Modeling Infrastructure Vulnerabilities and Adaptation to Climate Change in Urban Systems: Methodology and Application to Metropolitan Boston

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Abstract

Much of the infrastructure in use today was designed and constructed decades if not centuries ago. Many of these infrastructure systems are vulnerable to a variety of anthropogenic or natural disruptions even though their functioning is vital to the creation and maintenance of quality of life in a region. Moreover, concepts and designs have persisted even as technologies have changed. Yet the demands and technologies of the future may require infrastructures – both material facilities and human institutions – that are radically different from those of the present. Dealing appropriately with immediate infrastructure vulnerabilities and infrastructure evolution requires a combination of effective short-term crisis management and anticipatory, strategic thinking and planning. Both the "material nature" and institutional issues surrounding urban infrastructure in a changing environment pose formidable challenges to efforts by industrial ecologists to improve the sustainability of urban areas.

This presentation describes a collaborative study carried out over the course of more than three years by a group of scientists from engineering, policy analysis, geography and public health, together with a local planning agency and over 200 stakeholders from the public, private and non-profit sectors in metropolitan Boston. The research was conducted as part of the CLIMB project, which explores Climate's Long-term Impacts on Metro Boston. Special focus was given to vulnerabilities and dynamics of urban infrastructures for energy, communication, transportation, water run-off, and water quality, as well as the interrelatedness of these systems, and implications for public health. Computer-based scenarios are presented for potential future infrastructure dynamics under a variety of assumptions about changes in technology, infrastructure investment, and local climates. The presentation concludes with a set of lessons for research on climate impacts and for environmental investment and policy making.

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1. Climate Change and Urban Infrastructure Systems

1.1 A Climate for Human Development

Since early human history, it has been the goal of many technological innovations and infrastructure developments to stabilize environmental conditions and decouple economic growth and sociocultural development from the vagaries of environmental change. Pottery facilitated storage of food stuffs away from moisture and rodents, prolonging supply for humans. Terraces reduced erosion rates and helped maintain agricultural productivity. Aqueducts controlled distribution of water and equalized supply across regions. Use of fire wood, and later of fossil fuels, helped maintain indoor ambient temperatures throughout the seasons within narrow ranges. Synthetic fibers provide year-round protection from the elements. Other improvements include development of rituals, conventions, rules, regulations, and institutions to coordinate human activities with each other and to ensure that those activities are in synch with environmental conditions (Ausubel 1999). Examples include water rights, futures markets for agricultural products, and insurance markets.

The list of products, processes and infrastructure systems – both “hard” structures and institutions – which are used to achieve autonomy by humans from their biophysical environment is long and growing. To a significant extent the items on that list define how we live and who we are. The many new technologies and institutions have helped reduce human vulnerabilities to adverse environmental conditions and have also broadened the scope of economic activity. As a consequence they have also fostered increased throughput of materials and energy to produce and distribute ever larger amounts of goods and services (Daly 1991). Expansion of the human endeavor required that more energy of higher quality is being used to convert larger amounts of materials into finished products. Early energy sources included muscles of animals or people, and wood or peat (Ayres 1978; Smil 1997). Each of those sources had only limited ability to provide heat or power for production processes and where ultimately replaced significantly by the combustion of fossil fuels – most notably coal, oil and natural gas (Grübler, Nakicenovic et al. 1999). Fossil fuel combustion began to proliferate across all sectors of the economy by the mid to late 1800s in Europe and North America, and continues to do so in the industrializing world of today.

For decades economic growth closely followed fossil fuel use (Schipper and Meyers 1992). But the confidence that perpetual economic growth and development could occur irrespective of biophysical constraints was punctured by temporary fossil fuel shortages of the 1970s and 1980s. Rapid increases in human population, growing disparity in affluence across the globe, rapid loss of pristine ecosystems and biodiversity, and urbanization caused concern among an increasing number of analysts (Meadows, Meadows et al. 1972; Barney 1980). Others, in contrast, dismissed these trends as temporary challenges which will be met and overcome by continued technological progress (Simon 1980; Simon 1981).

While the debate about the adequacy of finite natural resources and the ability of technology to overcome limits continues to be waged, a set of new, global issues has shifted the debate from its emphasis on the sources of material wealth to the sinks of waste products. Losses of stratospheric ozone were related to the release of chlorofluorocarbons (CFCs) from industrial processes and consumer products, and elevated UVB radiation associated with ozone loss was identified as a contributor to human disease and a decline in the health of ecosystems. Then, elevated carbon concentrations in the atmosphere – triggered by combustion of fossil fuels – were linked to changes in global atmospheric temperatures. Subsequently, the list of gases potentially contributing to changes in global climate, and the processes leading to their release, was significantly extended to include, among others, methane from rice paddies, livestock and termites, halocarbons used in air conditioning, refrigeration and plastics, and sulfur dioxide from coal fired power plants (Wigley 1999). Now, the confluence of changes in the size of the human population, increases in use of energy and material resources, loss of habitat and species diversity, the spread of many diseases and the decline of environmental waste absorption and assimilation capacities are all seen as potentially interrelated with climate change. These revelations occurred at a time in human history when decoupling economic growth and development from the vagaries of the environment seemed *oh so close*.

Societies around the globe slowly began to respond to scientific information about global environmental change (Lemons and Brown 1995). Strategies to reduce emissions of ozone-depleting CFCs were readily identified and implemented, in part because the number of sources were limited and substitutes for many chlorofluorocarbons were available. Reduction of emissions of gases contributing to climate change proves infinitely more challenging because these emissions are intimately related to all aspects of life – from the food we eat, to the houses we occupy, to the clothes we wear, the entertainment we enjoy, and the way we move goods, services, people and messages across space and time.

Recognition of the many fundamental relationships – material and immaterial – of culture, society, and economy with the environment and heightened sensitivity to previously unknown global environmental uncertainties and risks occurred also at a time of increased disillusionment of the public with official scientific expertise (Ravetz 1999) and at the turn of the century and dawn of a new millennium – a time when deeper perennial questions of human existence tend to emerge (Hicks 2000). Calls abound for humans to be not just custodians of the planet, but to rekindle spiritual values (Barney 1999) and shape viable futures with meaningful legacies for posterity (Valemoor and Heydon 2000). Others (e.g. (Ausubel 1999)) make a convincing point to distrust the "threat industry" with its inherent tendency to seek out problems faced by humanity and capitalize on subsequent attention to these problems while belittling the ability of humans to adapt and meet new challenges.

It is in this context that we discuss in this paper potential impacts of climate change on infrastructure systems and services. In the discussion we concentrate on urban infrastructure systems for three main reasons. First, in the USA and worldwide, the majority of people live in urban areas, and second, it is there that we find the highest concentration of infrastructure systems and accumulated value. Third, changes in urban systems are often the drivers for social and economic change in a region and on international scales due to the dominant role of cities as centers of cultural, financial, and technological innovation activities. As a corrolary of these observations, impacts on urban infrastructure systems may be felt well beyond their boundaries.

1.2 Cities and Climate Change

To date, most of the work on climate change impacts has been on individual sectors of a national or the global economy, with major focus on the impacts of climate change on agriculture (Schmandt and Clarkson 1992), (Rosenberg 1993; Rosenberg 1993; Rosenberg, Crosson et al. 1993), (Crosson and Rosenberg 1993), (Cohen 1996; Cohen 1997; Cohen 1997), (Huang, Cohen et al. 1998). However, the number of studies conducted on regional, and integrated impacts of climate change is increasing. These studies suggest that the sum of sea level, energy, water, and recreation impacts (each infrastructure-related) far exceed agricultural impacts (Ruth and Kirshen 2001). If air pollution and human life impacts are also included, the exceedances are even greater. Even if low estimates of economic impacts of sea level rise hold true, the combined damages on infrastructure systems for energy, water and recreation still significantly exceed agriculture (Yohe, Neuman et al. 1996). Though these results are by no means intended to divert attention away from potential dangers to agriculture and food supply, they do highlight that the economic impacts of climate change on infrastructure disruptions are similar or even greater in magnitude, and potentially regionally more concentrated because the bulk of infrastructure is typically located in urban areas.

Increasing standards of living – whether in the developing or industrialized world – often not only mean more cars, more refrigerators and more air conditioners, and thus lower ambient air quality and larger emissions of greenhouse gases. Emission from energy conversion in power plants and end-use devices such as cars also means increased heat island effects and changes in local temperature and precipitation patterns. The changes in climate regimes of cities observed in Turkey (Tayanc and Toros 1997), Austria (Böhm 1998), South Africa (Hughes and Balling 1996) and elsewhere may be a harbinger for a new round of induced energy demand for cooling and air conditioning, and thus further disrupt local and global climate (Kalnay and Cai 2003).

Urbanization rates around the globe are increasing. Seventeen of the world's 25 largest megalopolises are located along coastlines and prone to suffer from sea level rise (Nicholls 1995), (Timmerman and White 1997). Twelve of the most populated cities in the US are tidal waterfron cities[1], three are on the Great Lakes[2], three on navigable rivers[3], and two are on non-navigable rivers[4]. The advantages that historically have led to the location of cities on the coast (geographical control, access to transportation, trade, access to fish as food source etc.) are eroding at the same time as their infrastructure (transportation, flood control, sewage treatment etc.) is impacted by climatic change. Gradual sea level rise and temperature changes are likely to be accompanied by more severe weather conditions such as higher wind and snow loads on buildings and extended droughts. Disruptions of power and water supplies, transportation and communication, and loss of many other infrastructure services may result. Direct impacts of such

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[1] Baltimore, Boston, Houston, Los Angeles, Miami, New York, Philadelphia/Wilmington, San Francisco/Oakland, San Diego, Tampa/St. Petersburg and Washington D.C.

[2] Chicago, Cleveland and Detroit.

[3] Minneapolis, Pittsburgh and St. Louis.

[4] Atlanta and Dallas.

disruptions include economic losses, human health impacts, and increased susceptibility to further disruptions. For example, climate-change induced increases in precipitation in the Midwestern parts of the USA will likely result in increased traffic accidents, flight delays, and potentially airplane accidents (Changnon 1996).

While disruptions of infrastructure systems are most felt among the inhabitants of urban areas, and especially the cities of the developing world, they will ripple through the social and economic fabric to affect systems of interconnected cities and the larger regions and hinterlands with which cities interact. Even in industrialized countries, the role of cities as national and international drivers of economic growth, development, innovation, financial and other management may be reduced in light of climate-induced losses of infrastructure services and reductions in quality of life. The extent of climate impacts on households and firms in different regions depends on the degree to which they are connected with the rest of the economy, and the relative magnitide of negative and positive impacts. The same individuals, households, firms or entire regions may be harmed by some manifestations of climate change while they may benefit from others. For example, milder winters will reduce demands for heating oil, while higher summer temperatures will increase expenditures for cooling and air conditioning. The opening of the Northwest Passage in response to snow and ice melt will, in effect, bring the major cities on the US American East Coast closer to Asia, enhancing their national and international competitiveness in trade of agricultural and manufacturing products. Climate change will thus have far-reaching implications for the re-distribution of wealth and welfare within a generation, across regions, and across time.

1.3 The Case of Metro Boston

Metropolitan Boston – as defined by the Metropolitan Area Planning Council – consists of 101 communities (Figure 1) and is home to more than three million people. The high density of population, diversity of businesses, government agencies and eductional institutions, and central location in New England and its location on the coast make metropolitan Boston a major center of economic activity within the New England region and larger, eastern megalopolis.

For the purpose of analyzing and modeling the potential impacts of climate change on Metro Boston, seven zones are defined (see Figure 1). Their definition has been guided by the need to distinguish (a) areas along the coast from those more inland and less directly affected by sea level rise and storm surges; (b) coastal areas that are more rocky and steep (the north) from those that are more shallow and sandy (the south); (c) areas with high population densities and mature infrastructure systems (cities and developed suburbs) from developing regions (mainly along the Interstate 495 corridor). Within these regions, notable differences exist, for example, in the type and level of economic activity, incomes and age composition of households, rates of change in land use and population, and potentials to mitigate and adapt to climate change.

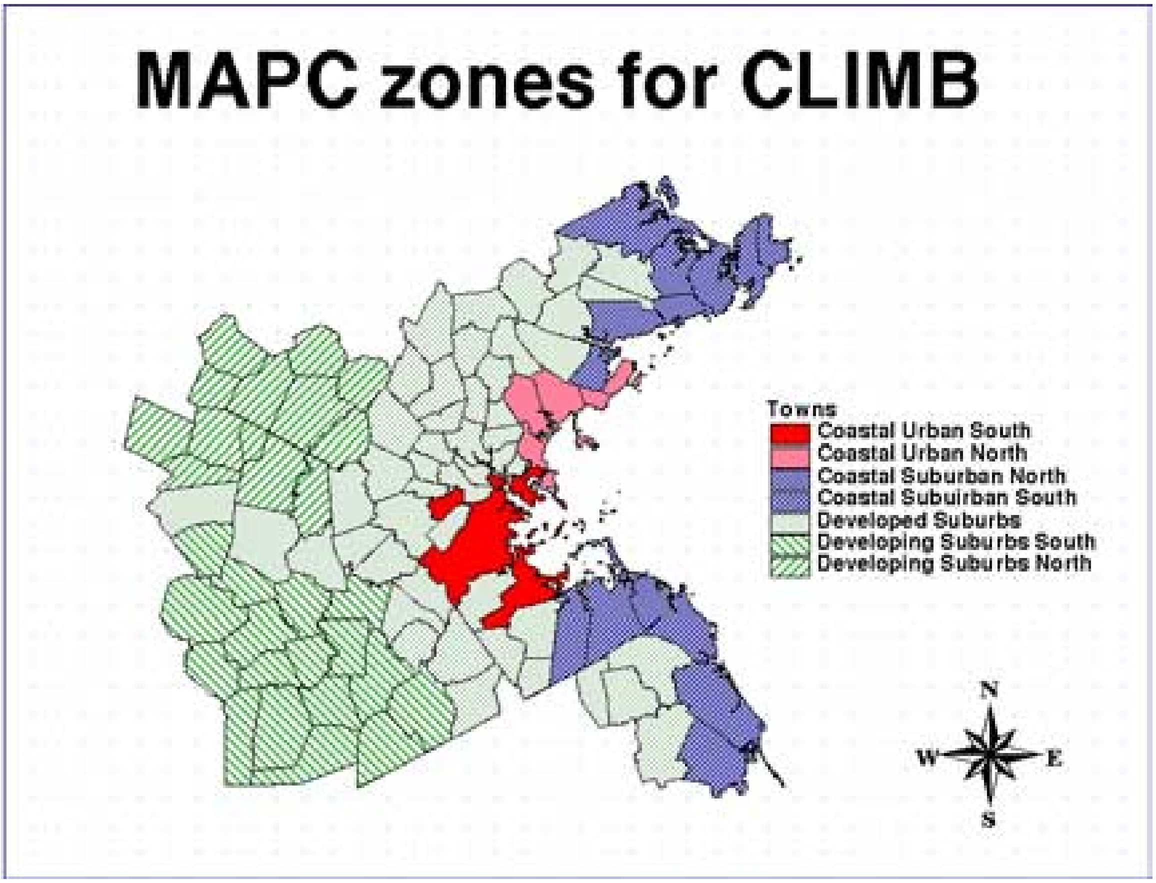


Fig. 1 Metropolitan Boston and seven zones defined for CLIMB

One scenario of potential climate change in metropolitan Boston (NAST 2000) suggests that annual temperatures increase 2 – 5 degrees C (4-9 degrees F), that annual precipitation changes by 0 - 25 percent, that the frequency and intensity of extreme precipitation events and droughts increase as well. These annual changes will likely be accompanied by continual rise of sea levels and will play themselves out differently throughout the seasons, will continue for centuries, and may exacerbate already existing natural hazards. According to the Massachusetts Emergency Management Agency (MEMA 2000) the list of present natural hazards in order of frequency in Massachusetts includes: floods, heavy rainstorms, northeast (extra-tropical) storms, coastal erosion, hurricanes (tropical storms), tornadoes, urban and wild fires, and earthquakes.

Anecdotal evidence from past climate-related events in the region – though not necessarily indicative of climate-induced changes – provide powerful illustrations of potential climate impacts on the region. For example,

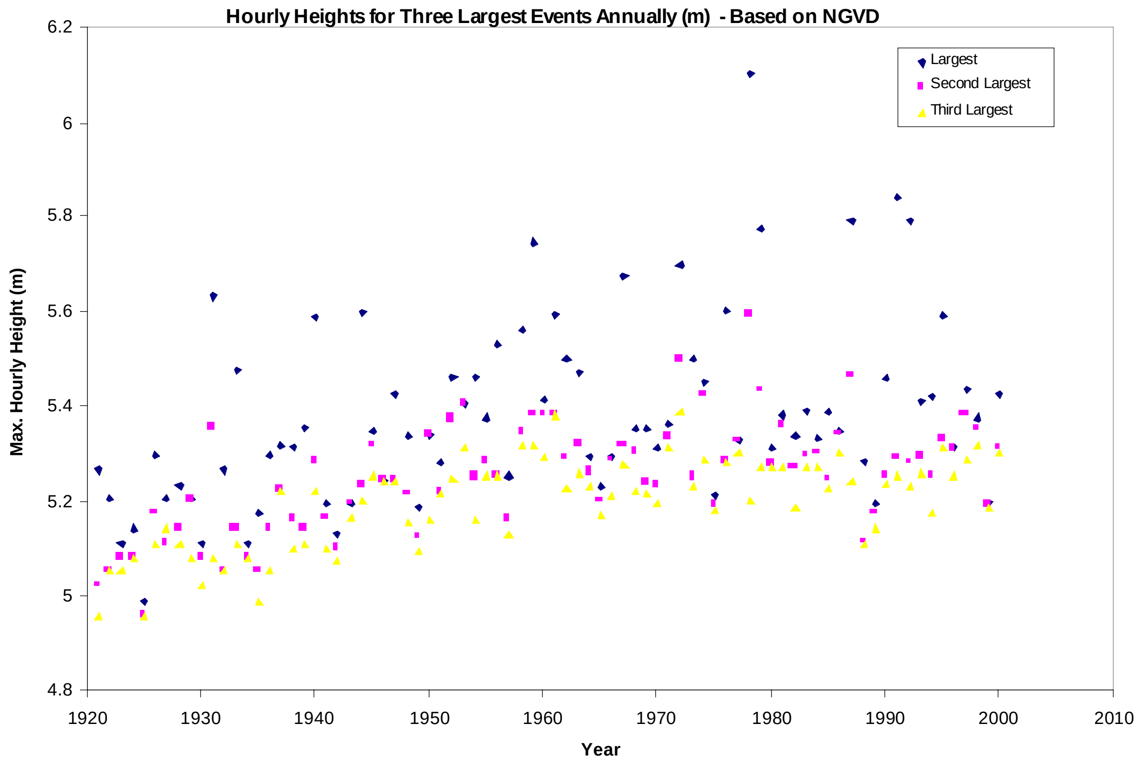
- hundreds of thousands of customer-hours of electricity demand are periodically unmet during peak summer loads because of small distruptions in the grid that triggers large-scale scheduled outages, or during winter storms, because power lines are downed, such as during summer months in 2001 and the winters of 1996 and 1998;

- heating oil deliveries are being disrupted because barges on the Hudson river require ice-breakers to free shipping channels;
- flooding of subway stations and tunnels can result in major interruption of service for several weeks and large cost of clean-up, repair and retrofits, such as during an October 1996 storm;
- collapse of bridges can result in increased commuting and requires major adjustments of emergency service routes, as illustrated by a recent (2001) collapse on Route 117 in Lincoln.

The list of anecdotal illustrations could easily be extended by additional historical observations and may also be enriched by preliminary results from the CLIMB study and related research efforts. For example,

- water stress already exists in the region because of overuse in some basins, with the Charles and Ipswich rivers routinely becoming dry in some reaches in the summer;
- non-point source bacteria concentrations in the Mystic River basin are expected increase 10 times or more under wet weather conditions because of combined sewer overflows and other sources of wet bacteria.
- increases in sea levels (see Figure 2) may result in land loss (Table 1), add stresses on existing shore protection structures, impact sediment movement, exacerbate storm surges, and increase damages from storms.
- if annual temperature increased 2 degrees C, then potential evapotranspiration will increase by 6 percent, and streamflow decrease by 8 percent (Kirshen and Fennessey 1995).

It is the combination of historical evidence, anecdotal observations and mounting scientific support that are increasing awareness among stakeholders in the region about potential climate impacts. Within this context, the CLIMB (“Climate’s Long-term Impacts on Metro Boston”) project attempts to analyze existing information and substantiate scientific research, while at the same time bridgning the gap between the science and policy of climate change in the region.



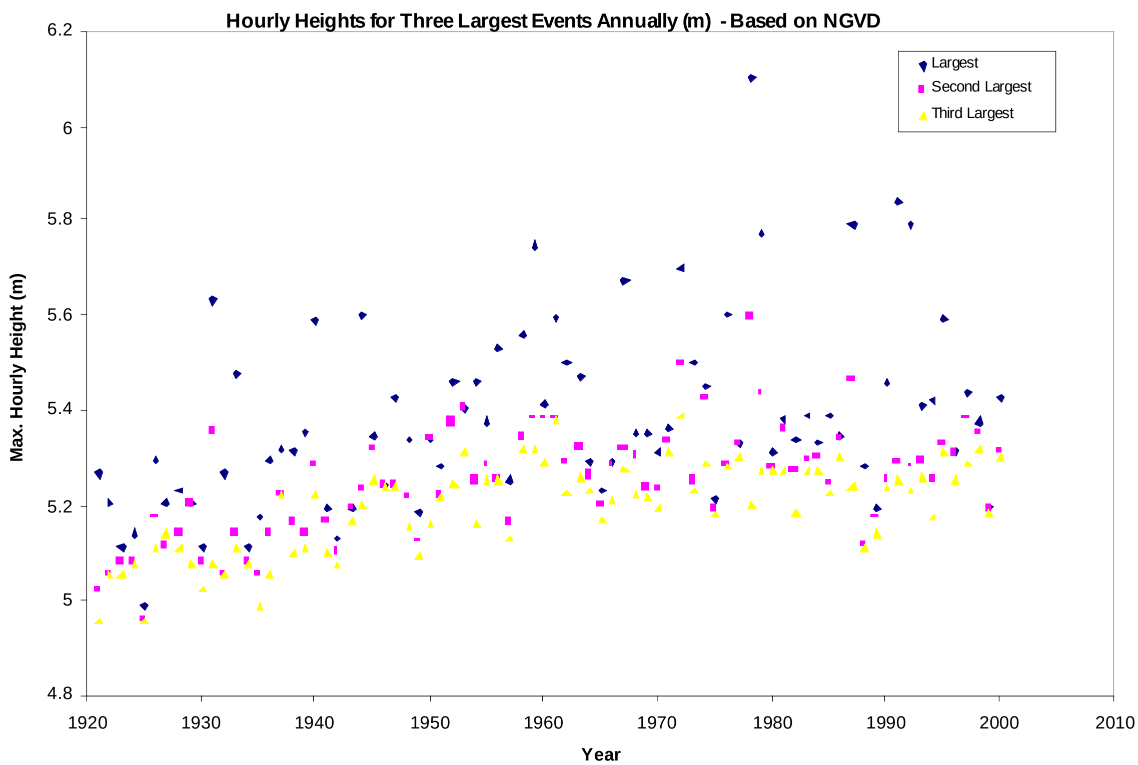


Figure 2. NOS Gage Data Boston

Town	Area at Risk (hectares)	% Land Area Flooded	Town	Area at Risk (hectares)	% Land Area Flooded
Beverly	14.5	0.36	Marblehead	11.6	0.99
Boston	92.9	0.74	Marshfield	410.1	5.56
Braintree	3.3	0.09	Medford	6.8	0.32
Chelsea	8.8	1.56	Milton	13.1	0.39
Cohasset	18.5	0.72	Nahant	12.8	3.97
Danvers	8.2	0.24	Peabody	0.5	0.01
Duxbury	55.4	0.90	Quincy	44.0	1.01
Essex	119.9	3.27	Revere	35.7	2.33
Everett	6.8	0.78	Rockport	21.2	3.80
Ipswich	225.9	2.60	Salem	22.3	1.06
Gloucester	112.4	5.48	Saugus	17.0	0.60
Hingham	41.8	0.72	Scituate	116.2	2.61
Hull	49.0	6.38	Somerville	2.0	0.18
Lynn	7.3	0.26	Swampscott	2.2	0.28
Malden	0.4	0.03	Weymouth	20.7	0.47
Manchester	15.0	0.74	Winthrop	20.0	3.89

Table 1. Percent Permanent Land Lost from One Meter of Sea Level Rise

2. Approach of the CLIMB Project

The CLIMB project is a multi-year endeavor to
(1) document and analyze present infrastructure systems,
(2) investigate the multidimensional climatic, socio-economic and technological driving forces behind infrastructure change in the region,
(3) determine the integrated direct and indirect effects of climate change on infrastructure and its services, using dynamic modeling and scenarios,
(4) identifying present policy and research needs to ease transition to changed climate, and
(5) collaborate with stakeholders.

The project is supported by US-EPA's Office of Research and Development and carried out jointly by scientists and engineers at Tufts University, the University of Maryland's School of Public Affairs, and Boston University's Center for Transportation Studies. Partners in the project are the Metropolitan Area Planning Council (MAPC) – the local planning agency in the region – and various stakeholder and project advisory group, as well as more than 200 stakeholders from the public, private, and non-government sectors.

Four infrastructure systems and their relationships to each other and to socioeconomic development, technological change and human health are distinguished:

- transportation and communication;

- drainage, and coastal and riverine flood management;
- water supply and wastewater treatment; and
- energy.

The focus and approach of the CLIMB poject make this a unique endeavor in the nation: The nature of the problems addressed in the CLIMB project and the goals of bridging the gap between investment and policy making on the one hand, and natural, social and engineering sciences on the other hand, require that stakeholders are involved throughout the project. The intent to capture the dynamics of a highly complex system – with uncertainties in data and surprises about future trajectories associated with every aspect of the project – make it necessary to chose a transparent modeling approach that facilitates that the ramification of alternative assumptions are readily explored by project participants and that consensus on mitigation and adaptation strategies can be generated. The upshot of all this is that significant emphasis needs to be placed on the *processes* by which analytical, modeling and policy results are achieved . This focus on process is quite different from many other climate change studies which predominantly concentrate on forecasts of future states of the world and then raise considerable debate about the reliability of these forecats after the study has been conducted. Process orientation manifests itself in two central and closely related components of the CLIMB project – stakeholder involvement at all thages of the project, and dynamic modeling – each of which are discussed in more detail below. Rather than "forecasting", CLIMB has the goal of consensus generation about the relationships among potential climate futures, their impacts on the region, and possible response strategies.

2.1 Stakeholder Involvement

The roles of experts and modelers in investment and policy making has often been perceived as "speaking truth to power". That perception is being challenged by an increased realization how prevalent and influential subjective value judgments are in modeling (see, e.g. Shackley and Wynne 1995), how peer review of science and modeling self-select and reinforce the preferences of modelers for a narrow range of modeling and quality criteria (Pahl-Wostl et al. 1998), and how fundamental uncertainties and surprises are to our ability to use models for decision making (Funtowicz and Ravetz 1990). That realization has lead some to re-interpret the role of expert advise and formal models as a component of social discourse in which researchers, policy makers and the public form "mutual learning systems" (Robinson 1992a, b). Evaluation of the role of modeling in the investment and policy debate will then require an increased focus on procedural rather than simply substantive issues (Faucheaux et al. 1995). Stakeholder involvement can be a key component of research and modeling that foster mutual learning. However, stakeholder involvement is sometimes perceived as "endangering" the actual research and modeling components of a project and may "get in the way" of identifying long-term viable management and policy strategies for a number of reasons:

- Research objectives may be jeopardized because researchers attempt to address those questions that are of direct concern to stakeholders and abstain from dealing with issues that are more complex, more subtle and less tangible to stakeholders.
- Methodologies may be impoverished because stakeholders may not appreciate or may not be able to evaluate sophisticated, scientific problem solving methods.

- The participating group of stakeholders may be strongly self-selected, and as a result may be a biased sample of the public at large. Any input into the research project, and consensus among stakeholders generated on the basis of the science, may be dismissed in later stages of management and policy decision making as being not representative of, or relevant for the larger group of constituents to which the decisions apply.
- Involving stakeholders throughout a project and maintaining their interest and active participation is costly in terms of time and money. These cost occur not only among the scientists who continue to struggle for continued stakeholder contributions, but also among stakeholders who devote time, effort and resources to a project. One likely result is "stakeholder fatigue" – another is "researcher fatigue".

While recognizing these potential drawbacks to stakeholder involvement, the CLIMB research team has made stakeholders and integral part of the project, at least for the following reasons:

- There is an inherent, democratic value in including in a research project those segments of society who are ultimately affected by the decisions that are based, at least in part, on that research. The responsibility of researchers to include stakeholder involvement is the greater the more a project attempts to address issues that are of direct relevance to the lives of stakeholders, and the more the project relies on funds made available by the tax payers.
- Stakeholders can possess valuable knowledge that may be difficult to access by researchers. Stakeholder involvement can thus not only broaden the information base on which science operates, but can provide a powerful means for "ground-truthing" of data, models, and model scenarios.
- Different institutions typically have taken it upon themselves to be advocates for individual segments of society, economy or environment. By including in science and decision making stakeholders from a range of social, cultural and economic institutions, alliances can be forged to help disseminate research results, and help the broader public make the connection between a project and people's own personal and professional lives. Leveraging the interest of institutions in disseminating select pieces of information is particularly valuable in projects that tackle highly complex human-environment systems in interaction. For example, the topic of climate change can become less abstract and more tangible to individuals if implications for people's economic welfare or personal health can be identified, and if decisions of individual firms and consumers can be influenced.

By including stakeholders at the outset of, and throughout a project, buy-in into research design, use of data, and generation of scenarios can be better achieved than by excluding them from the research and modeling process altogether. As a consequence, stakeholders may be more prone to support policy conclusions drawn from a project if they have been involved with the project. Subsequent compliance, enforcement or monitoring cost may be reduced.

2.2 Dynamic Modeling

The emphasis on the *process* by which models of climate impacts on metropolitan infrastructure are created and interpreted, and the inclusion of stakeholders in this process call for a dynamic modeling approach (Hannon and Ruth 2000, Ruth 2001) in which (a) the dynamics of interrelated system components are explored in space and time and (b) in which opportunities are created for a dynamic interaction between researchers and stakeholders on the one side, and the model and model results on the other side. Such a dynamic modeling approach afford participants with opportunities to

- *Guide data collection*. (The fact that a model may be sensitive to one set of assumptions rather than another also can be exploited for data collection purposes. If model results do not significantly change, for example, under alternative assumptions about a parameter's value or an initial condition, then effort may be spent better on other aspects of the model rather than collecting more data and information on that parameter or initial condition. Unfortunately, a lot of data regularly gets collected before its need, use, or potential value within the context of a model is known.)
- *Share knowledge*. (A graphical prgramming language is used to make the structure and functioning of the model transparent, to give stakeholders opportunities to understand the deeper assumptions in the model, to show to stakeholders their own personal contribution to the model itself, and thus make stakeholders the intellectual owners of the models in a very different way as if they simply had hired a consultant.)
- *Lay open and reconcile differences in viewpoints among stakeholders.* (Bringing together a diverse group of stakeholders therefore often requires that special attention is given in the modeling process to issues that span across different hierarchical levels of system organization, and across multiple boundaries in space and time.)
- *Create systems memory*. (At each step of model development, the model contains a representation of their current understanding of a system. They can revisit that model at will, use it to focus and refine investigation into, and understanding of individual system aspects, use it to broaden their viewpoint by enlarging system boundaries, and to engage themselves in a continuous learning process that is both guided by, and guides model development.)
- *Learn "normal" system behavior*. (Decision makers may see smooth dynamics, or perhaps erratic transitions from one system state to another. Knowing what is "normal" for a system as a whole may help decision makers maintain their calm and avoid choosing actions that may have undesired consequences.)
- *Compare model behavior with desired system behavior and thus identify ways to optimize system performance*. (System interventions, such as investment or policy decisions may be identified and prioritized with respect to their ability of achieving a goal.)
- *Generate consensus*. (If stakeholders contribute to the model at all stages of model development, if they see how the model captures the dynamics of the system of interest with increasing accuracy, and if they see how different influences on the system translate into different outcomes, then the likelihood that they agree with a particular type of policy decision can be significantly increased. They can then concentrate on the economic or environmental cost and benefits that are associated with alternative actions. And they can do this quickly any time the system evolves. Dynamic modeling thus becomes a key tool for adaptive leadership.)

3. Information Management, Modeling, and Scenario Development

Each of the infrastrucutre systems analyzed and modeled in the CLIMB project are described by a set of state variables, pressures that are exerted on the status of the system, impacts that those pressures have on system performance, and potential response strategies to affect system performance. The variables describing each individual infrastructure system are related with each other and related across systems with the help of a dynamic computer model as illustrated in Figure 3. A set of indicators are developed to assess the ability of each individual infrastructure system to provide services over time, and the impacts that climate change and other drivers have on individual infrastructure systems and their collective performance.

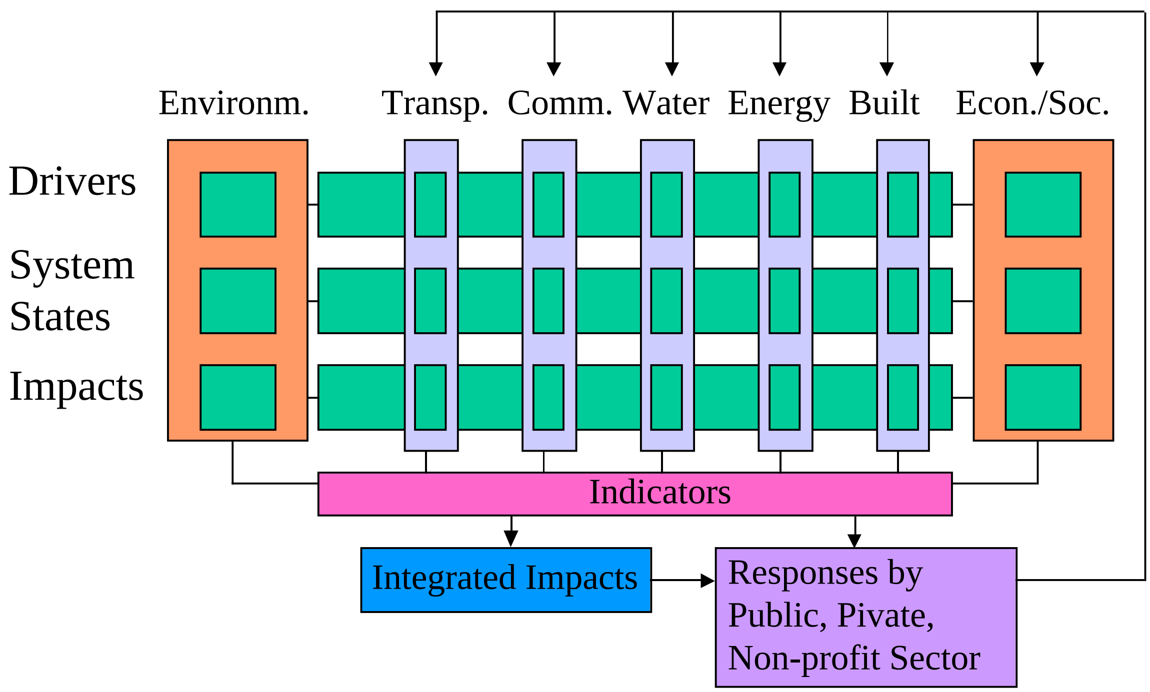


Figure 3. Sectoral and Integrated Analysis of Climate Impacts on Urban Infrastructure Systems and Services.

Since future climate, socio-economic, and technological (SET) changes are unknown, scenarios of these are input for each subarea for each year for the period 2000 to 2100. The impacts of the present climate and different changing climates are simulated annually on infrastructure systems and services under three different, internally consistent SET scenarios. Since yearly climate conditions vary from year to year even without climate change, different sequences of yearly climate conditions are simulated for each separate climate change scenario. If sufficient sequences are simulated (Monte Carlo simulation), then the aggregate output of all the sequences is the expected impacts under a particular climate change scenario given a SET scenario. The selection and generation of different yearly climate conditions with and without climate change are discussed in more detail below.

The annual performance of every type of infrastructure system is sensitive to certain set of annual climate parameters. For example, water supply systems are dependent upon mean annual streamflows and temperatures, energy systems upon total heating degree days and cooling degree days, health systems upon lengths and numbers of heat and cold wave periods, transportation systems upon closure based upon flooding, and building and content losses upon the extent of coastal storm surges. For each year of the historic climate records in metro Boston, we have determined the values of these climate parameters. Thus, if we simulate one SET scenario with this record, we would have the response of that scenario to an exact repeat of the present climate over the length of the historical time series. To develop many possible representative time series of the present climate so that Monte Carlo simulation techniques may be used to remove sensitivity to the present natural variability of climate events, and to extend our climate record from the present length of approximately 50 years to 100 years, we use moving block bootstrapping (Vogel and Shallcross, 1996). This is a nonparametric statistical method that maintains the probability relationships both within years and over years of time series values. To build the time series used in the Monte Carlo simulation for present climate conditions, sampling with replacement from the existing time series of annual climate events is used until the desired number of time series is obtained. To model time series of climate change scenarios, trends of climate changes are applied to the set of time series representing the present climate. For example, if sea level rose by 1 percent per year, each year the sea level of each time series representing the present climate would be increased by one percent. This set of changed climate time series can then be used to explore the impacts of changing climate upon on SET scenario.

Socioeconomic scenarios are created from population, household and economic forecasts by MAPC (MAPC 2001). These forecasts are available at the community level until 2020 and are used to down-scale the corresponding socioeconomic variables available from the New England Climate Assessment, which contains scenarios until 2100.

Technology scenarios assume diffusion of various advanced engineering practices in the region. The technology scenarios are thus closely related to behavioral and policy variables (Table 2), creating the challenge of making all exogenous drivers consistent with each other across time and space.

The effects of alternative assumptions about future climate, socioeconomic characteristics and technological potentials in the region are assessed, among others, with respect to various cost to the region – infrastructure replacement and repair requirements, loss of services, and cost of adaptation (Figure 4). Many of these costs can be, and are, expressed in monetary terms, others are not. Examples of non-monetary costs to the region include increases in mortality and morbidity, infrastructure reliability, and land loss.

As the various exogenous drivers influence the various internal dynamic of infrastructure systems – for example, their reliability in providing services to the region – different investment and policy responses may occur (Table 2). The “Ride it Out” scenario in essence assumes that no adaptation to climate change occurs. In contrast, the “Green” scenario assumes conscious, sustainable, responses to observed trends, as well as pro-active implementation of policies and technologies in efforts to counteract, and prepare for, adverse climate impacts. The “Build Way Out” scenario assumes that replacement of failed systems is undertaken and susceptible systems are protected. For example, in the case of sea level rise, the “Ride it Out” scenario would be characterized by a lack of attempts to protect land, and in extreme cases, to simply abandon it. In contrast, “Build Way out” adaptation responses may include a set of engineering measures that help to accommodate climate change (e.g. to move living and work spaces in building to higher floors, to place entrances at higher levels, or to elevate structures), protect against it (e.g. holdback the sea with structures (seawalls, barriers, pumps), or foster beach nourishment (IPCC 2001, NAST 2000). To judge which strategy to pursue will require estimates of the relative costs of action compared to inaction. Preliminary estimates indicate that, for example, protecting coastal shoreline will cost approximately $3,000 per foot. Aside from monetary measures, a host of longer-term behavior variables need to be assessed as well, such as the false sense of security that may be created by various accommodation and protection measures, which may result in more building development along coastlines (NAST 2000).

Expert judgement and interaction with stakeholders are key to “ground-truthing” the different assumptions that underlie exogenous drivers and their consistency with each other. Expert contributions are also invaluable in identifying relevant data and information, and in making the various scenarios operationally meaningful guides to future investment and policy decisions. To facilitate dialog with stakeholders, each of the exogenous and endogenous components of the model are presented to them by topic, and interrelationships are explored collectively with them in a series of meetings that focus on internal consistency of the model, and consistency of the resulting cost estimates with historic experience, expert judgments and anticipation (Figure 5).

	Exogenous Drivers			
Scenario	**Demographic**	**Economic**	**Technology**	**Policy**
"Ride it Out"	Same as current MAPC scenarios of continued sprawl, low population growth rate, major growth at fringes and outside of the region.	Same employment by sector as current MAPC scenarios	Low penetration rate of "green" and innovative technology by sector.	Present trends in region continue; there are no adaptation actions; current policies continue to maintain existing land use, energy use, water resource management, flood control and transportation practices
"Green"	Same population growth as "Ride it Out" scenario, but more centralized.	Same as above.	High rate of adoption of "green", innovative technology	Restriction on construction locations; stronger building codes; natural hazards zoning; no more sea walls except for major commercial areas; emphasis on more centralized development.
"Build Way Out"	Same as "Ride it Out" scenario.	Same as "Ride it Out" scenario.	Same as "Ride it Out" scenario.	Same as "Ride it Out" scenario, but replace and protect systems as they fail.

Table 2. Three CLIMB Model SET Scenarios

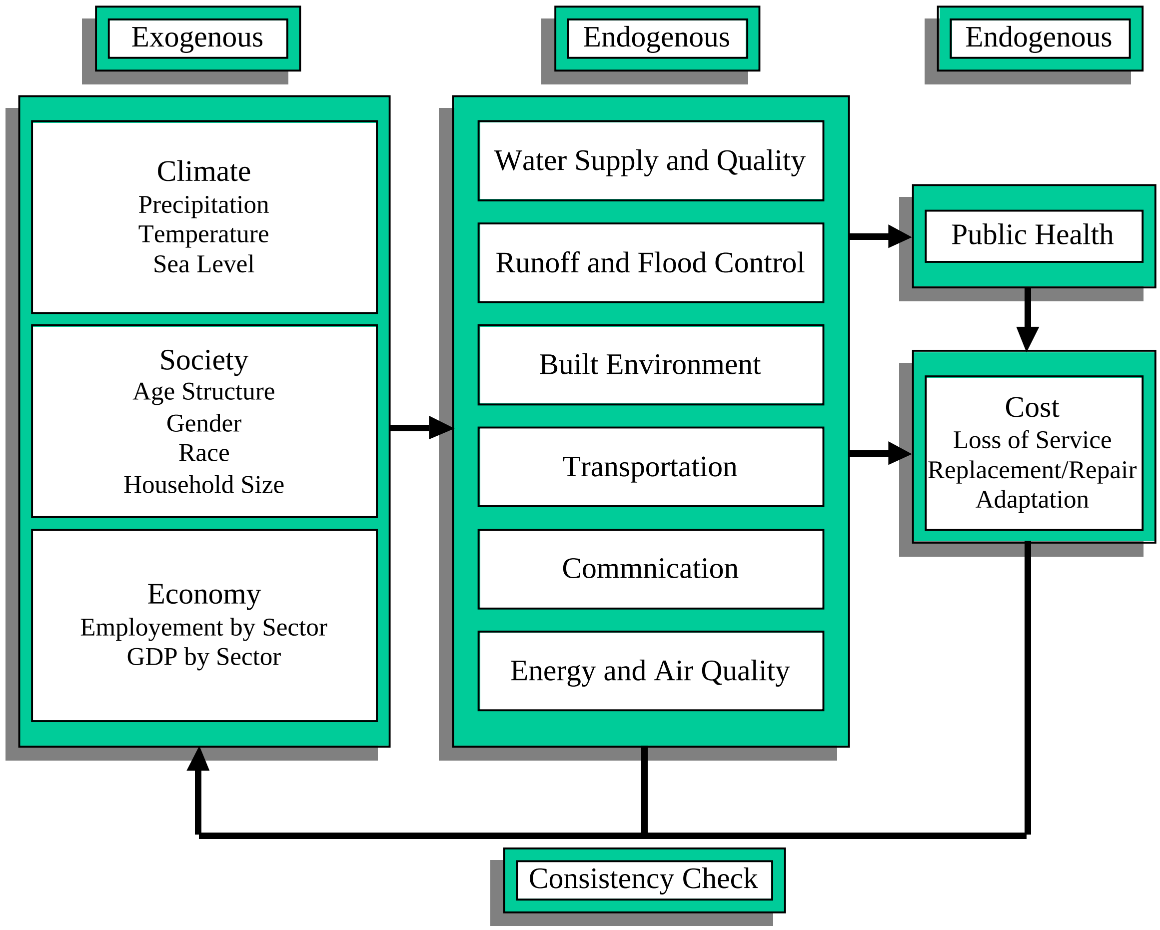


Figure 4. Structure of Dynamic Modeling Component of CLIMB

The following mechanisms are set in place to ensure that neither the science is compromised in a project that is so heavily oriented towards outreach and decision support, nor the ability of stakeholder's to contribute to, and learn from the research is hampered. An independent Project Advisory Group (PAG) has been created to periodically provide feedback on the CLIMB's natural, social and engineering science components, the computer model, and scientist-stakeholder interaction. A Stakeholder Advisory Group (SAG) has been created to ensure that stakeholders are drawn from a wide range of backgrounds and that participation of individual members or groups does not skew the stakeholder process. These groups are periodically convened in small working group sessions, brown-bag lunches, and day-long workshops. Depending on the type of meeting (working groups, luncheons, workshops) and purpose (brainstorming, technical review, critique of analyses and model components, etc.), anywhere between 5 and 150 participants are usually present. These meetings have helped to focus and substantiate many of the infrastructure system aspects that are analyzed and modeled in the CLIMB project, and have helped create a forum and environment for mutual learning about climate impacts and potential response strategies in the region. The meetings, together with the model, have also begun to highlight a set of challenges for research, education and decision making, which are discussed below.

4. Methodologies and Results

The following subsections briefly describe results of analyses for each of the main CLIMB project components. More detailed, sector specific background on methodologies, model assumptions, data, and results are available at http://www.puaf.umd.edu/faculty/papers/ruth.

4.1 Coastal and Riverine Flooding

Table 3 presents average a set of results from one of 100 bootstrapped model scenarios, assuming, alternatively that a) there is no climate change, b) sea level changes are only affected by subsidence and c) both subsidence and climate change alter sea levels in the region. Since the forecasts are based on historical data and no 500-year flood occurred over the period of past observations, the bootstrapped model likewise does not show any 500-year floods over the simulated 100 years. However, the results clearly indicate that the interpretation of a 100-year flood needs to change. What is currently considered a flood with an expected occurrence of once in 100 years may happen even more frequently than once every 10 years, if subsidence and climate change occur.

Overlaying in a areal photographs and a Geographic Information System (GIS) flood zones for the region with data on land use and infrastructure (e.g. Figure 5 for the case of Boston Harbor), can help identify structures that are most susceptible to flooding. Combining that information with emergency management and insurance data for these structures can provide valuable information on potential damages within subregions of the CLIMB study area and the region as a whole (e.g. Table 4) under different management strategies.

	No Change			Subsidence			Subsidence and CCC		
Year	Zero Damage Threshold	100-Year Flood	500-Year Flood	Zero Damage Threshold	100-Year Flood	500-Year Flood	Zero Damage Threshold	100-Year Flood	500-Year Flood
2000-2025	4.4	100	N/A	4.4	100	N/A	3.4	71.4	N/A
2026-2050	4.6	67.5	N/A	3.5	67.5	N/A	1.6	25.2	N/A
2051-2075	5.1	80.6	N/A	3.4	48.0	N/A	1.0	7.08	N/A
2076-2100	4.7	92.5	N/A	2.5	38.4	N/A	1	3.7	N/A

Table 3. Sample Results for Coastal Flooding Events.

Figure 5. CLIMB Flood Zones for Boston Harbor.

Run	Total Residential Damage	Total Commercial /Industrial Damage	Emergency Costs	Total Adaptation Cost	Damages Avoided	Net Benefits
Base	1205	4305	937	0	0	-6447
RIO	3563	13525	2905	0	0	-19994
Green	756	3393	587	1766	13593	7091
BYWO	1091	3984	863	3462	12014	2614

Table 4. Cost-Benefit Overview for 100 Averaged Bootstrapped Scenarios.

The results clearly indicate that anticipatory management strategies (e.g. relaocation of economic activity from flood plains and retrofitting of existing structures with the best available technology) are more cost-effective than “riding climate change out” or “building ones way out” (e.g. by building more and higher sea walls).

4.2 Flooding and Transportation

Area flood maps (Figure 6) can be combined with maps of the region's surface transportation system (Figure 7) to identify specific routes that are likely to be interrupted in case of flood events. Detailed transportation models of the region can then identify changes in model and route choice and calculate changes in the number of trips, distances traveled, average speeds, and more (Table 5).

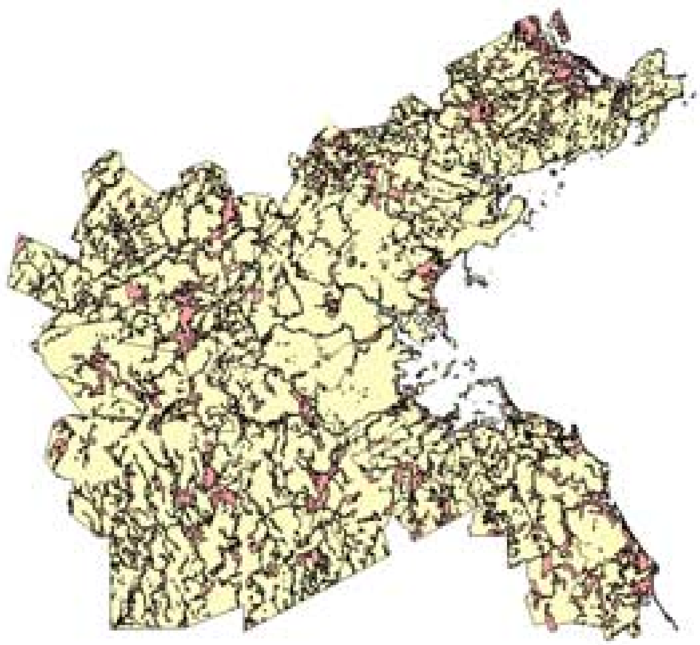


Figure 6. FEMA (Federal Emergency Management Agency) Flood Plain Map for the CLIMB Region.

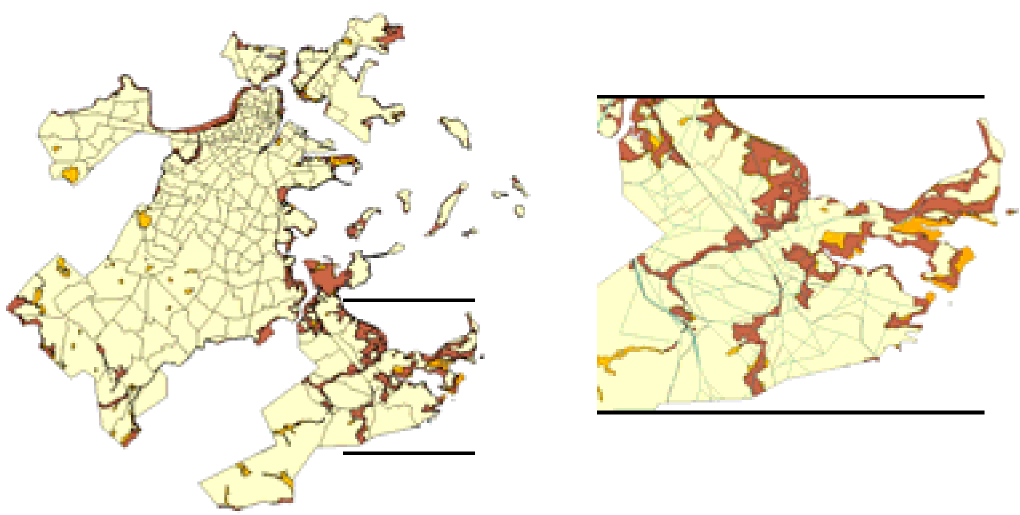


Figure 7. Overlay of Flood Plains and Transportation Network in one of Seven CLIMB Sub-regions.

	Base	Riverine (Change) 100	500	Coastal (Change) 100	500	Combined (Change) 100	500
Loss of Routes	0	445	673	196	236	642	908
Number of Trips (‘000)	16,455	-69	-165	-165	-185	-193	-225
Vehicle Miles (‘000)	158,717	1,824	3,389	-1,711	-2,079	1,321	3,178
Vehicle Hours (‘000)	4,562	198	346	-44	-54	206	380
Average Speed	34.79	-1.06	-1.77	-0.04	-0.05	-1.23	-2.04

Table 5. Model Results for Flooding Impacts on Area Transportation.

4.3 Energy Demand

The CLIMB energy demand module calculates weather-sensitive energy demand as a function of ambient temperatures. In a first step of the analysis time series data of energy consumption in the residential, commercial and industrial sectors is used together with demographic and employment data, energy price data, length-of-day information and temperatures to estimate the region’s balance point temperature (Figure 8). In a second step, sector-specific balance point temperatures are used to calculate heating and cooling degree days for each sector. In the third step of the analysis a fixed effects regression model is employed to statistically identify energy demand – temperature relationships (Tables 6 and 8). These statistical relationships are then used in conjunction with bootstrapped climate data to explore potential future energy consumption under different climate scenarios. The results in Figure 9 – 18 show energy consumption in the residential and commercial sectors for 2 sets of climate assumptions – one from the Hadley model the other from the Canadian Climate Centre. Each of these climate models have been used to generate separate sets of 100 bootstrapped forecasts, and are averaged separately. Since energy demand by the industrial sector is not noticeably climate sensitive, no results for that sector are reported here.

Differences between Hadley model Canadian Climate Centre model results are the consequence of different heating and cooling day profiles that result from the two models. Since not all changes in energy consumption are attributable to climate change – some are the result of proliferation of energy-using equipment, changes in life styles, etc. – each graph in Figures 9 – 18 shows the percentage change in energy demand that is due to climate change.

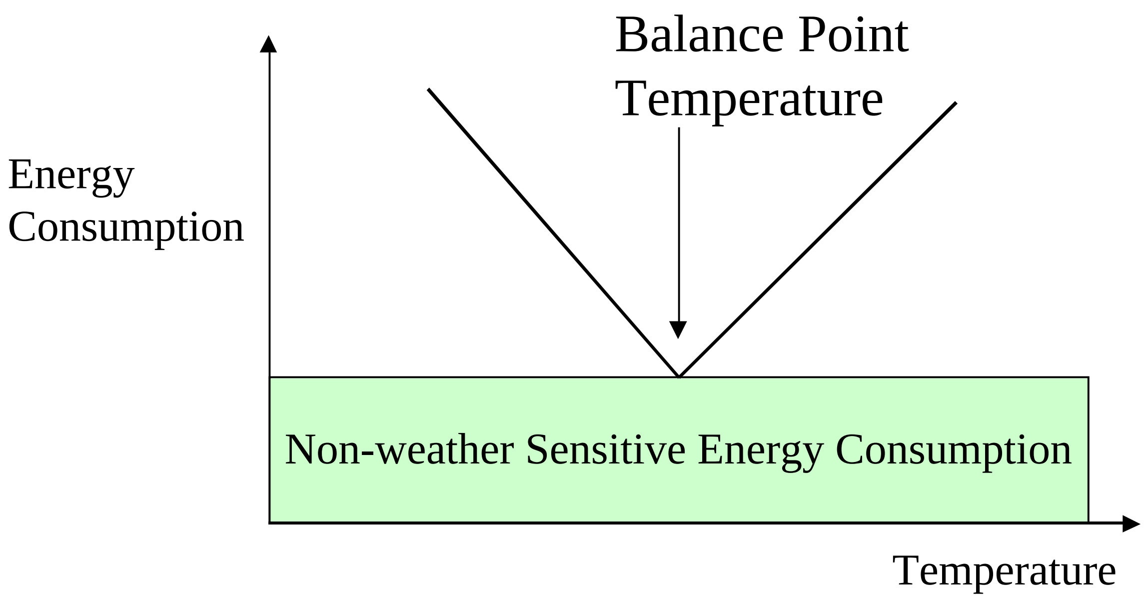


Figure 8. Determination of Balance Point Temperature and Weather-sensitive Energy Demand.

	Log monthly electricity per capita (kWh / month)
Constant	5.971958***
Annual Trend	0.0030124
Hours of Daylight	-0.0101859***
Monthly HDD (Base 60°F)	0.0004722***
Annual Trend HDD (Base 60°F)	-0.00000545
Monthly CDD (Base 60°F)	0.0003818***
Annual Trend CDD (Base 60°F)	0.0000456***
Log Electricity Price	-0.3340608***
R^2	0.8931
Durbin-Watson statistic	1.8561

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

Table 6. Residential Electricity Demand

	Log Natural Gas per capita (cubic ft / month)	Log Heating oil per capita (gallons / day / month)
Constant	7.064334***	4.194367***
Annual Trend	0.0111487	-0.0789409***
Monthly HDD (Base 65°F)	0.0017359***	0.001334***
Annual Trend HDD (Base 65°F)	0.00000884	0.000033***
Log Natural Gas Price	-0.3956136***	
Log Heating Oil Price		0.352137***
R^2	0.8831	0.9223

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

Table 7. Residential Heating Fuels Demand

	Log monthly electricity per employee (kWh / employee)	Log monthly natural gas per employee (Cubic feet / employee)
Constant	6.543654***	6.7899***
Annual trend	0.038953	.0081153
Hours of Daylight	-0.012406***	
Monthly HDD (Base 55°F)	0.000195***	
Annual trend HDD (Base 55°F)	-0.00000821	
Monthly CDD (Base 55°F)	0.0003468***	
Annual trend CDD (Base 55°F)	0.0000861	
Monthly HDD (Base 60°F)		0.00097***
Annual Trend HDD (Base 60°F)		0.00000118
Log Electricity Price	-0.0841782**	
Log Natural Gas Price		0.14944
R^2	0.9039	0.7491
Durbin-Watson statistic	2.0088	2.0082

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

Table 8. Commercial Energy Demand

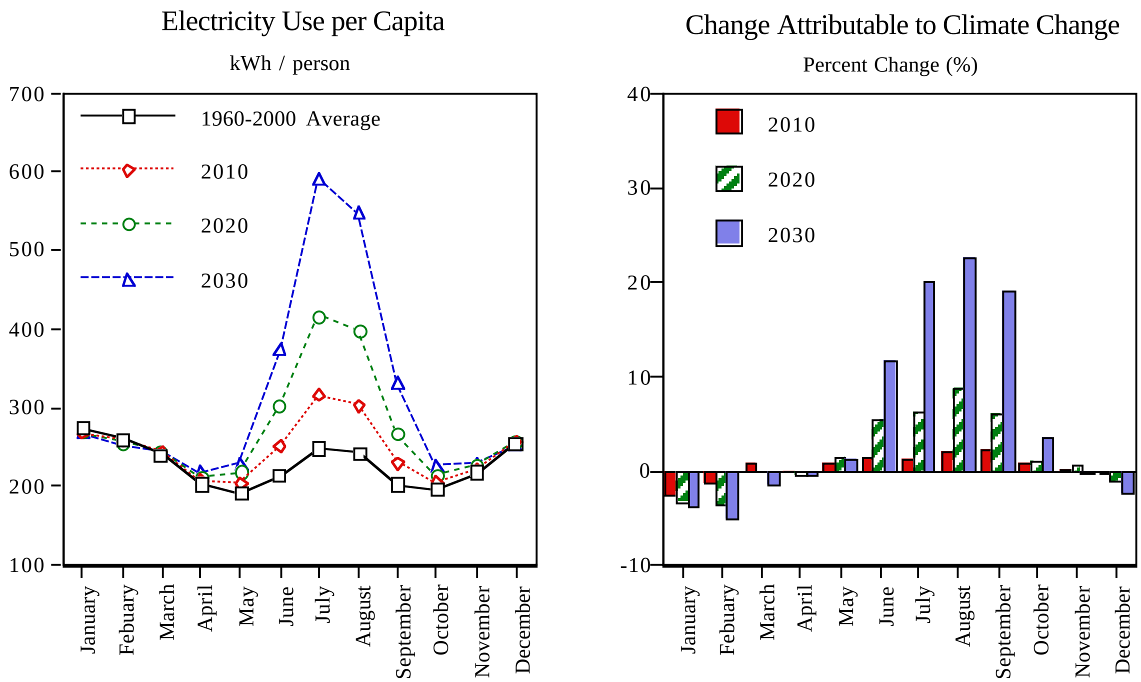


Figure 9. Residential Electricity per Capita Under Canadian Climate Centre Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

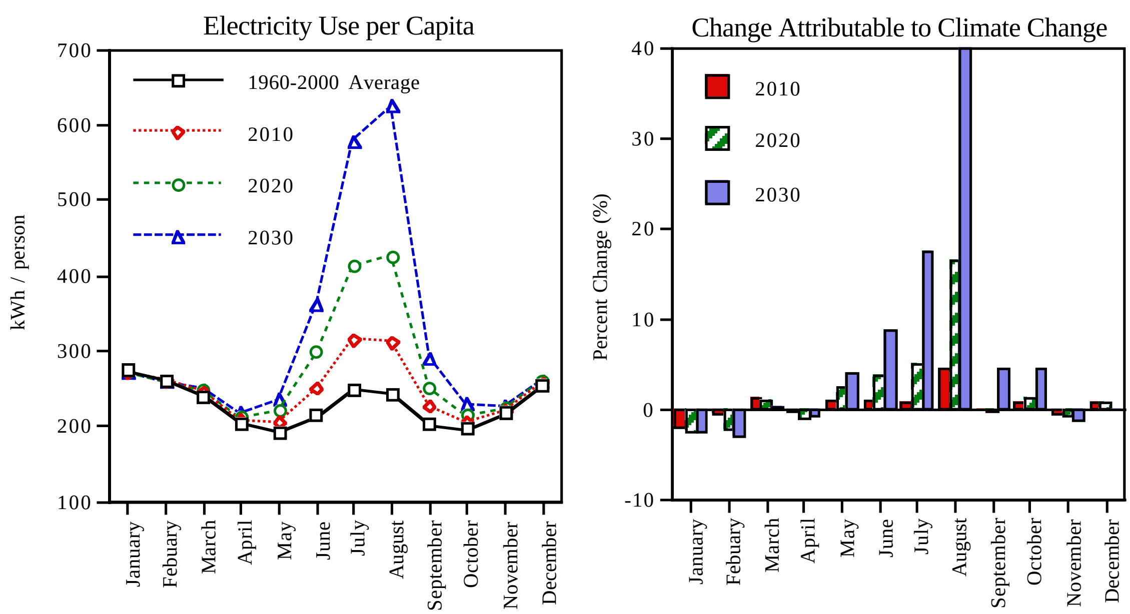


Figure 10. Residential Electricity Use per Capita Under Hadley Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

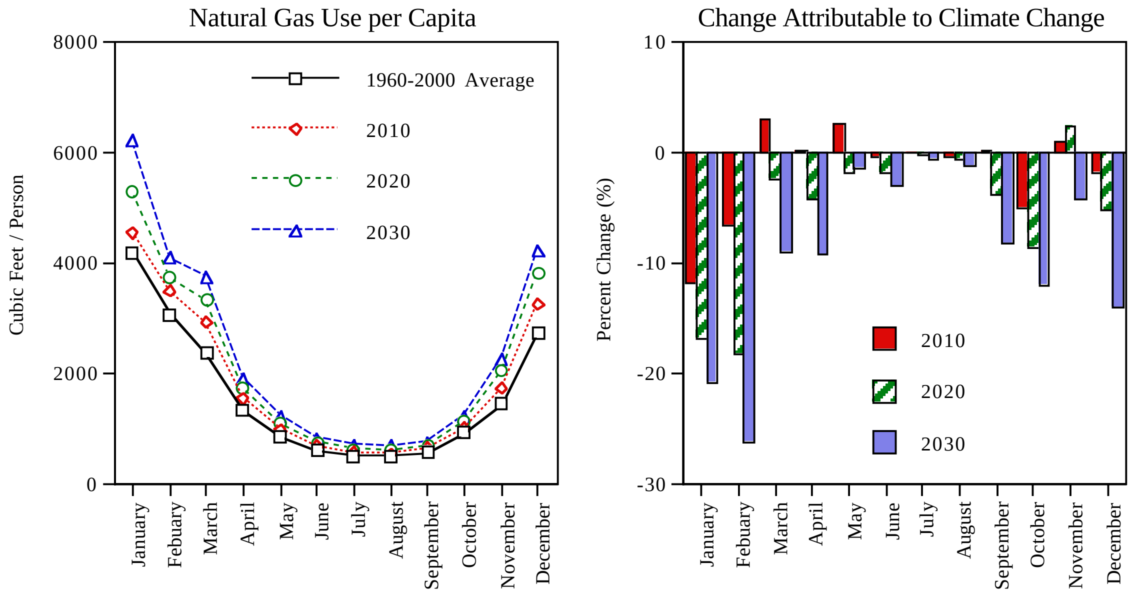


Figure 11. Residential Natural Gas Use per Capita Under Candian Climate Centre Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

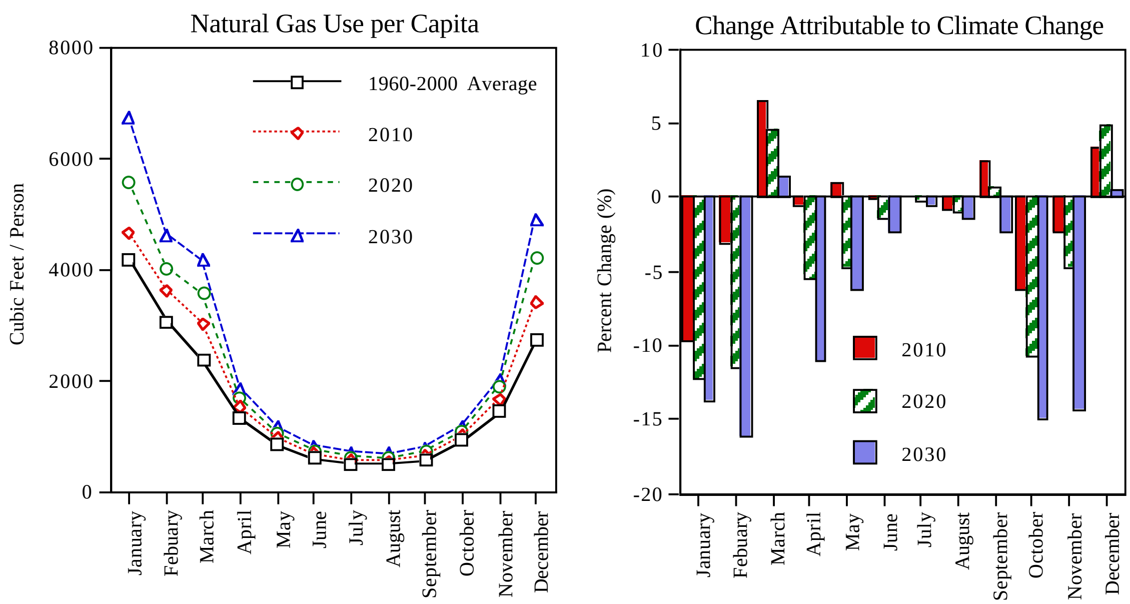


Figure 12. Residential Natural Gas Use per Capita Under Hadley Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

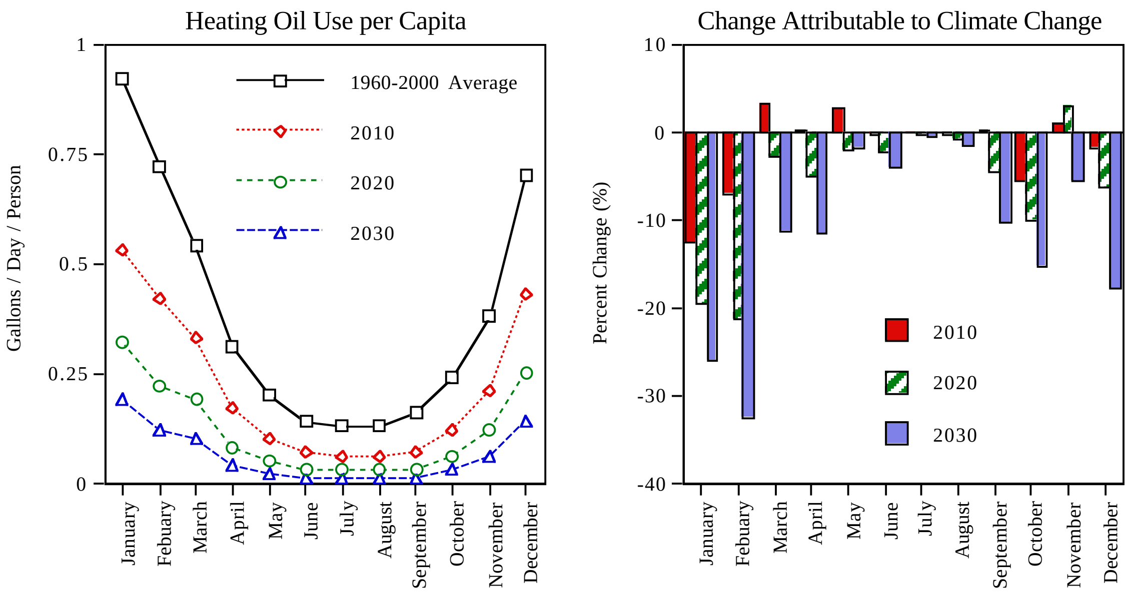


Figure 13. Residential Heating Oil Use per Capita Under Canadian Climate Centre Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

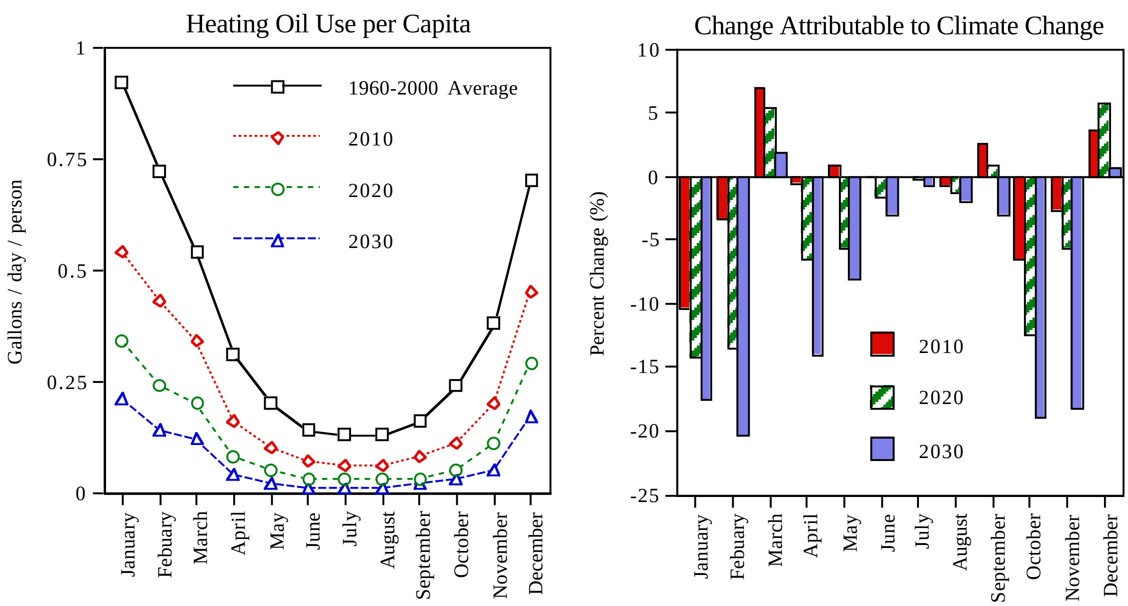


Figure 14. Residential Heating Oil Use Capita Under Hadley Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

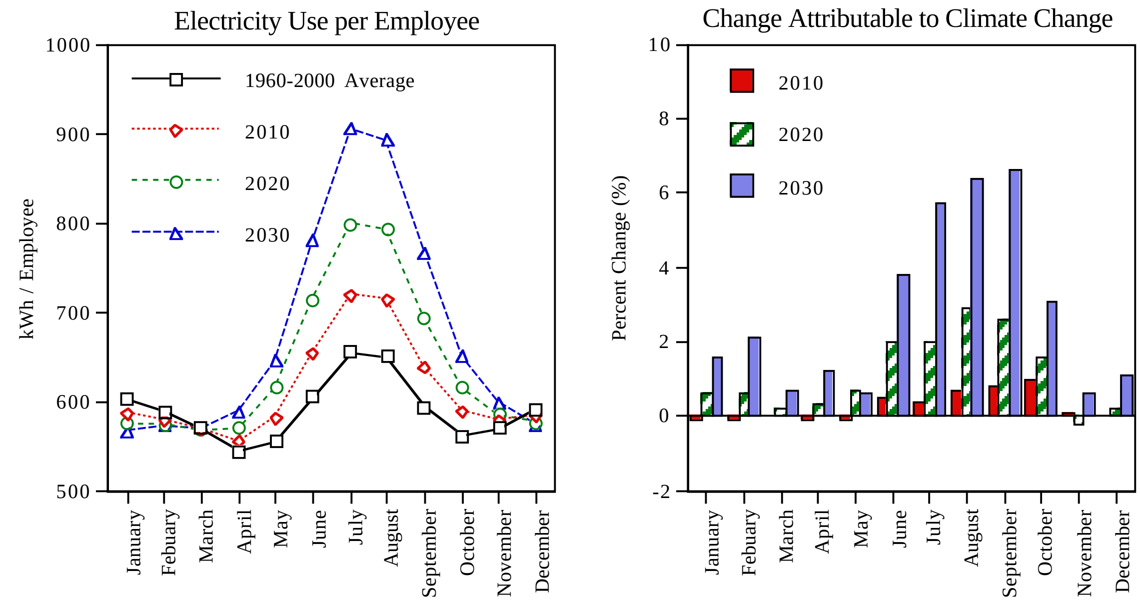


Figure 15. Commercial Electricity Use per Employee Under Canadian Climate Centre Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

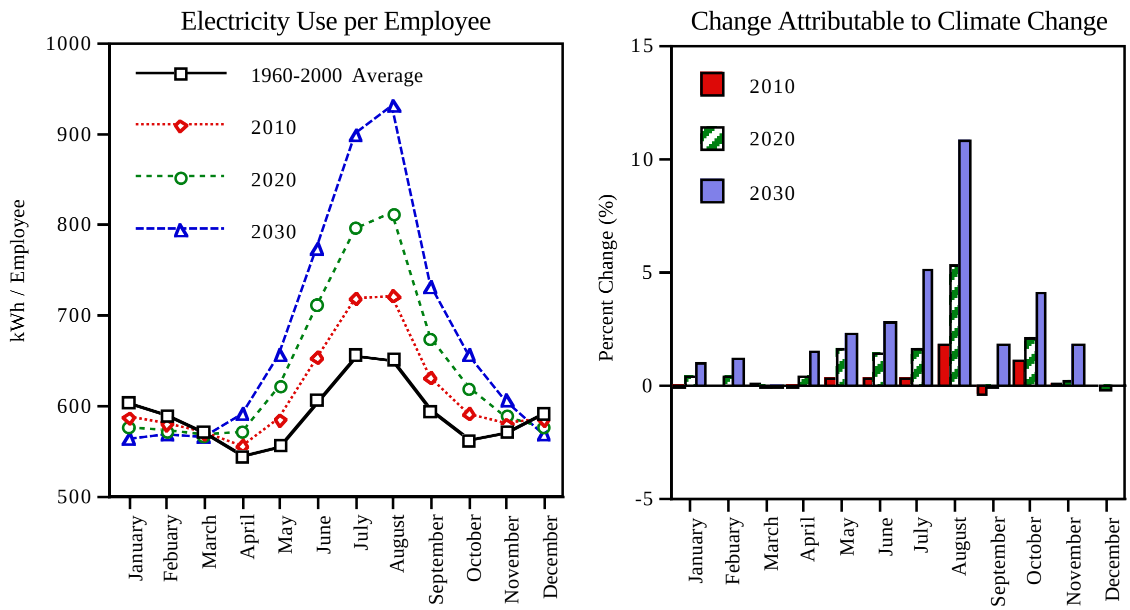


Figure 16. Commercial Electricity Use per Employee Under Hadley Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

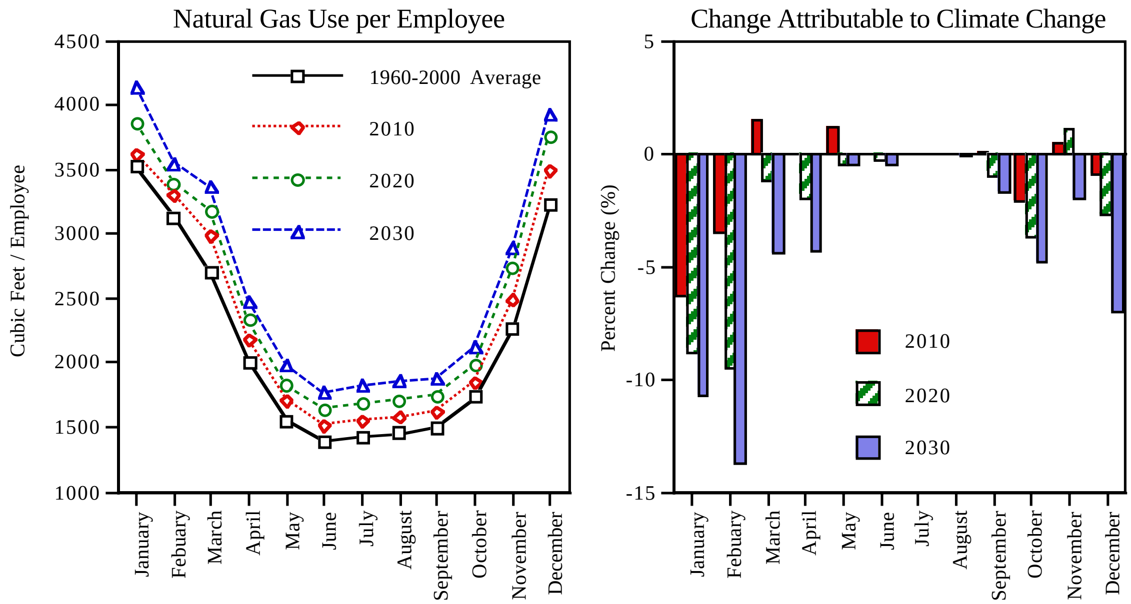


Figure 17. Commercial Natural Gas Use per Employee Under Canadian Climate Centre Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

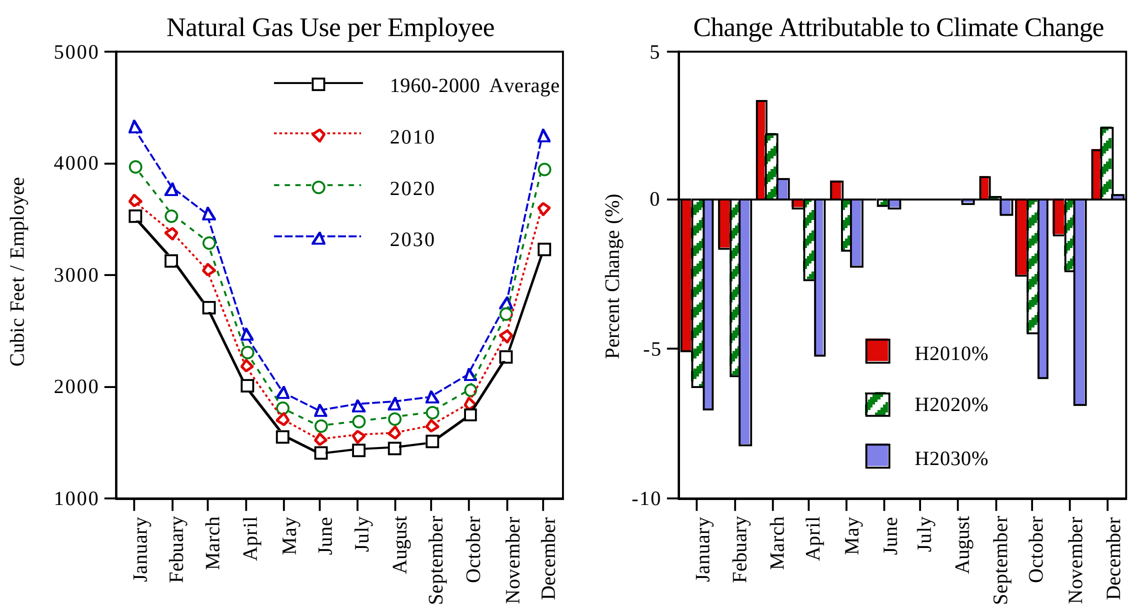


Figure 18. Commercial Natural Gas Use per Employee Under Hadley Climate Scenarios (Results are Averages Across 100 Bootstrapped Climate Scenarios).

The results clearly indicate potentially significant changes in seasonal energy use profiles as well as notable changes in the region's fuel mix. Also, although total energy demand will be reduced by climate change, significant increases are likely to occur in those months which already experience peak demand. Increases in peak demand may thus necessitate infrastructure investments today to address potential shortages in the future. Alternatively, demand side management, changes in energy efficiencies of end uses, planting of shade trees, and many other strategies may be chosen to address potential energy shortages.

4.4 Public Health

The Public Health module of the CLIMB project currently focuses on the impacts that temperature may have on mortality in the region. The approach is similar to estimation of temperature impacts on energy demand, following a multi-step estimation and simulation process. In a fist step we estimated heat and cold thresholds beyond which mortality in the region increased noticeably (Figure 19 and Table 9). Then we identified temperature-mortality relationships above the heat threshold and below the cold threshold, using fixed effects regression models (Table 10). These relationships are then employed in conjunction with bootstrapped temperature data to explore likely changes in mortalities in the future.

	Mortality per day per million people
Constant (January)	27.24***
February	-0.47**
March	-1.37***
April	-2.33***
May	-3.17***
June	-3.81***
July	-3.86***
August	-4.40***
September	-4.08***
October	-2.73***
November	-2.23***
December	-1.44***
Annual Trend	-0.10***
High Temp = 80°F (t)	-0.07
High Temp = 81°F (t)	-0.30
High Temp = 82°F (t)	0.00
High Temp = 83°F (t)	0.44
High Temp = 84°F (t)	-0.13
High Temp = 85°F (t)	0.47*
High Temp = 86°F (t)	0.13
High Temp = 87°F (t)	-0.08
High Temp = 88°F (t)	0.35
High Temp = 89°F (t)	0.51*
High Temp = 90°F (t)	0.93***
High Temp = 91°F (t)	1.93***
High Temp = 92°F (t)	1.26***
High Temp = 93°F (t)	1.59***
High Temp = 94°F (t)	1.79***
High Temp > = 95°F (t)	3.48***
High Temp = 35°F (t-2)	0.05
High Temp = 35°F (t-3)	-0.33

High Temp = 34°F (t-2)	0.65*
High Temp = 34°F (t-3)	0.79**
High Temp = 33°F (t-2)	-0.01
High Temp = 33°F (t-3)	0.08
High Temp = 32°F (t-2)	0.40
High Temp = 32°F (t-3)	0.29
High Temp = 31°F (t-2)	0.99***
High Temp = 31°F (t-3)	0.74
High Temp = 30°F (t-2)	-0.12
High Temp = 30°F (t-3)	0.68
High Temp = 29°F (t-2)	0.59
High Temp = 29°F (t-3)	0.68
High Temp = 28°F (t-2)	0.51
High Temp = 28°F (t-3)	0.29
High Temp = 27°F (t-2)	0.02
High Temp = 27°F (t-3)	0.54
High Temp = 26°F (t-2)	0.73
High Temp = 26°F (t-3)	1.07**
High Temp = 25°F (t-2)	1.21**
High Temp = 25°F (t-3)	0.98*
High Temp = 24°F (t-2)	1.05*
High Temp = 24°F (t-3)	0.96
High Temp = 23°F (t-2)	1.08
High Temp = 23°F (t-3)	0.21
High Temp = 22°F (t-2)	0.27
High Temp = 22°F (t-3)	-0.90
High Temp = 21°F (t-2)	1.23*
High Temp = 21°F (t-3)	-0.29
High Temp < = 20°F (t-2)	0.95**
High Temp < = 20°F (t-3)	0.37
Snow (t)	0.74***
Snow (t-1)	0.56***
Snow (t-2)	-0.05
R^2	0.1872
Durbin-Watson (DW) Statistic	2.04

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

Table 9. Regression Results for Temperature Threshold-Mortality Relationships.

	Mortality per million people per day	Percent Change in Mortality with Extreme Heat (1970)	Percent Change in Mortality with Extreme Heat (1990)
Constant (January)	27.33***		
February	-0.46**		
March	-1.48***		
April	-2.50***		
May	-3.36***		
June	-4.14***		
July	-4.41***		
August	-4.75***		
September	-4.31***		
October	-2.90***		
November	-2.38***		
December	-1.51***		

Annual Trend	-0.10***		
High Temp > = 90°F (t)	2.21***	+9.8% †	+5.9% †
Trend High Temp > = 90°F (t)	-0.05**		
High Temp > = 90°F (t-1)	2.37***	+10.5% †	+5.7% †
Trend High Temp > = 90°F (t-1)	-0.06**		
High Temp > = 90°F (t-2)	0.76***	+3.4% †	+2.7% †
Trend High Temp > = 90°F (t-2)	-0.01		
High Temp > = 90°F (t-3)	0.42		
Trend High Temp > = 90°F (t-3)	-0.03		
High Temp < = 28°F (t)	-0.62***		
High Temp < = 28°F (t-1)	0.26		
High Temp < = 28°F (t-2)	0.38*		
High Temp < = 28°F (t-3)	0.59***		
High Temp < = 28°F (t-4)	0.42**		
High Temp < = 28°F (t-5)	0.11		
Snow (t)	0.69***		
Snow (t-1)	0.63***		
Snow (t-2)	0.05		
R^2	0.20		
Durbin-Watson (DW) Statistic	2.04		

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level † Relative to August's mortality rate

Table 10. Regression results for Temperature-Mortality Relationships.

Our analysis indicates that there is no clear, discernible cold threshold for the population in the metropolitan Boston region, nor is there a strong statistical association between historically observed low temperatures and cold-related mortality. In contrast, we do find a heat threshold of 90°F and a strong influence on heat-related mortality by the number of days above that threshold. Using the derived statistical relationship between mortality rates and the number of days above 90°F in conjunction with simulations of alternative future climate, we find that more frequent occurrence of heat episodes will not result in higher mortality in metropolitan Boston, presumably because of more aggressive adaptation to those events (Figure 20).

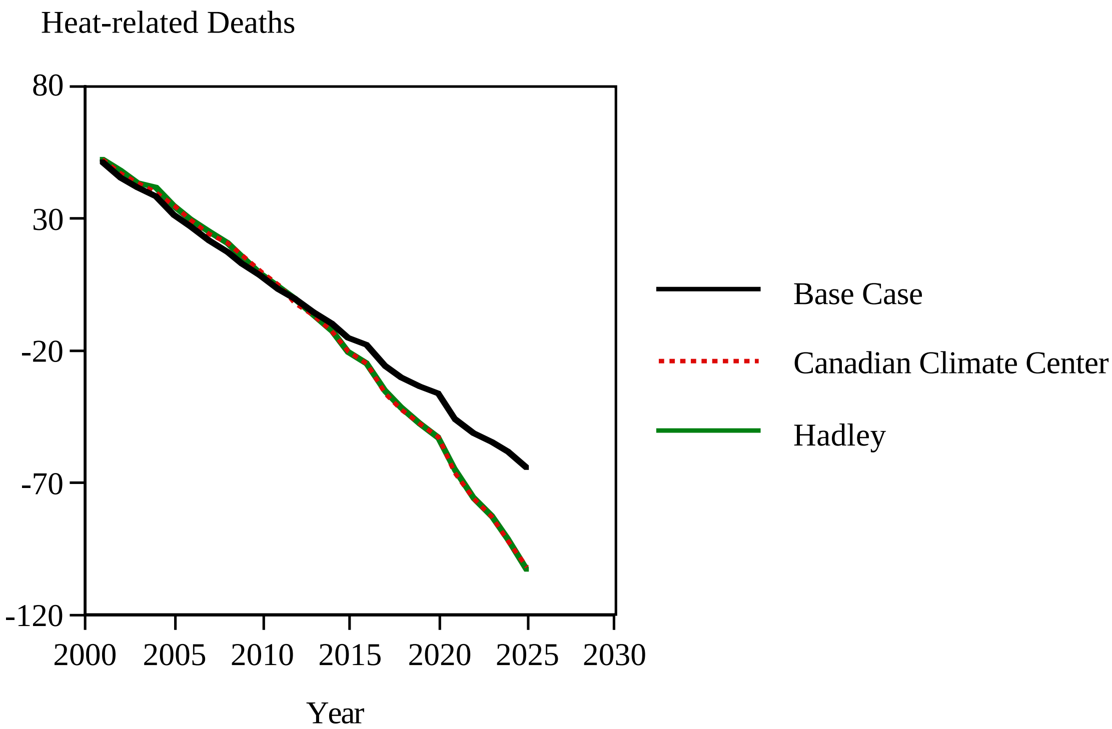


Figure 20. Heat-related Deaths in the CLIMB Region.

These findings are subject to several interrelated assumptions about socioeconomic characteristics in the region. First, many key characteristics of the regional population have not been explicitly considered here, such as its age distribution, ethnic mix or economic prosperity, many of which may influence the population's susceptibility to weather and climate, and many of which are likely to change over the simulated one hundred years.

Second, a variety of behavioral and technological changes may likely occur as the region's climate changes. For example, an increase in the use of air conditioning will likely reduce susceptibility to heat waves for those individuals who have access to air conditioned space. Similarly, improvements in health care, use of early warning systems for individuals most prone to changes in temperature and its often associated low outdoor air quality will likely reduce respiratory and cardiovascular stress, and thus also likely reduce heat related morbidity and mortality. Other adaptations to extreme temperatures include changing the extent to which individuals remain outdoors. Already, people in climates with extreme heat or cold periods have found ways to reduce exposure by moving from one cooled or heated space to another (e.g. from the home to the car to the store and back) with little time spent outside.

Increases in access to air conditioned space, many improvements in health care and a multitude of behavioral changes have been observed in the past two decades on which the statistical analysis of this paper is based. These improvements largely determine the sign and magnitude of the trend variable discussed above. For that variable to continue its relevance over the simulated future one hundred years requires that the factors contributing to it remain, in aggregate, comparable to the past. However, rates of expansion of air conditioning, for example, may likely be lower in the future than they have been in the past because continued proliferation tends to be more difficult as near 100 percent saturation is reached. Also, expansion of air conditioning itself is not without problems as it increases regional energy consumption, contributes to urban heat island effects, and potentially exacerbates health risks associated with low outdoor air quality.

Improvements in health care have likewise been quite significant over the last two decades. Not only are there now regular weather and health warning systems in place – from forecasts in daily news media of heat indices and chill factors to pollen counts and ground level ozone concentrations – but also the population and its health care system have found numerous ways to deal with cold spells or heat waves. Whether a continued high rate of improvements in warning and health care systems can possibly been maintained over the next one hundred years is open to debate.

As any of the factors that influence the trend variable reduces its impact on lowering cold or heat-related mortality rates, the other factors need to make up for it, so that the results continue to hold. Alternatively, additional adaptations to climate change may be needed. For example, the region has seen only few efforts to increase the use of shade trees to decrease albedo, increase moisture retention and thus contribute to local cooling. Similarly, little new construction uses materials or designs that reduce a building's albedo, its heating and cooling needs, and thus energy consumption and impacts on local air quality. Such engineering approaches to prepare the local building stock to a changing climate, together with appropriate zoning and transportation planning could go a long way in reducing, for example, urban heat island effects, which may be exacerbated by climate change.

The results presented above suggest that future reductions in heat-related mortality are likely under a wide range of climate scenarios. For these results to be achievable requires aggressive investments in all areas ranging from health care to space cooling to smart land use, as well as potentially drastic behavioral adjustments of the local population. On the one hand, such adjustments will need to be large, yet given past experience seem doable. On the other hand, they will quite likely entail major changes in lifestyles in the region. The analysis presented above calls for public debate on these trade-offs and necessary investments in climate change mitigation and adaptation strategies.

5. Conclusions: Six Challenges for Research, Education and Decision Making About Climate Impacts on Urban Infrastructure

We opened this paper by stressing humanity's ability to respond to a broad set of environmental challenges. While the historic record may give us considerable hope for human problem-solving skills to lead to further improvements in living standards, we wish to point out that such improvements are neither inevitable nor may they arrive with sufficient speed and at a large enough scale as to avoid at least in the short term significant cost. The CLIMB project has begun to suggest adaptation strategies which may be chosen to prepare for climate change in the metro Boston region. The insights achieved so far are the result of intensive dialog with stakeholders, combined with select economic and engineering analyses, computer modeling, and scenario development. The CLIMB project has also begun to point at major challenges for research on regional impacts of climate change, and for investment and policy making that strive to utilize the best available information. In this concluding section we wish to briefly address these challenges in the broader research and decision making context.

(1) Avoid the Dangers of Environmental Ambulance Chasing

For years, climate change has been a hot topic in science and policy. Major efforts worldwide are made to reduce remaining uncertainties about biogeochemical processes. Billions of dollars are spent on research programs that support the activities of tens of thousands of scientists. A lion share of these funds are allocated to the natural sciences for monitoring and modeling projects, attracting ever larger numbers of investigators to compete for available funds. Stepping up research on climate change has helped reduce uncertainties about some of the issues and led to the discovery of uncertainties about others. The fundamental complexities of the climate system and its interdependencies with human activities suggest that some significant level of uncertainty about the future climate will always remain (Ausubel 2001). Expanding the scientific endeavor with the claim that the remaining uncertainties will ultimately all be resolved is disingenuous and may, in the long run, affect the credibility and respectability of those involved.

Tying ever more topics to the climate change issue – from migration and local wars (Foley 1999) to the spread of diseases (Martens 1996; Martens 1998) – may on occasion be justified but it may also divert attention from more dominant causes. As a consequence, in some instances too much emphasis may be placed on policies that address climate change compared to tackling other causes. While potentially a serious challenge to the welfare of humankind, other, very immediate challenges beside climate exist as well. At a minimum, the implications that one draws from thinking about climate change highlight current shortcomings of infrastructures (broadly defined) and institutions, and the social cost associated with inefficiencies of the existing system. Revisiting these shortcomings and identifying changes that make good economic and political sense in their own right seems the honest and prudent thing to do.

(2) Foster Diversity of Problem-Solving Approaches

The urge to identify single causes behind complex environmental, social and economic processes may be topped by the urge to identify quick fixes to perceived problems. Climate-susceptibilities of agricultural yields may be addressed with genetically engineered crops, diseases hitherto unknown or unnoticed in some regions may be combated by raising the chlorine content of water or spraying insecticides to control the spread of vectors of the disease, or the elderly and urban poor may be urged to seek shelter in fast food restaurants and other air conditioned public places during episodes of prolonged heat or low urban air quality. Nuclear power may be promoted again, this time for its apparently GHG-free generation of electricity. Focussing on easy solutions to the various challenges may mean missing opportunities for more fundamental structural change. Widespread use of genetically engineered crops may seriously affect genetic diversity of non-cultivated plants; more aggressive treatment of water or combating of disease vectors with chemicals may have unanticipated environmental and human health consequences; urging the disenfranchised to frequent fast food restaurants may, on occasion, shift the problems from acute respiratory to chronic cardiovascular ones; expanding nuclear power will certainly exacerbate the already existing challenges encountered when dealing with nuclear waste.

But even if individual strategies can clearly be identified as improving human welfare in the light of climate change, a danger remains of investing in a small set of strategies while neglecting to sufficiently explore others. A wide range of technology, infrastructure and institutional strategies are in principle possible to reduce, in the long run, human, social and economic vulnerabilities, and many of these strategies may be equivalent from a cost perspective (Gritsevskyi and Nakicenovic 2000). Yet, the evolution of these strategies is path dependent, and it is not possible, a priory, to identify an optimal development strategy. Consequently, there is a need for diversity in developing these strategies so that a large set of sources for positive spill-overs is made possible and sufficient flexibility exists in the future to change development paths.

(3) Leverage Interdependencies Among Infrastructures and Institutions

Infrastructure systems and the institutions, which govern their implementation and use, tend to co-evolve. Similarly, individual infrastructure systems in a region evolve in relation to each other. Yet, institutional barriers exist (and are frequently reinforced) to jointly manage urban infrastructure systems from a holistic perspective. For example, water systems can be overwhelmed by increased demand during droughts. They can also be overwhelmed when drainage systems are incapable of removing excess water fast enough, which may not only lead to local flooding, but where storm water is channeled through combined sewer overflows, flooding may also directly affect water quality. Water quality may further be affected by changes in temperature – either directly because of changes in biological oxygen demand and decreases in oxygen saturation, or indirectly by favoring the growth of bacteria or the concentration of particulates due to higher evaporation. And in regions where power generation requires significant sources of cooling water, low stream flow conditions may constrain generation. Conversely, as precipitation events become more severe, transportation may be impaired, leading to delays, accidents, and economic loss. Transportation and communication may be affected also by disruptions to the energy system to the extent that both rely on energy supply. Also, private passenger transport may become increasingly electricity-based, leading to new demands on energy infrastructure. And vice versa, electricity generation and distribution rely on modern communication and data storage, and the transportation of fuels, such as oil and coal, is susceptible to changes in surface transport and storage conditions. Thus, water quantity and quality issues, electricity generation and transportation are in many ways interrelated with each other. Each of these issues is typically dealt with separately by individual institutions and analyzed by experts with different expertise. To date, few incentives are present to infrastructure managers and planners to improve communication (let alone coordination) across institutional boundaries.

The many potential interrelationships among infrastructure systems, between infrastructure and physical environmental change, and between infrastructure and the socioeconomic system call for analyses in which various system components are interrelated and for management strategies that allow easy adjustments of one as new information becomes available about another. A key challenge to any analysis and management of these systems is to be able to explore and anticipate how change in one system component cascades – through space and time – to affect the entire system. The computer modeling and scenario building approaches mentioned above have started to provide tools for system analysis and to sensitize decision makers about system-wide implications of their decisions.

(4) Design and Implement Forward-looking Design Criteria and Standards

Traditionally, design criteria and standards have been developed and established on the basis of historical observations. In many cases, modern infrastructure is built on the assumption that future climate will look much like the past. Management of these systems, too, is done on the basis of past experience. For example, water managers are technical and empirical pragmatists. They are trained to react to real events, and their tools of choice are physical rather than economic or institutional. The real uncertainties about future climate – which are unlikely to ever be fully resolved – are significant barriers to action (Schilling and Stakhiv 1998). Thus, identifying new standards and technologies to meet them is only part of the challenge. Another challenge – potentially more daunting – is to change the institutions that coevolved with the respective technologies (Unruh 2000), (Geels and Smit 2000). For example, in many countries centralized energy supply from large-scale fossil fuel-based or nuclear power plants spawned government agencies for oversight of those plants, agencies to control distribution of electricity to consumers and energy prices, and consumer groups contributing to the decision making process. Government and private research and development laboratories emerged to address the needs for refinement of those technologies. Financial markets evolved to broker energy. The coevolution of institutions and technologies has in many cases locked in a pattern of energy supply that makes it difficult, for example to promote alternative energy sources. As a consequence, development of new energy technologies is often relatively straightforward in comparison to their social and institutional implementation (Elliott 2000), and significant effort should therefore be directed towards understanding and promoting institutional change that is necessary to accompany technology and environmental change.

Insurance companies will likely raise awareness about climate impacts on urban infrastructures, demanding higher premiums to match higher risks. As rates are set, they should ideally be oriented towards expected losses, not past losses. The differences may be placed in a trust to be reimbursed to policy holders in case actual risks turned out to be lower than expected. As a consequence, stimulus will be given to society to actively address climate change issues through mitigation and adaptation.

(5) Get Multiple Bangs for the Buck

The discussion above contrasted mitigation and adaptation strategies to address climate change. Yet, some policy and investment choices can be cost effective now and simultaneously reduce GHG emissions and vulnerabilities to climate change. For example, installing photovoltaic (PV) systems for electricity generation on the consumer-side of the electric meter can translate not only into energy and demand-charge savings by households and industries but also reduce susceptibilities to power interruptions when power lines are downed, air quality standards are surpassed or scarcity of cooling water for power plants occur. If installed on the utility-side of the meter, PV systems help avoid costly generation and transmission capacity additions, and reduce utility fuel and variable operation and maintenance costs. And in either scenario they reduce GHG emissions per unit of electricity used. Similarly, expanding the use of natural gas-fired combined cycle generation or combined heat and power plants creates an opportunity to direct some of these projects to brownfield sites in non-attainment areas to capture benefits from improved air quality, reduced transmission congestion, and stimulate economic development (see, for example, (CCAP 2001)).

In each of these examples, GHG emissions can be reduced, cost cut, and system reliabilities increased. Other non-technology specific strategies include improving home-ownership rates in metropolitan areas and revitalizing communities to address the principal agent problems which so often plague energy conservation efforts – for example, people who own their home and live in it for longer periods of time are more likely to invest in insulation or energy efficient equipment than landlords whose interest in minimizing expenditures on construction and outfitting a building, rather than total cost including energy expenditures. Increased home ownership may obviously also be good for community development. Choosing strategies that simultaneously generate economic, environmental and societal benefits is really what we would want. If we do it right, we could not just be getting more bang for the buck – but multiple bangs for the buck!

<u>(6) Promote International Collaboration without Stooping to Lowest Common Denominators</u>

While challenges (1) – (5) above mainly address actions on the local or sectoral scale – the place where policy and investment decisions ultimately need to be implemented – there is little doubt that successfully addressing climate change will require some level of global collaboration. This insight has often been taken to imply common GHG emissions goals with which individual nations must comply, and institutional mechanisms implemented on a multi-nation scale to facility emissions reductions and give credit to those facilitating or achieving reductions. The Kyoto Protocol (FCCC 1997), for example, heavily reflects this logic. By virtue of trying to achieve an international agreement that does right by most, if not all, signatories, emissions targets had to be set at levels too low to have any noticeable ability in halting or reversing climate change, and complex institutional mechanisms had to be proposed to guide decision making, monitoring and enforcement in government and industry around the globe.

Could alternative approaches be envisioned to lead to larger GHG emissions reductions at low administrative burdens? There is a good chance that such alternatives to rigid global coordination will be more thoroughly explored in the future. Those improvements may occur expressly as part of a climate change policy or they may be carried out to address other economic and societal goals. Where sufficient domestic resources exist, improvements may be funded by domestic industry and government (separately and in partnerships) in efforts to foster their own institutional and infrastructure development. But since the bulk of future GHG emissions will come from the developing world, technology, infrastructure and institutional improvements may be part of bi-lateral or multi-lateral agreements, aid programs or development assistance plans. In either case, the goal would include fostering diversity of problem solving approaches, and to fine-tune those approached in the light of existing cultural, social, economic, institutional and technological constraints. Rather than globally shooting for minimal emission reductions goals, the various strategies may well attempt to maximize society's benefits from alleviating existing or anticipated inefficiencies – including climate-change induced misallocations of resources and their associated environmental, social and economic cost.

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