs will capture all possible adaptation actions and the substitutabilities and complementarities among them, cost estimates will inevitably be biased by the selection of adaptation measures. For example, since both the development of hard protective structures and coastal wetlands may provide flood control, the choice of approaches – and their combination – will considerably affect the ultimate cost estimate. Also, because it is easier to cost hard structures than ecosystem protection, those estimates may be biased (c.f. Berry, 2007).

- Sixth, the technologies used to adapt to climate change, such as early warning systems for extreme events or changes in building shells that alter urban heat islands, change rapidly. Estimates of future adaptation costs will hinge on assumptions about technological progress and adoption.

- Seventh, subsequent impacts of climate change may have disproportionate effects on the reliability of infrastructures and thus the costs of adaptation. For example, a second and third flooding event could lead to progressively larger bridge scours or shoreline erosion than the first one, even though the later events are of smaller magnitude. Whether and how effects of such "one-two-punches" on infrastructure are accounted for will influence both the size of the cost estimate and its attribution to individual events.

- Eighth, sophisticated sector-specific economic models of adaptation costs rarely are used for inter-temporal optimization. As a result, the cost estimates are likely to be inefficient (World Bank 2010). And inter-temporal aggregation of the costs and benefits of adaptation hinges on the choice of discount rate – a perpetual nuisance in policy-oriented economic analysis.

- Ninth, proper use of costs in guiding adaptation actions requires these costs to be compared not to a no-cost environment but instead to the cost of inaction. Calculating the latter encounters many of the same challenges as discussed here for the cost of adaptation (EEA, 2007).

- Finally, since urban and non-urban areas are typically closely tied to each other, e.g. through complex value chains, movement of people and flows of capital, estimates of urban (or non-urban) adaptation costs fundamentally hinge on the geographic boundaries that are employed.

4.5.4.2 International Finance Instruments for Climate Adaptation

The challenges of estimating climate adaptation costs notwithstanding, international institutions have for over a decade now recognized the need to support adaptation actions. As with the literature on cost estimates, documentation of practices of funding adaptation has largely concentrated on international finance and rarely concentrated on urban areas. There is also a high level of fragmentation among finance programs by international finance institutions that adds to the complexity of any analysis of funding flows and the role of financial instruments in support of these flows. For example, the United Nations Framework Convention on Climate Change, with its Conference of Parties (COP7) in 2001 requested that the Global Environment Facility (GEF) fund "…pilot or demonstration projects to show how adaptation planning and assessment can be practically translated into projects that will provide real benefits" (UNFCCC, 2001). At the COP13 meetings in Bali in 2007, an Adaptation Fund (AF) was established to support adaptation funding (Müller, 2008).

Alongside these efforts, the World Bank Climate Investment Funds (CIFs) provides concessional loans for policy reforms and investments that achieve development goals through a transition to a low carbon development path and a climate-resilient economy (World Bank, 2008b; Ayres, 2009). Others active in climate financing, such as the European Investment Bank (EIB), issue bonds in the capital markets as a supplement to their public funds to generate new finance for climate-related lending activities. To the extent that private investors invest in generic bonds used for such activities, private investors are already an important source of climate finance (Persson, 2009). Where private investment takes place in direct support of climate adaptation, it tends to be heavily concentrated on the performances of specific sectors in the economy. Public finance therefore has a crucial role to play in ensuring adequate finance is available to those sectors not benefiting from private flows, and in creating conditions that leverage more private capital.

4.5.4.3 Country and Region-level Finance for Urban Climate Adaptation

Collectively, public and private, national and local funding must be leveraged to meet the nation's urban adaptation finance challenges. Since part of adaptation funding would help secure returns on investments that have already been made, or help ensure returns on investments to be made, adaptation finance is, in this sense, a complement to any other financial investment decision. For that matter, it is complementary to other decisions that promote the reliability of service provision from investment projects – such as establishment and enforcement of design criteria and engineering standards. As a consequence, the success of implementing and capitalizing on the introduction of adaptation finance instruments requires a balance of public and private interests that is commensurate with the types and distribution of benefits derived from the investment.

A variety of mechanisms can be used to bring about that balance. For example, value capture mechanisms, such as district improvement fees or taxes could be employed to re-distribute some of the value accrued to private developers and owners as a result of local government investment in adaptation (e.g., shoreline protection, flood control systems, decentralization and diversification of power supply). The resultant proceeds to local authorities, in turn, could be allocated to climate-proof private investments.

Climate impact bonds could be issued to generate revenues in support of reducing costs associated with climate change impacts. In such a scheme, the cost savings from adaptation are predicted and the bond issuer, the investor, and, potentially, third parties that undertake the adaptation action, negotiate the sharing of savings that come from implementation of adaptation measures. Climate impact bonds can incentivize adaptation investments by providing a mechanism to share benefits from adaptation if those benefits can be clearly identified, quantified and traced to the implementation of specific adaptation measures. However, given the discussion of challenges surrounding a quantification of costs and benefits from adaptation, climate impact bonds may have only very limited application.

Catastrophe bonds can be used to pass extreme risks on to private investors who are willing to assume the risk of losing their entire investment principal, should a particular catastrophic event occur. In return, they are given the opportunity to earn substantial interest on their investment.

Of course, the most widely used finance mechanisms to reduce the extent of possible losses from climate impacts are insurance and re-insurance instruments discussed above. These play a particular role in addressing residual risks not covered, for example, through "mainstreaming" climate risk reduction strategies into conventional project or coverage through catastrophe bonds. The availability of insurance can lower the hurdle for investors to allocate funds by enabling them to manage the residual risk. Re-insurance further allows insurers to fine-tune the risks they manage across a portfolio of policies while passing on the remainder to re-insurers for a contracted premium.

Figure 4.3 highlights key areas for finance innovation along a spectrum from low to high levels of uncertainty about returns on investments and relative to the complexity of adaptation measures that may be deployed (ICLEI 2011). Considerable room exists to devise new instruments to meet the particular needs associated with a range of actions that address situations at higher levels of risk and uncertainty.

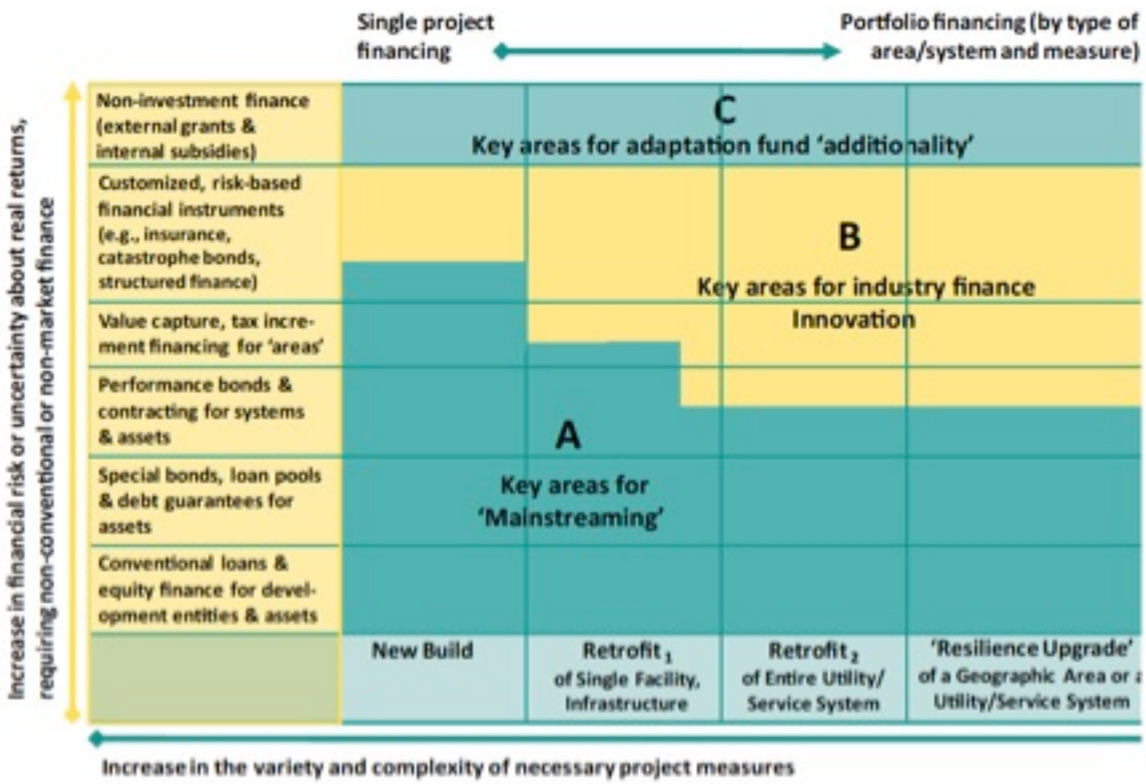

Figure 4.3: Key Areas for Finance Innovation. Source: ICLEI, 2011.

A key challenge in tailoring finance mechanisms to individual urban adaptation projects and strategies comes from the potential for co-benefits and co-costs to be generated by adaptation. Examples of co-benefits include improvements in public health that may result from better air quality when power generation is decentralized and renewable fuels are used in order to reduce susceptibility to disruptions in supply during adverse weather events. Co-costs may result when decentralized power supply requires fossil-fuel based generators to bridge intermittent supply from wind and solar power, for example, thus lowering ambient air quality and affecting public health. Dealing with such co-benefits and co-costs requires an ability to identify the affected parties and quantify their share in the total costs and benefits.

4.5.4.4 New Instruments and Interventions to Stimulate Urban Climate Adaptation

Some of the non-investment finance instruments in Figure 4.3 above, such as grants and subsidies, require revenue generation for their support. Several sources may be tapped for such revenue, beyond the traditional taxes already at play at regional and national levels. For example, revenues from public carbon markets, where emissions allowances are auctioned and traded, such as in the Regional Greenhouse Gas Initiative (RGGI), can be used to provide funds for efficiency improvements and related measures that reduce climate vulnerability. Energy Service Contracts (ESCOs), which provide capital for energy efficiency improvements that get paid back through energy savings, help building owners and cities reduce not just their carbon footprints but also their dependence on energy. Similarly, San Francisco's GreenFinanceSF program uses public-sector funding from the Property Assessed Clean Energy (or PACE) program to cover up to 100 percent of the cost of building performance upgrades. Such approaches to adaptation financing combine incentives for mitigation efforts with adaptation, thus leveraging synergies that may exist between the two. Similarly, taxation of international air travel, shipping, trucking or international financial transactions could be used to raise considerable revenue (see, e.g., Müller 2006). Recognizing that regional carbon footprints are a function, in part, of emissions that occur elsewhere, border adjustments may be used to correct for carbon leakage while providing resources locally to carry out adaptation projects. At the urban and regional level, congestion charges and other fees targeted toward environmental improvements may provide proceeds to climate proof infrastructures, protect or restore wetlands and otherwise increase climate resilience.

Beyond such revenue raising mechanisms, development of a concept of odious debt may further provide incentives – financial and otherwise – for proper investments in climate-resilient infrastructures by making lenders just as responsible as borrowers if the debt is wrong. For example, if an infrastructure investment turns out to be misguided given the impacts of climate change on the region, reliability for the debt incurred in making the investment would explicitly lie with both the entity making the capital available and those borrowing it.

While there are a number of instruments and sizeable funds available for international adaptation finance, estimates on adaptation costs at the urban scale – whether globally or in the US – are scant. The lack of detailed knowledge of adaptation costs and benefits is accompanied by a dearth of mechanisms to finance adaptation actions. Considerable room for innovation exists to create the institutions and instruments that provide incentives for and support of adaptation investment.

[iii] http://www.mrgo.gov/ProductList.aspx?ProdType=study&folder=1320
[iv] http://www.nps.gov/climatechange/
[v] http://www.blm.gov/wo/st/en/prog/more/climatechange.html
[vi] http://coastalmanagement.noaa.gov/issues/ climate_activities.html
[vii] http://www.georgetownclimate.org/adaptation /state-and-local-plans
[viii] http://www.opr.ca.gov/s_ceqaandclimatechange.php
[ix] http://www.deq.state.va.us/coastal/ climatechange.htm
[x] http://www.mass.gov/czm/stormsmart/
[xi] http://www.bsc.ca.gov/codes/localfilings.aspx
[xii] http://www.usgbc.org/DisplayPage.aspx?CMSPageID=2078
[xiii] http://www.bostonredevelopmentauthoritynews.org/2011/09/15/e-design-winners-announced/
[xiv] http://www.ccdc.com/media-and-publications/news/644-ccdc-news-mayor-sanders-unveils-green-building-program-for-downtown-san-diego.htm
[xv]http://www.cityofchicago.org/city/en/depts/cdot/provdrs/conservation_outreachgreenprograms/svcs/chicago_sustainablebackyardprogram.htm
[xvi] http://www.spur.org/publications/library/report/ climate-change-hits-home
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[xxiii] http://www.ccrif.org/content/about-us
[xxiv] http://www.lloyds.com/usnatcatreport
[xxv] http://www.sustainabilityconsortium.org/

5 Sustained Urban Climate Assessment

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"*I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.*" Physicist, Lord Kelvin (1824-1907)

The reliable and continuous monitoring of a set of key climate change indicators is essential for the development and the assessment of flexible climate change adaptation pathways. The goal of this chapter is, therefore, two-fold: firstly, to set forth a vision for nested, multi-level indicators and monitoring framework that underpins and supports adaptation pathway assessment and adjustment. Secondly, the goal is to highlight examples of extant networks and organizations that conduct urban climate assessments for adaptation purposes.

5.1 Indicators and Monitoring

Although qualitative assessments provide vital information to climate change studies, when the matter he mentions has to do with urban climate change adaptation and mitigation strategies, Kelvin's purely quantitative statement is that much more resonant, for, indeed, we cannot manage or adequately prepare for what we cannot measure or project. One of the primary objectives of this National Climate Assessment Technical Report study is to assess current and emerging key of impacts and vulnerabilities to climate change in U.S. cities and to document adaptation strategies and pathways which urban decision-makers and stakeholders are developing and implementing in response to changing climate risk.

This critical objective requires ongoing, consistent, reliable, high-resolution spatial and temporal monitoring of key, regional climate indicators. The proper monitoring and analyses of these relevant indicators can then assist in augmenting or correcting adaptation policies and/or shifting the timing of their implementation. Of necessity, these indicators must be linked to changes in climate, climate science, climate impacts, and adaptation activities. They, therefore, need to be devised and monitored longitudinally if they are to provide useful guidance to decision makers who must make informed judgments and choices about the timing and the extent of their adaptation actions.

During the last few decades, various methodologies for designing appropriate indicators have been developed (see e.g., Huntington et al., 2004; Hodgkins et al., 2003, Insaf 2012), often in the context of environmental sustainability or for directly tracking climate change and its impacts. One key example is the work on indicators and monitoring done by the New York City Panel on Climate Change (NPCC) (Box 5.1) (Jacob et al., 2010). In the future, similar studies are expected to also incorporate not only impact assessment, but also incorporate the evaluation of the adaptation efforts and pathways themselves.

Box 5.1. Climate Indicators for New York City

The New York City Panel on Climate Change developed and implemented a set of criteria for selecting climate change indicators to address the needs of infrastructure managers in the New York City region, on the Pressure/State/Response (PSR) method (Jacob et al., 2010; OECD, 2004). In the context of climate change, pressure can be taken to mean the various types and levels of hazards associated with climate change (such as heat waves, extreme precipitation events, sea level rise, and coastal flooding). State relates to the impacts of the hazards, and response to the adaptation measures.

The goals of the NPCC indicator and monitoring system are to:

- Create a mechanism for alerting stakeholders to emerging climate change data and related risk information;
- Warn of certain thresholds, some of which may lead to “tipping points” that may alter elements in a risk assessment process;
- Provide decision triggers for altering a certain adaptation path; and
- Initiate course corrections in adaptation policies and/or changes in timing of their implementation if and when necessary.

The NPCC indicators are divided into three categories.

- Physical climate change variables;
- Risks, exposure, vulnerability, sensitivity and observed impacts; and
- Adaptation measures.

Included in each of the categories is the explicit tracking of new research as it is published so that New York City decision-makers can avail themselves of the latest knowledge as it emerges.

There is a wide range of stakeholders, including the managers of critical infrastructure, who need readily available and accessible climate risk information at both citywide and neighborhood scales. Furthermore, climate change information needs to be easily understood by the public in order to contribute to effective urban decision making. Some indicators may be considered as tools for management, often applying to highly aggregated units (e.g., for an entire city), while others incorporate community-based engagement and stakeholder involvement. The latter may be tailored to the needs and objectives of individual neighborhoods and community groups.

A broad set of indicators is likely to be useful since climate change is only one possible motivation for a course correction in adaptation pathways. Shifts in projected impacts due to population growth rates and socio-economic changes (e.g., income, energy use, land use/urbanization, demographic changes) and shifts in the perceived relative merit of different adaptation strategies (e.g., due to technological innovations or emerging evidence of strategy co-benefits unrelated to climate change or risk tolerance) might also lead to effective policy generation. Therefore, indicators of these factors are needed as well.

5.1.1 Selecting and Developing Key Indicators

Huntington et al. (2004), Hodgkins et al. (2003), Whitford et al (2001), and Insaf et. al. (2012), have provided guidance and methodologies for the selection and development of appropriate indicators for environmental sustainability and for directly tracking climate change and its impacts. To be useful and practical, indicators and indicator categories should be:

- Regional and derived from easily accessible and verifiable data;
- Dynamic: That is, not only do they need to encompass physical climate data collection, but they must also be robust enough include state-of-the-art climate change research findings and projections;
- Long-term: Long-term, quality-controlled data are critical to the understanding of environmental challenges (NOAA, 2009a, 2009b);
- Developed in cross-disciplinary partnerships: climate scientists and agency experts need to work collaboratively on a host of urban impact indicators so that effective monitoring is conducted to inform future decision making;
- Policy relevant, analytically sound, and measurable (Jacob et al., 2010);
- Identified for physical climate change variables (ex. temperature, precipitation, and sea level rise), risk exposure vulnerability and impacts.

5.1.1.1 Climate Indicators

Moreover, physical climate change trends need to be monitored relative to forecast values, for example, those used by the National Climate Assessment and the IPCC Fifth Assessment Report (AR5) (http://www.ipcc.ch/activities/activities.shtml). For many decades, climate has been monitored and archived by federal and regional institutions, such as NOAA and the regional climate centers. Examples of this effort are depicted in (Figure 5.1). Besides mean temperature and precipitation indicators, extreme events such as heat stress, dangerous winds, droughts and floods are other climate indicators that ought to be monitored. Sea level rise and coastal storms need to be tracked as well for urban areas that are close to coasts. Additionally, long-term data from a range of disciplines are needed to detect the presence of significant trends. This is a challenging task, and interpretation depends on how trends affect associated risks and vulnerabilities. Criteria are especially needed to flag ‘thresholds’ and ‘trigger points.’

5.1.1.2 Adaptation Indicators

Key indicators for adaptation will also need to be monitored. Examples of current climate change adaptation indicators include the percentage of building permits issued in any given year in current FEMA coastal flood zones, and in projected 2080 coastal flood zones; building permits that have measures to reduce precipitation runoff; insurance data on perceived risk and adaptive capacity in urban areas; bond ratings issued by cities or infrastructure operators for capital projects with climate change risk exposure; trends of weather-related emergency/disaster losses

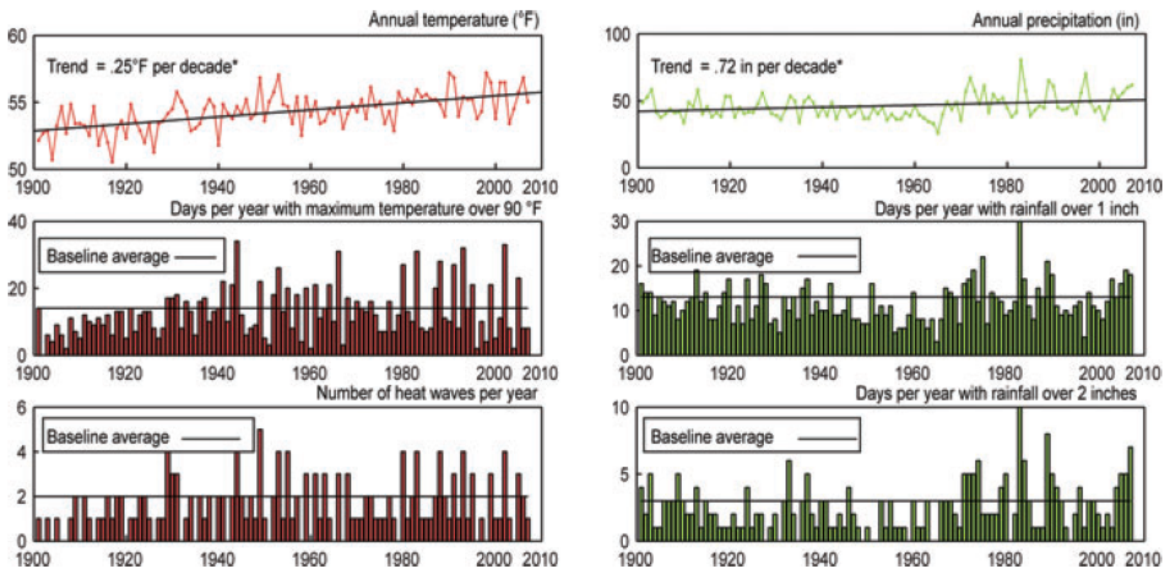

Figure 5.1. Historic tracking of temperature and precipitation climate change indicators. Source, Jacobs et al 2010.

(both insured or uninsured), relative to the total asset volume; and the number of days with major telecommunication outages (wireless versus wired), correlated with weather-related power outages (Jacob et al., 2010).

5.1.2 Criteria for Indicator Selection

To be useful and practical, indicators must be based on easily accessible and verifiable data and be tailored to the circumstances of individual cities, while simultaneously establishing comparability across and within cities. To the extent possible, a given climate indicator should fulfill the multiple criteria of being policy relevant, analytical sound, and measurable (Table 5.1) (Jacob et al., 2010). A *sine qua non* is that the data required to create the indicator should be both available and measurable. Not all of these criteria can be met for each indicator, and new indicators will need to be developed for some categories. A consensus for what are appropriate, suitable, and effective indicators will emerge over time, on the basis of gradually gained learning and experience.

Table 5.1. Criteria for Urban Climate Indicators. Source: Jacob et al., 2010.

Policy Relevance
• Provide a representative picture of climate conditions; • Measure stakeholder-relevant climate change hazards and society's responses; • Be simple, easy to interpret, and able to show trends over time; • Be responsive to changes in climate and related human activities; • Provide a basis for intra-and intercity comparisons; • Have a scope applicable to critical regional climate change issues; and • Have a baseline, threshold, or reference value or range of values against which to compare, so that users can assess the significance of the values associated with it through time.
Analytical Soundness
• Be theoretically well founded in technical and scientific terms; • Based on local, national, or international standards with consensus about its validity; and • Readily linked to economic models, scenario projections, and information systems.
Measurability
• Based on readily available data or data available at a reasonable cost; • Be adequately documented and of known quality; • Updated at regular intervals, in accordance with reliable procedures; and • Of sufficient length in time and numbers to allow a quantitative statistical evaluation of the uncertainties associated with the data.

5.1.3 Nested Top-Down, Bottom-Up Monitoring Framework

Comprehensive, high-resolution (temporal and spatial), incisive, and cost-effective monitoring of key indicators on a multi-level scale will require a combined "top-down, bottom-up" monitoring framework. Scholarly work by Pretty (1995), Bell et al. (2001), Freebairn et al. (2003), and Reed et al. (2006) provide details on these two broad categories of indicator development, monitoring, and assessment. The "top-down" approach is driven and controlled by experts in the field (climate scientists and agency personnel). This approach is rooted in scientific reductionism and explicitly focuses on quantitative indicators. However, it does not readily lend itself to the perspective of the end-user.

The "bottom-up" approach, on the other hand, is driven and controlled by the local community. This approach emphasizes community activism and a keen understanding of the local context. It stresses and views sustainability monitoring as a continual learning process for the community, and it empowers the community to actively engage the research process and thus become the champions for social adaptation/mitigation action and change. Thus, a national combined "top-down, bottom-up" approach is envisioned. The proposed framework of this nexus is depicted in Figure 5.2. Partnerships between the community and stakeholders would result in trained community groups increasing the monitoring density and thereby supplementing and augmenting both climate-related impacts and climate hazard data for the stakeholders. The stakeholders would then send the combined data to national processing centers for analyses. The output from the analyses (climate change adaptation indicator database, including GHG emission reduction targets) would then be used to guide and to drive regional climate change policy.

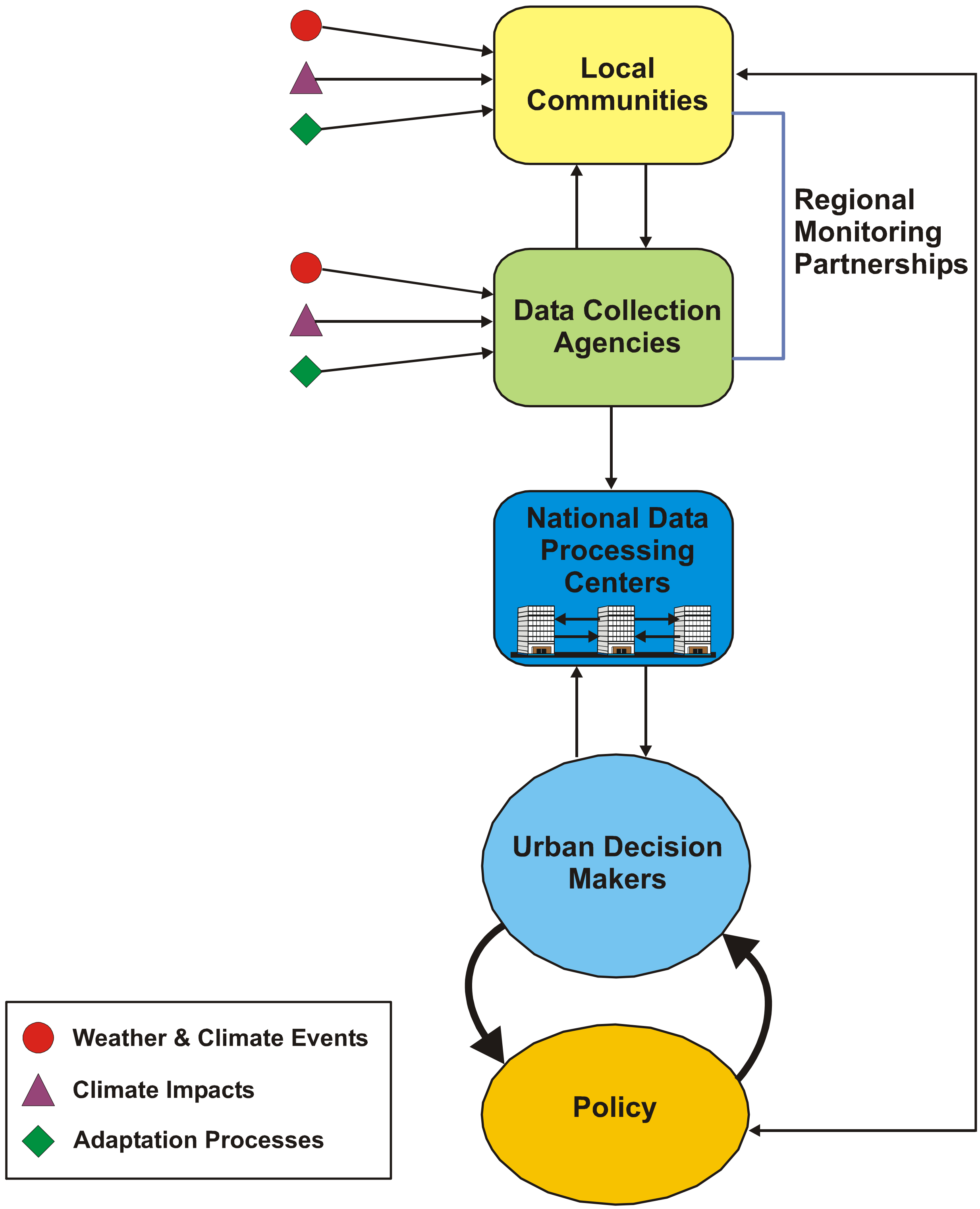

Figure 5.2. Proposed "Top-Down, Bottom-up" Indicator and Monitoring Framework for Climate Change Adaptation Strategies. Source: authors.

For this type of framework to be useful, regional community based organizations will have to be networked with thousands of extant public and private middle and high schools and universities within their locales to form a dense climate data network. This type of network already exists in places like New York City where the NOAA-CREST MetNet (http://nycmetnet.ccny.cuny.edu and Figure 5.3) works with THE POINT Community Development Corp in Hunts Point, Bronx NY (http://www.thepoint.org/) and a myriad of schools in the New York metro-region to produce high resolution climate data. This framework would also require data standardization, decision support tools, database management, computer processing and storage. Agency stakeholders would train and collaborate with community groups to provide appropriate data to the national centers for analyses. Getting adaptation measures and knowledge down to the community and to K – 16 students would enhance climate change education and perhaps even help to inspire the next generation of climate scientists. Moreover, an added benefit of this approach is that it provides and opens the channels for dialogue and partnership between stakeholders and the communities that are directly impacted and affected by the policies they make. This new mode of enlightened science communication between the two groups will help to reduce the ambivalence, apathy, ignorance, confusion, and distrust that currently prevail with regards to climate change science and policy.

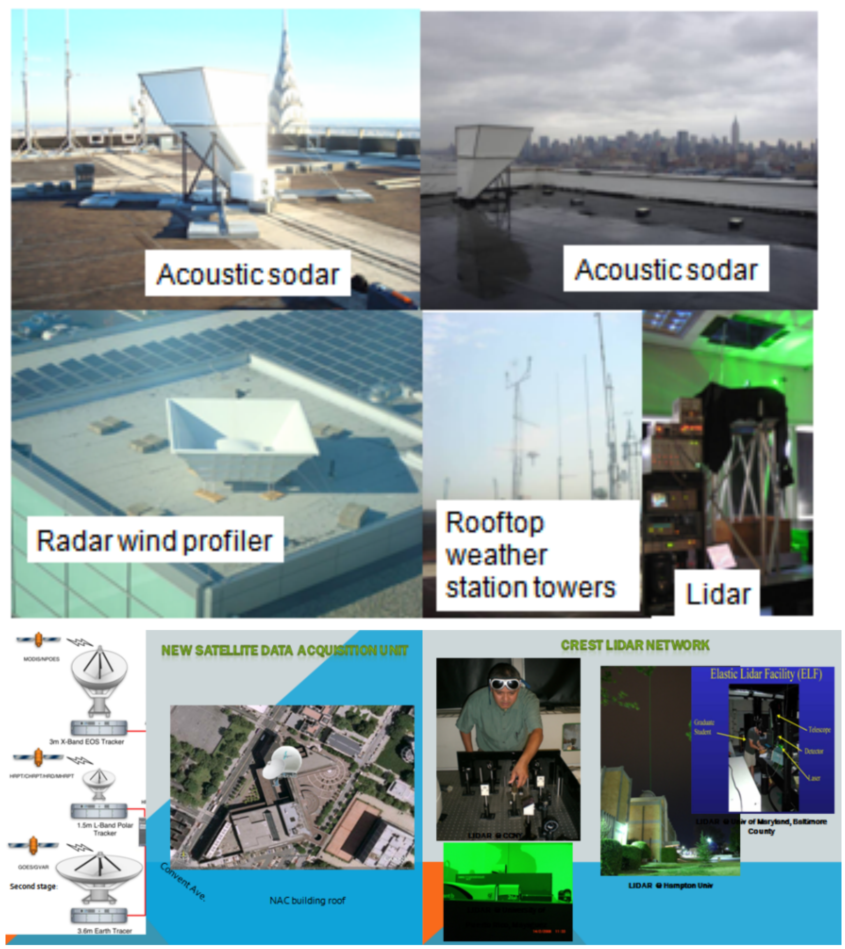

Figure 5.3. NOAA-CREST New York City Regional MetNet Instruments and Capabilities: Top - weather station, acoustic sodar, lidar, and radar wind profiler. Bottom –Satellite Receiving Station and Lidar Operations. Source: NPCC 2010.

To be effective and useful on both national and regional levels, this proposed framework also calls for:

- the creation of high resolution regional climate data networks;
- multi-state data sharing with coordinated local and regional data collection and analyses;
- clear organizational structure to streamline agency responsibilities to collect, analyze, quality control, and distribute the data and their derived products;
- data that are available in usable formats;
- a training program to educate lay people to not only the basics of climate science, but also to involve them as key participants in the framing of climate change adaptation policies;
- free-flowing, seamless collaborations between jurisdictions;
- new, bold partnerships between Federal, State, local agencies, research institutions, and local communities (Salkin et al 2009);
- the creation of national repositories that not only collect and archive climate data, but also help to develop and sustain indicators and monitoring as policy and practice;

5.1.4 Climate Risk Assessment Tracking

Indicators that are developed from the interaction of climate hazards and impacts need to be carefully tracked and analyzed by stakeholders so that adequate assessment of the risks of climate change may be conducted. Local, regional, and national risk assessment tracking is necessary to: a) evaluate the effectiveness of adaptation measures, b) appraise regional vulnerabilities and susceptibility to harm from climate hazard risks, and c) identify and forewarn of tipping points and critical thresholds so that flexible adaptation pathways and corrections may be pursued.

5.2 Role of Urban Climate Networks, Organizations, and Programs in Assessments

This section describes urban climate networks and organizations, including NGOs, climate justice organizations, and others that have the potential to play an important role in building a sustained urban climate assessment.

Building local resilience towards weather and climate impacts as well as reducing greenhouse gas emissions requires collaboration across traditional geopolitical boundaries. To achieve this goal, a number of formal and informal urban climate networks have emerged that cross levels of social organization and often traditional sector boundaries (Mitchell, R.B., et al., 2006). These networks run the gamut from government operated, non—profit managed, academically structured, to self-organized. The specific focus on these networks as well as their geographical reach varies. The section below uses geography to distinguish between some of the most notable urban climate networks currently in operation. It should be noted that this section does not attempt to list all the urban climate networks available in the US but instead provides an overview that is indicative of the types, geographical focus, and mission for a selection of existing networks.

Overall, these networks serve complementary purposes. While duplication does exist in the areas of membership and network focus, to-date, these duplications have been minimal. All of these organizations are operated by non-profit organizations whose primary source of revenue is grants from governments and private foundations.

5.2.1 International City Networks

Three primary organizations provide urban climate networking opportunities for local governments on an international level: C40 – Climate Leadership Group, ICLEI and United Cities and Local Government. Both the C40 – Climate Leadership Group and ICLEI provides support resources, technical assistance, and networking opportunities to members specifically pertaining to climate change mitigation, adaptation, and sustainability.

ICLEI is the longest-running network specifically focused on climate change and sustainability and works with municipalities of all sizes (cities, towns, counties, villages, boroughs, and tribal governments) – although small and medium sized local governments outnumber large communities in regards to membership. Created in 1990, ICLEI is a global membership based organization that provides technical support resources, networking platforms, training opportunities, and general support resources to municipalities of all sizes in the areas of climate adaptation, climate mitigation, and sustainability. Currently, ICLEI USA has approximately 550 local government members, ranging in size from locations such as New York City, Los Angeles, and Chicago, to smaller municipalities such as Devens, MA.

Founded in 2005, the C40 is a network of the largest current and future global cities; currently, 58 of the largest cities from around the world make up the C40 Climate Leadership Group. With a focus on helping cities implement meaningful and sustainable climate-related actions locally that will help address climate change globally, the C40 provides members technical assistance, project assistance, purchasing assistance, financial advice, and networking opportunities.

United Cities and Local Governments (UCLG) is a non-profit membership association of local governments with a goal of being "the united voice and world advocate of democratic local self-government, promoting its values, objectives and interests, through cooperation between local governments and within the wider international community." UCLG is a traditional membership organization for local governments that's primary focuses are in building a more democratic system and in making sure the concerns of local governments are integrated into international decision-making. While no formal working group on climate change exists, UCLG does provide regular updates and networking opportunities to its members about international climate change development and offers networking opportunities for members to share best practices and lessons learned.

5.2.2 National Networks

In the United States, many national local government networks have emerged that entirely or partially address climate-related issues. On the mitigation side, many cities have joined the U.S. Mayors Climate Protection Agreement. To date, 1,055 mayors around the country have signed the Agreement, committing their jurisdictions to:

- Strive to meet or beat the Kyoto Protocol targets in their own communities, through actions ranging from anti-sprawl land-use policies to urban forest restoration projects to public information campaigns;
- Urge their state governments, and the federal government, to enact policies and programs to meet or beat the greenhouse gas emission reduction target suggested for the United States in the Kyoto Protocol – 7 percent reduction from 1990 levels by 2012; and
- Urge the U.S. Congress to pass the bipartisan greenhouse gas reduction legislation, which would establish a national emission trading system.

A number of national networks have arisen to assist local governments in meeting their goals around both emissions reduction and climate preparedness. Some of the preeminent local government climate and sustainability networks that exist include the Urban Sustainability Directors Network (USDN), the Water Utility Climate Alliance (WUCA), the American Society of Adaptation Professionals (ASAP), and ICLEI USA. It should be noted that additional networks focused on components of climate issues and/or sector-specific issues also exist.

The Urban Sustainability Directors Network (www.sustainablecities institute.org/usdn) emerged in 2009 after an upsurge in the creation of Sustainability Directors within local governments. With approximately 75 core members, USDN is specifically focused on networking and best practice sharing between individuals in local government who are responsible for spearheading their municipalities overall sustainability efforts.

The Water Utility Climate Alliance (www.wucaonline.org) is an alliance formed by water agency manages of the country's largest water providers to provide leadership and collaboration on climate change issues affecting the country's water agencies. Ten of nation's largest water providers make up WUCA, which is responsible for supplying drinking water to more than 43 million people in the U.S. WUCA provides sector specific guidance and resources, networking opportunities, and professional development for their respective membership.

A newly formed non-profit that strives to provide professional development and networking opportunities to individuals that work on climate change adaptation issues is the American Society for Adaptation Professionals (ASAP). Open to public, private, non-government, and academic individuals, ASAP is an emerging organization that seeks to replicate the successful model embodied in organizations such as the American Planning Association. While initially launched from the University of Oregon, ASAP has since spun off into its own non-profit, professional organization.

Finally, ICLEI-Local Governments for Sustainability USA (www.icleiusa.org) is a national non-profit organization that works with US local governments to achieve their mitigation and adaptation goals by providing tools, trainings, and technical assistance to member cities and counties. ICLEI's membership base is comprised of approximately 550 U.S. local governments from all states.

These national networks regularly collaborate with the scientific community to ensure their members have timely, relevant, and accurate information from which to base decisions. This existing relationship presents an opportunity for future collaboration as it pertains to building a sustained urban climate assessment.

5.2.3 Regional Networks

In the last few years, regional networks have been emerging to help facilitate the exchange of information and enhance collaboration across geopolitical boundaries. Some of the most notable regional networks in the U.S. as of late 2011 include the Urban Climate Change Research Network (and other Regional Integrated Sciences and Assessments), the Great Lakes Cities Climate Adaptation Project, the Southeast Florida Climate Compact, the Bay Conservation and Development Commission's Adapting to Rising Tides Project, the San Diego Bay Sea Level Rise Initiative, EPA Climate Change Networks in multiple regions, and state-driven municipal climate networks.

The Consortium for Climate Risk in the Urban Northeast (CCRUN) and the Great Lakes Cities Climate Adaptation Project (GLIESA/GLCCAP) are both efforts partly funded through the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessment office. Both efforts are driven by academic institutions and strive to bridge the gap between scientists and decision-makers, with a key focus on creating best practice sharing networks in their respective regions (GLIESA/GLCCAP in the Great Lakes and CCRUN in the Northeast). These two networks have a joint mission to advance scientific understanding of the needs, barriers, and successes of local level adaptation and mitigation efforts as well as to help devise resources that are more useful and useable by local decision-makers.

Another type of regional network that is emerging is local government driven networks. In the case of the Southeast Florida Climate Compact and the San Diego Bay Seal Level Rise Initiative, local governments in each of these regions identified the need for more regional collaboration. In Southeast Florida, the four southern most counties of Broward, Miami-Dade, Palm Springs, and Monroe all came together to devise regional solutions to reduce the region's greenhouse gas footprint and build regional resilience towards weather and climate change impacts. In the San Diego Bay region, ICLEI USA worked with the cities in the region, the Port District, and the Airport Authority to assess regional vulnerabilities and recommend adaptation responses. The effort led to the creation of the *Sea Level Rise Adaptation Strategy for San Diego Bay* and a continued commitment from The San Diego Foundation to support implementation of the Strategy.

In the San Francisco Bay Area, the San Francisco Bay Conservation and Development Commission and NOAA Coastal Services Center are supporting a regional sea level rise planning network through their Adapting to Rising Tides (ART) project. This effort grew from concern expressed by a local agency about the impacts of sea level rise on bayfront wetlands, into a regional, multi-jurisdictional collaborative effort to increase regional resilience towards rising sea levels. The ART project brings community officials and stakeholders together to collectively gain a better understanding of how sea level rise and other climate change impacts will affect the Bay Area's ecosystems, infrastructure, and economy. Additionally, participants of the ART project are identifying strategies for community-based adaptation planning to address these challenges and develop a process for implementing them. This effort is particularly noteworthy for its integration of a top-down and bottom-up stakeholder approach.

In addition, a number of state networks have emerged with a specific focus on climate change and sustainability. States such as New York, California, Colorado, Massachusetts, Connecticut, and Florida all have had municipal climate networks that bring together local communities throughout the state to learn about new developments in climate change and sustainability and provide opportunities for networking and best practice sharing. In Massachusetts, for example, ICLEI-USA convened a network that connected local governments with research scientists and state and federal agencies looking at the state's climate vulnerabilities. Often, these networks are supplemental networks to the larger national or international networks that exist.

5.2.4 Urban Research Networks

On the research side, the Urban Climate Change Research Network (UCCRN) is a group of researchers dedicated to providing science-based information to decision-makers in cities around the world as they respond to climate change. Founded in 2008, the UCCRN published the First Assessment Report on Climate Change and Cities (ARC3) in 2011, with over 100 authors from over 50 cities around the world (Rosenzweig et al., 2011). The goal is to develop an on-going assessment process for climate change and cities similar to the IPCC assessment process that focuses primarily on nation states.

The Habitat University Partnership Initiative is another network of research institutions, international agencies, and local practitioners. Initiated by United Nations Human Settlements Programme (UN-HABITAT), the initiative aims to strengthen the cooperation between UN-HABITAT and institutions of higher education, as well as facilitating exchange and cooperation between universities in developing and developed countries. It was piloted between 2008 and 2010, and fully launched with the adoption of the Initiative Charter in 2011.

The Alexander von Humboldt Cities and Climate Change Network was formed in 2010 to advance academic research on the cutting-edge topic of urban climate change mitigation and adaptation. The network consists of some seventy researchers and practitioners worldwide who represent different disciplinary perspectives and who specialize in different aspects of urban climate change mitigation and adaptation. The network aims to inform scientific and policy discourses, and to promote research and innovations based on exchange and cooperation among network members, from different disciplines and with different research foci. The network also aspires to propose thoughtful solutions to the interrelated issues of urban development, energy, and global climate change. With the support of the Alexander von Humboldt Foundation, network members convened a Cities and Climate Change Conference at the Freie Universität Berlin in 2011.

5.2.5 Federal Programs

Lastly, state and federal agencies play a significant role in some areas of the country in creating and maintaining regional networks focused on climate change and/or sustainability data and information production and flow (Table 5.2). The U.S. Environmental Protection Agency currently has regional networks in Region 1 – New England, 4 - Southeast, and 5 - Midwest. These networks also focus on best practice sharing and ensuring local communities have access to federal resources.

Table 5.2. Assessment Relevant Federal Actions on Urban Climate Change Issues

Federal Agency	Name of Action	Description
Dept. Health and Human Services (DHHS)	Climate Change Adaptation Task Force	Integrating adaptation/mitigation to sustainability and health programs
Department of Commerce (DOC)	Climate Adaptation Plan (CAP)	Analysis of DOC's vulnerability to cc, adaptation strategies
Department of Commerce (DOC) NOAA	RISA Programs	Assess climate variability in different regions of the U.S. – Northeast RISA focused on urban
Department of Energy (DOE)	2012 Strategic Sustainability Performance Plan	Assess vulnerabilities, plan for adaptation
Department of Labor (DOL)		Raise awareness of cc impacts on DOL properties/employees, incorporate adaptation program
Department of Transportation (DOT)	Automotive Fuel Economy Program	Fuel economy standards increased, now also include light trucks
DOT	Congestion Mitigation and Air Quality Improvement Program	Funds State DOT/transit authorities to reduce emissions
DOT	Bicycle & Pedestrian Program of the Federal	Promote non-motorized transportation

	Highway Administration's Office	
EPA/HUD/DOT	Partnership for Sustainable Communities	Promote sustainable development

5.3 Role of Knowledge and Information Generation on Adaptive Capacity

The amount of climate change information has grown dramatically in recent years, and will continue to develop and emerge over the next decade and beyond. Knowledge and information generation plays a critical role in promoting adaptive capacity in several ways. First and most obviously it promotes fundamental understanding of the current state of climate science. Second, it instills the notion that the process of science knowledge and information generation is continual, additive and that the science-policy linkage process is ever developing. And third, the process of developing and incorporating new science in the adaptation process allow for capacity building and social learning among scientist-stakeholder collaborations and for the stakeholders themselves.

Climate change knowledge and information as mechanism for enhanced adaptive capacity can best understood within a set of stakeholder learning frames and opportunities. These can be defined as specific actions that the climate change specialist can take when engaging with stakeholders (NRC 2011). An important component of the learning process is connecting one's knowledge and information transfer with the process and mission of the stakeholder agency and organization, and to explicitly think about what connection points with climate change will make sense to the stakeholders. Climate risk is perceived differently within agencies, offices, bureaus, or departments in any specific governmental entity (e.g., municipal, county, state, federal). Climate risk, for example, can be either defined as a problem within a suite of other critical public policy issues (e.g., housing, transit congestion; as an incremental problem which demands response within existing management cycles and planning activities such as water supply and sewerage system regular capital upgrades); or, as a condition which could result in a potentially catastrophic disaster (e.g. storm surge emergency response and management planning). Consideration of the linkages between climate risk and agency mission, and making appropriate adjustments before and during stakeholder engagement could have a very positive impact on the effectiveness of the educational experience for all parties.

Furthermore, an overall picture has started to emerge of the roles, responsibilities, and conditions that stakeholders use to connect with climate change risk and adaptation. These include the following: Specify activity/infrastructure at risk to climate; define risks in current and future climate; characterize adaptation options; operations/management, infrastructure investment, policy; link to capital cycles; time-scales - short, medium, long-term; conduct feasibility screening; engineering, institutional, and regulatory feasibility; and evaluate adaptation options. The recognition and incorporation of these into one's climate change presentations and conception of stakeholder interests will enhance the transfer experience.

Another critical component of the transfer experience is to empower stakeholders to make the climate change information and data their own. Empowerment can be fostered through at least three actions. First, it is valuable to connect with leading individuals and/or early adaptors in the stakeholder entity and partner with them as potential champions of the issue in their agency or organization. These individuals will legitimate the process and method of engagement, and the knowledge and information itself to their peers and colleagues. Second, it is worthwhile to understand within the empowerment process when it is appropriate to step back from the stakeholders as they begin to consider, interpret, and apply the climate information and data within their own decision frames. As knowledge and information are received within the stakeholder agencies and organizations, the material should become part of their operations and planning. It is advisable to let the stakeholder test applications of the knowledge without additional intervention while to keep available and engaged if misrepresentation occurs.

5.4 Summary and Recommendations

To be sure, adequate indicator development and monitoring is the cornerstone to any climate change adaptation initiative. An inventive and effective indicator development and monitoring program that support regular integrated assessments should include the following key elements:

- Stakeholder and community partnerships
- Local community "buy-in"
- Community outreach programs that will educate, properly inform, mobilize, and encourage active community participation in local adaptation strategies and plans
- Dense, high-resolution monitoring networks
- Routine updates for stakeholders and decision-makers of new and emerging climate change information and knowledge
- Interdisciplinary collaboration that may include for example: a) the insurance industry for risk assessment; b) engineering firms for vulnerability and risk assessments to the built environment
- Region-specific adaptation strategies
- Federal, State, and local funding support of each segment of the "top-down bottom-up" nexus to climate change adaptation

Coordinated, urban responses to the impacts of and the vulnerabilities to climate change is a national imperative. Urban sustainability will require innovative, integrated approaches to building climate change resilience and in advancing climate change adaptation initiatives. To this end, U.S. cities like Boston, Seattle, and New York and international cities like Toronto and London have taken bold and novel approaches to establish and support climate change adaptation partnerships between, agencies, research institutions, universities, and local communities. These partnerships have proven to be fruitful in enhancing and fostering sound, dynamic adaptation planning, initiatives, and pathways.

6 Summary Conclusions and Recommendations

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The objective of this technical report is to provide a state-of-the-art assessment of how climate change is impacting and will impact U.S. cities and, in turn document recent research literature on associated infrastructure and population vulnerability, and ongoing and emerging adaptation planning strategies.

6.1 Urban Climate Risk Assessment Framework

Urban climate risk assessment includes several critical aspects including how 1) The fundamental connections between urban systems and the climate system and the associated climate risks and hazards are defined; 2) These interactions manifest as impacts, vulnerabilities, and adaptations among the key urban sectors and services which enable cities and their residents to thrive; 3). Socio-political factors mediate the ability of cities to manage and respond to the opportunities and challenges of climate change in the context of adaptation planning, and 4). A sustained urban climate change assessment can be undertaken for cities in the U.S.

Several specific conclusions and recommendations are drawn from this assessment of climate change with respect to U.S. cities. These include the following:

6.2 Conclusions

The following are drawn from the conclusions present in the report's chapters.

Urban Systems and Climate System Interactions

- Climate change already is impacting the urban areas of the United States. The nature and magnitude of the impacts vary. The levels of future impact will differ depending in the location and time in the future.
- Urban systems and sectors currently under stress are likely to become more stressed due to climate change. For example, water supply for urban areas in the West, currently under stress, will be further stressed.
- Degrees of stress vary spatially now and will be so in the future.
- Modest changes – slow modest sea level rise – in large scale means can affect the impacts on local scales from extremes, e.g., coastal flooding from a storm event.
- Cities are variable with respect to size, density, and climate. These variable condition set in motion a broad range of impacts and vulnerabilities.
- Modest global-scale changes can cause non-linear impacts resulting from local extremes. Global mean change can have extreme local impacts.

- Urbanization is the United States is an ongoing and dynamics process which presents additional challenges to urban climate change response and adaptation.
- Cities are significant drivers of climate change.

Urban Sectors and Services - Impacts, Vulnerability, and Adaptation

- Climate change impacts, vulnerability and adaptation are public safety and national security issues.
- Some short-term positive outcomes also have long-term negative consequences. It is important to consider timescale when considering impacts and vulnerability.
- Impacts of climate change affect groups of people differently. Some groups face a disproportionate amount of impact.
- Climate change is not isolated; its impacts are imbedded in other ongoing stresses.
- Climate change provides some opportunities and benefits however, the challenges and negatives predominate.
- A great diversity of adaptation strategies exists among cities.
- Adaptation cannot only be local and dependant on state and federal partners for resources. Local adaptation depend on many actors.
- Local adaptation action is dependent upon cooperation between the government and private stakeholders to implement adaptation.
- U.S. cities are prepared in many ways to deal with climate change. Given their past history of responding to extreme events and climate variation impacts on local residents and businesses, many cities are capable of starting to work on climate change adaptation.

Pathways and Cross-Currents to Adaptation Planning

- Cities are prepared for climate change in some ways, but not in others including issues of finance and equity.
- Preparing for climate change will be less costly than responding to future climate impacts.
- Climate change adaptation isn't a stand-alone effort, embedded in it are many facets of urban functions, including sustainability.
- While cities and their response capacity is highly variable, cities can and increasing do learn from one another with respect to lessons learned from their actions.
- Climate change impacts connect with many of aspects of urban life and conversely aspects of urban life including social, economic and political considerations influence the ability of cities to respond to climate change.
- A risk-based approach gives cities tool to address to address a lack of knowledge about costs which can hinder decision making.
- Cross spatial scale impacts influence the ability of cities to adapt to climate change. For example in the Gulf Coast climate change impacts the region however, levees cross jurisdictions. Cities need better regional cooperation to deal with climate change.
- Do nothing scenario is present in many cities; however there are costs of inaction. Specific examples of large costs from not acting are evident; e.g., Cambridge, MA storm surge flooding.
- Being climate change ready is a good component of a well prepared city.

- Many cities are showing leadership in climate change in the absence of federal government support.
- Climate change presents an opportunity to initiate adaptation for a broad suite of risks.
- Some localities do not have access to response mechanisms which limits their response capacity.
- A communication issue is how the public interprets weather observations and weather's relation to climate and climate change. The urban residents are often confused about the connections.
- Adaptation is a process which gives cities an opportunity to make investments over time as long as adaptation is initiated at an early stage.

Sustained Urban Assessment

- Cities are learning from one another. Assessment knowledge and information can enhance what cities can learn from each other.
- Federal government has an important coordinating and leadership role in providing data, analytical tools, and science.
- Many cities are showing leadership in climate adaptation.
- Preparation for climate change is a component of well managed city which requires an understanding of location-specific concerns. Climate change should be engaged from the policy, managerial, social and cultural perspectives.
- Build capacity at local scales to respond to and build resilience to climate change. These efforts enhance the level of the response capacity.
- Current tools do not give sufficient details for engineering design – we cannot assign probabilities for these outcomes.
- Cities are at the forefront of climate change adaptation. Will this continue to be the case in the future?

6.3 Recommendations

Several general recommendations are provided as a result of the conclusions above.

- Cities need better and greater capacity to monitor changing environmental and climate conditions.
- City planners need to include climate change impacts and response into their planning efforts.
- Cities need to review their level of preparedness and make sure that they defined ways to improve their preparedness.
- The federal government has several roles to play including promoting data accessibility, adaptation coordinating, and leadership. They also should keep these roles for climate research needs such as data accessibility and analytical tools.
- Effective adaptation will require greater coordination among jurisdictions or new institutional arrangements. E.g., Gulf coast, climate effects felt throughout – coordinated effort would be most effective.

- Planning as preparedness. It is important to earmark funds for future adaptation and plan for adapting in the future when the opportunity arises instead of only acting now.
- Research is needed on ways to communicate adaptation strategies and develop communication tools to connect weather and adaptation.
- Tools' for climate change attribution are needed.
- Engage the private sector because a) they have a vast wealth of knowledge and b) the private sector is a major component of cities and urban life. Cities can offer incentives to private developers. E.g., 2010 Swiss Re and State Insurance Fund of Alabama.
- Data are not available on climate change impacts, and there needs to be some input on that so as to create agreed upon metrics.
- Cities need a diversity of adaptation strategies, not just one.
- Cities need to better monitor environmental change.
- Tools we have do not give sufficient information to guide engineering practices. These points to the lack of confidence problem, which hinders engineering adoption of climate change information.

Technical Report on U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues

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Chapter 3. Urban Sectors and Services

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Chapter 6. Summary Conclusions and Recommendations