CHAPTER 4

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE NORTHEASTERN UNITED STATES

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CHAPTER SUMMARY

Regional Context

The Northeast is characterized by diverse waterways, extensive shorelines,and a varied landscape in which weather and the physical climate are dominant variables. The contrasts,from mountain vistas and extensive forests to one of the most densely populated corridors in the US,are noteworthy. The Northeast includes the largest financial market in the world (New York City),the nation's most productive non-irrigated agricultural county (Lancaster, PA),and the largest estuarine region (the Chesapeake Bay) in the US. The Northeast is dominated by managed vegetation,with much of the landscape covered by a mosaic of farmland and forest. The varied physical setting of the Northeast is matched by its highly diversified economy and by the character of its human populations. The majority of the population is concentrated in the coastal plain and piedmont regions,and within major urban areas. The economic activities within the region range from agriculture to resource extraction (forestry, fisheries,and mining),to major service industries highly dependent on communication and travel,to recreation and tourism,to manufacturing and transportation of industrial goods and materials. Assessment of the impacts of climate change is based on observed climate trends, climate simulations,and the importance of past extreme weather events.

Climate of the Past Century

- The Northeast has been prone to natural disasters related to weather and climate,including floods,droughts,heat waves,and severe storms.
- Temperature increases of as much as 4°F (2°C) over the last 100 years have occurred along the coastal margins from the Chesapeake Bay through Maine.
- Precipitation shows strong increases,with trends greater than 20% over the last 100 years occurring in much of the region. Precipitation extremes appear to be increasing while the amount of land area experiencing drought appears to be decreasing.
- The period between the first and last dates with snow on the ground has decreased by 7 days over the last 50 years.

Climate of the Coming Century

- The Northeast has among the lowest rates of projected future warming in comparison with the other regions of the US.
- Winter minimum temperatures are likely to show the greatest change,with models projecting increases ranging from 4-5°F (2-3°C) to as much as 9°F (5°C) by 2100,with the largest increases in coastal regions. Maximum temperatures will possibly increase much less,but again the largest changes are likely to occur in winter.
- For precipitation,model scenarios offer a range of potential future changes,from roughly 25% increases by 2100 on average for the entire region,to little change.
- The variability in precipitation in the coastal areas of the Northeast is likely to increase.
- Models provide contrasting scenarios for changes in the frequency and intensity of winter storms.

Key Findings

- On the time scale of a century, winter snowfalls and periods of extreme cold are very likely to decrease. In contrast, heavy precipitation events have been increasing and warming is very likely to continue this trend. Potential changes in the intensity and frequency of hurricanes are a major concern.
- Climate change is very likely to exacerbate current stresses on estuaries, bays, and wetlands in the Northeast with rising sea level and increasing water temperatures, with significant effects on fish populations, productivity, and human and ecosystem health.
- Decreased snowfalls and more moderate winter temperatures are very likely to lower winter stresses in major northeastern urban areas. However, climate change has greater potential to add to existing stresses in urban areas due to the impact of rising sea level and elevated storm surges on transportation systems, increased heat-related mortality and morbidity associated with temperature extremes, increased ground-level ozone pollution problems associated with warming, and the impact of precipitation and evaporation changes on water supply.
- Typical summer recreational activities involving beaches or freshwater reservoirs are likely to experience extended seasons and the region's diverse waterways are very likely to become havens for escape from increasing summer heat. In contrast, negative impacts are likely to include inability of ski areas to maintain snow pack, muting of fall foliage colors, displacement of maple-sugaring, increases in insect populations, accelerated beach erosion due to sea-level rise, and worsening ground-level ozone pollution problems, even in the mountains of New England.
- The complex institutional framework of communities, municipal, county, regional, and statewide formal and informal governing bodies that characterize the Northeast is likely to limit the region's ability to deal with extremes in water supply.
- Infectious disease vectors, such as ticks and mosquitoes, are likely to be altered by warmer and wetter conditions. Increased rainfall and flooding have a historical association with contamination of public and private water supplies (e.g., with *Cryptosporidium*).
- Agriculture in the Northeast is very likely to be relatively robust to climate change although the crop mix may change. The ability to change crop types and to take advantage of hybrids limits vulnerability. Northern cool weather crops are a possible exception.
- The species composition of northeastern forests is very likely to change under the climate scenarios examined in this Assessment, with significant northward migration of forest types.
- Projected changes in temperature and precipitation are likely to have a direct impact on species distribution mix or an indirect impact associated with changing predator-prey relationships or changes in pests or disease. In many cases, the species effected may be truly characteristic of a region or may be of economic significance (e.g., lobster, migratory birds, and trout).
- Climate change, resulting in higher temperatures and poorer air quality, could lead to increases in heat-related mortality and morbidity and respiratory illness. The elderly, children, those already ill, and lower-income residents are groups most at risk.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE NORTHEASTERN UNITED STATES

PHYSICAL SETTING AND UNIQUE ATTRIBUTES

The northeastern United States is dominated by diverse waterways, extensive shorelines and a varied landscape in which weather and climate are dominant variables. The regional contrasts and strengths are noteworthy. Most mental images of New England focus on an environment of quaint villages, mountain vistas, extensive forests,and brilliant fall colors,maple sugaring,and skiing through forested glades. The Northeast also includes the most densely populated corridor in the US and is intimately connected to the North Atlantic coastline and ocean-accessible waterways. Of these waterways, the Chesapeake Bay is the largest estuarine region in the US and is unmatched in terms of its importance for recreation, fish,and wildlife. The Northeast is also crossed by a remarkable network of streams and rivers superimposed on the mountainous terrain of the Appalachians. The vegetative landscape has changed dramatically over the last 100 years,in part because of significant areas of forest re-growth.

SOCIOECONOMIC CONTEXT

The varied physical setting of the Northeast is matched by its highly diversified socioeconomic characteristics (NPA Data Services,1998;Bureau of Economic Analysis,2000; Polsky et al.,2000;Rose et al.,2000). The Northeast includes the largest financial market in the world (New York City),as well as the most productive non-irrigated agricultural county (Lancaster, PA) in the US. The economic activities in the region range from resource extraction (forestry, fisheries,and mining) and agriculture,to major service industries highly dependent on communication networks and travel,to recreation and tourism,to manufacturing and transportation of industrial goods and materials. The human populations are largely concentrated in coastal and urban areas. The region contains some of the most densely populated counties in the United States.

The socioeconomic characteristics of the Northeast vary considerably across the region. In the Mid-Atlantic region,more than 50% of the 35 million people and associated jobs are concentrated in six urban areas, for the most part within the coastal plain and piedmont regions. The Mid-Atlantic population increased nearly 20% during the last three decades,somewhat less than the 33% population growth experienced by the nation as a whole. The working age population increased by about 34%, the over-65 population by 72%,and the 0-19 age group declined by 16%. Per capita income increased by 82%,with the largest growth in total income in the service sector (300%). Farm employment declined by almost one-half, reflecting the national trend. The economy is diverse and substantial. The Mid-Atlantic region alone accounts for 13% of the total US economy, with sizeable export and import flows. Agriculture, forestry, and mining comprise about 2% of the region's economy, while manufacturing and service comprise 26% and 20% respectively.

The Northeast is characterized by a megalopolis that extends from Boston to Washington, D.C. The greater New York City area alone includes parts of three states,31 counties,and nearly 1,600 cities, towns,and villages with more than 19 million inhabitants. At the heart of this metropolis is a city with more than 7 million people. This population places tremendous demands on land and water resources. Approximately 30% of the 31 counties comprising the greater New York City land area is fully converted to urban uses,and the rate of conversion has accelerated even though the rate of population growth has slowed. As an example of water demand,the amount supplied by the New York City water system,serving the city, most of Westchester, and some additional communities,is approximately 1.3 billion gallons a day. The area's development is intimately connected with its 1,500 miles of coastline and a complex transportation infrastructure. The general economy of this metropolitan area is mostly based on service industries,of which the economic heartbeat is finance,corporate headquarters, and trade centers.

New England is a study in contrasts with a fascinating land use history (Cronon,1983). Most of the region's almost 13 million inhabitants live in the densely populated coastal segments in the south and east. To the north and west,New England is heavily forested and mountainous with more isolated smaller urban concentrations. The New England economy is dominated by the service sector (individual state averages range from 27 to 35% of their economies), followed by manufacturing of durable goods, finance,insurance and real estate,and trade. The service sector and the finance,insurance,and real estate sector, tend to be the fastest growing segments of the economy (ranging from 5 to 10% growth over the decade). New England also includes the state (Connecticut) with the highest per capita personal income in the nation but,within the region,only Massachusetts and Connecticut currently have per capita personal incomes that are growing at rates above the national average (NPA Data Services,1998). Data from the 1979-1989 Census placed Connecticut,Massachusetts,and New Hampshire with the highest percentage increases in median household income of US states for the decade of comparison.

The large urban areas of the Northeast include some of the oldest metropolitan centers in the nation,and are often characterized by aging infrastructure and a wide variety of stresses. The Boston to Washington corridor is largely an urban landscape,with the densest population in the nation.

CLIMATE VARIABILITY AND CHANGE

Historically, the Northeast has been prone to natural disasters related to weather and climate. Floods, droughts,heat waves,and severe storms are characteristic. For example,seven major tropical storms crossed the Mid-Atlantic region since 1986 and six years of the last 20 have been characterized by significant drought in some parts of the region. In addition,the major cities of the Northeast have experienced episodes of increased morbidity and mortality during heat waves (Kalkstein and Greene, 1997). The 1990s have been characterized by a number of significant winter precipitation events including a number of heavy snowfalls and major ice storms,while winter temperatures have tended to be mild. Both the weather events and mild winters raised the regional consciousness about climate and climate change.

The climate of the northeastern US experienced significant changes in temperature and precipitation during the 20th century (Hughes et al.,1992;Karl et al.,1996;Karl and Knight,1998). Based on observations derived from the highest quality US observing stations as a part of the US Historical Climatology Network,temperature increases of as much as 4°F (2°C) over the last 100 years occurred along the coastal margins from the Chesapeake Bay to Maine. Within the Northeast,the only area with a decreasing historical trend in temperature is a small portion of southern Pennsylvania. Analysis of extreme temperatures shows little change in the number of days exceeding 90°F or below freezing.

Precipitation trends also show strong increases over the last 100 years,with trends greater than 15-20% occurring in Pennsylvania, western New York,and from northern New York across the middle of New England (Karl et al.,1996;Karl and Knight,1998). Precipitation extremes show increases of 12% in highest annual 1-day precipitation total,and 3% in the number of days per year exceeding 2 inches of precipitation over the 20th century. The region of the Northeast adjacent to the Great Lakes had the largest annual increase in precipitation over the period 1931-1996 and the largest increases in very extreme precipitation events (Kunkel et al.,1999a).

For the region as a whole,the period between the first and last dates with snow on the ground has decreased by 7 days over the last 50 years, resulting in a shorter snow season (Karl et al.,1993;Groisman et al.,2000). The Palmer Drought Severity Index (PDSI),which indicates trends in drought and wet periods,confirms the precipitation patterns by demonstrating a tendency toward more wet periods in Pennsylvania and southern New England,and tendencies toward drier periods in northern New England and around the Chesapeake Bay. On average,the amount of land area experiencing drought appears to have decreased over the last half century.

Projections of future climate change in the Northeast based on the Hadley climate model (Mitchell et al.,1995;Mitchell and Johns,1997; Johns et al.,1997) and Canadian climate model (Boer et al.,1984;McFarlane et al.,1992;Boer et al.,1999; Boer et al.,1999;Flato et al.,1999) suggest lower than average temperature increases in comparison with other regions of the US. The Hadley model yields a trend for the 21st century of a 5°F (2.6°C) average temperature increase while the Canadian climate model indicates a 9°F (5°C) increase. Winter minimum temperatures increase by 4 to 12°F (2 to 7°C) in the Canadian model with the greatest increases in the western part of the region and the smallest increases in southern New England. In the Hadley model,winter minimum temperatures increase by approximately 7°F (4°C) in the entire region north of Maryland,with somewhat smaller increases immediately to the south. Summertime increases in minimum temperatures are projected to be greater than 5°F (3°C) in both models. Maximum temperatures also increase,with the largest changes in winter (from more than 12°F in West Virginia to less than 5°F in New England in the Canadian model,and from 3 to 5°F in the Hadley model). Climate models differ substantially in their projections of the summertime increase in maximum temperatures,with projections ranging from 2-3°F (1.3°C) to as much as 7-11°F (4-6°C),between the Hadley and Canadian models respectively. Both models used in this Assessment generally indicate small decreases in the variability of temperature (the exception is an increase in summer temperature variance in the Canadian model). The more limited warming in the Northeast relative to much of the rest of the US may be partially attributed to the cooling effect of sulfate aerosols that are concentrated in the Northeast and the maritime influences in the coastal regions,offsetting some of the warming.

The Northeast currently has more total precipitation than all other regions except the Southeast. The model simulations offer rather different scenarios for future changes. In the Hadley model, regional precipitation is projected to increase by as much as 25% by 2100. In summer, the greatest increases are in western portion of the region,while in winter the largest increases are in New England. In contrast,the Canadian model projects little change in precipitation or small regional decreases approaching 5-10%. The largest decreases are in the Mid-Atlantic region,during both winter and summer. Only small regions have a projected increase in precipitation. The variability in precipitation in the Northeast is projected to increase in both model projections (slightly in winter and substantially in summer in the Canadian model and substantially in both winter and summer in the Hadley model).

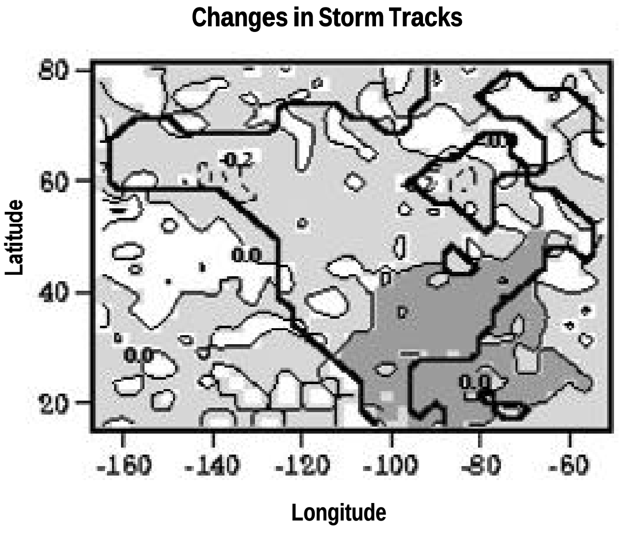
Changes in Storm Tracks

Figure 1. A storm track analysis from the Hadley climate model scenario projects a slightly strengthened wintertime storm track through the Northeast, in the 2020s, because the jet stream has a more north-to-south position along the East Coast. This scenario projects a slightly stronger winter storm area (dark shaded region). The Canadian climate scenario has a more east-west jet, and in general indicates slightly weaker storminess.

Severe storms are a major issue in the Northeast throughout the year. Given the spatial resolution of global climate models,neither thunderstorm activity nor hurricanes are simulated by the models. An analysis of sea-level pressure patterns in the Hadley and Canadian models,which provides some indication of the path of hurricanes if they form,suggests little reason to expect changes in the average track of hurricanes over the 21st century. Changes in frequency and intensity of hurricanes under future climate conditions remains a topic of considerable debate. Global climate models are capable of resolving and simulating mid-latitude cyclones responsible for winter storms,although the simulations are imperfect. For example,Hayden (1999) indicates that the Atlantic coast storm track in the Hadley model is displaced offshore in simulations of current conditions. In the climate projections the Northeast continues to be a location of winter storms,as an analysis of the winter storm variability and locations does not shift over the 21st century. However, an analysis of storm counts and intensities in the Hadley and Canadian climate scenarios yields some differences. The Canadian model produces decreased counts over much of the eastern seaboard,with the exception of small increases in parts of the Mid-Atlantic region. In contrast,the Hadley model indicates an increase over the coastal region with slightly stronger storms. The differences in these two scenarios reflect the position of the jet stream. The more zonal jet stream in the future simulated by the Canadian model would mean fewer cold-air outbreaks in the Northeast. The more north-south jet stream in the Hadley model results in an increase in east-coast storms. Carnell et al.(1996) and Carnell and Senior (1998) describe results from a storm analysis. Storm tracks in the Atlantic are weakened,but there is a statistically significant increase in storm counts across the Mid-Atlantic region. Further, they find a shift toward deeper low-pressure systems,and hence stronger storms. The strength of the storms is dependent on two factors. First,as the continental regions become warmer in winter in the future,the decreased temperature contrast between land and sea in the region tends to produce weaker storms. However, increased heating associated with higher atmospheric water vapor tends to counteract this effect to produce deeper low-pressure storms.

The Palmer Drought Severity Index derived from the model simulations provides two very different pictures for the Northeast. The Hadley model projects less drought tendencies in the Northeast while the Canadian model projects tendencies for severe drought to increase over the 21st century. This result follows from the precipitation and temperature projections in the two models,with the Canadian model projecting larger temperature increases but with smaller precipitation changes. Increased evaporation with the warmer temperatures yields a greater drought tendency. In contrast, the Hadley model projects a smaller warming,and with regional precipitation increases of as much as 24% by 2100.

For perspective,the specific conditions projected by the climate models for the end of the 21st century can be matched with areas in the US that currently experience these specific conditions. Such a comparison provides perspective on the magnitude and nature of the projected climate changes. For summer temperature and precipitation,the Hadley model projects that New York State will have summer conditions similar to present day Maryland and southern Pennsylvania by the end of the 21st century. In contrast,the higher temperatures and smaller change in precipitation found in the Canadian model yield a summer climate regime for NY by the end of the 21st century that is closer to present day central Illinois or Missouri.

ECOLOGICAL PERSPECTIVE

A mosaic of farmland and forest covers much of the landscape in the Northeast. The southern part of the region (including the Appalachian Mountains of West Virginia, Pennsylvania,and Maryland) is characterized by higher percentages of corn,cotton,soy, and grasses with forests,than the rest of the region. These forests include oak,oak-hickory-pine,mixed hardwoods,mixed pines,maple-ash-beech,and limited spruce-fir forests. The most northern states of the region exhibit northern hardwoods, red spruce-balsam fir, white pine-hemlock,oak,hickory, oak-pine,elm-red maple,and cool mountain spruce-fir forests. Human activities converted significant fractions of forested land to agriculture. However, since 1900 there has been extensive abandonment of agricultural land,and land covered by forest has increased significantly. One exception is in urban areas where significant conversion of land to human use continues. The forests of the Northeast are still about 70% of the level of the 1600s if USDA (1998) data are compared with early analyses (see Forest sector foundation chapter). Forest area has been relatively stable over much of the region during the last few decades,although biomass increased with the maturity of second growth forests (Powell et al., 1996). Estimates of the percentage of forest cover in the region range from 34% in Delaware to 88% in Maine and New Hampshire (Klopatek et al.,1979).

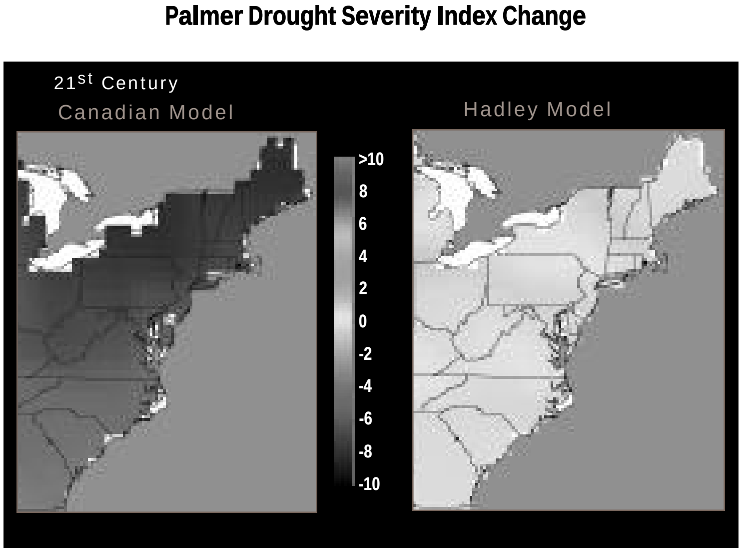
Palmer Drought Severity Index Change

Figure 2. The projected trends in the Palmer Drought Severity Index (PDSI) are dependent on the projections of temperature and precipitation. Large increases in drought tendencies occur in the Northeast in the Canadian model associated with substantial warming and small changes in precipitation. In contrast, the Hadley model yields larger increases in precipitation and a more modest warming, conditions under which the drought tendency tends to decline. See Color Plate Appendix.

Moderate species richness characterizes the northern half of the Northeast region,while the southern half exhibits moderately-high to high richness (Ricketts et al.,1999). For example,tree species richness in the Northeast region ranges from about 60 species in northern Maine to more than 140 species in parts of Pennsylvania, West Virginia,and Maryland (Currie,1991). Reptile species richness varies from fewer than 10 species in northern Maine to about 40 in Maryland and Delaware,while amphibian species richness ranges from fewer than 20 to more than 30 species per state.

Ecosystem Models

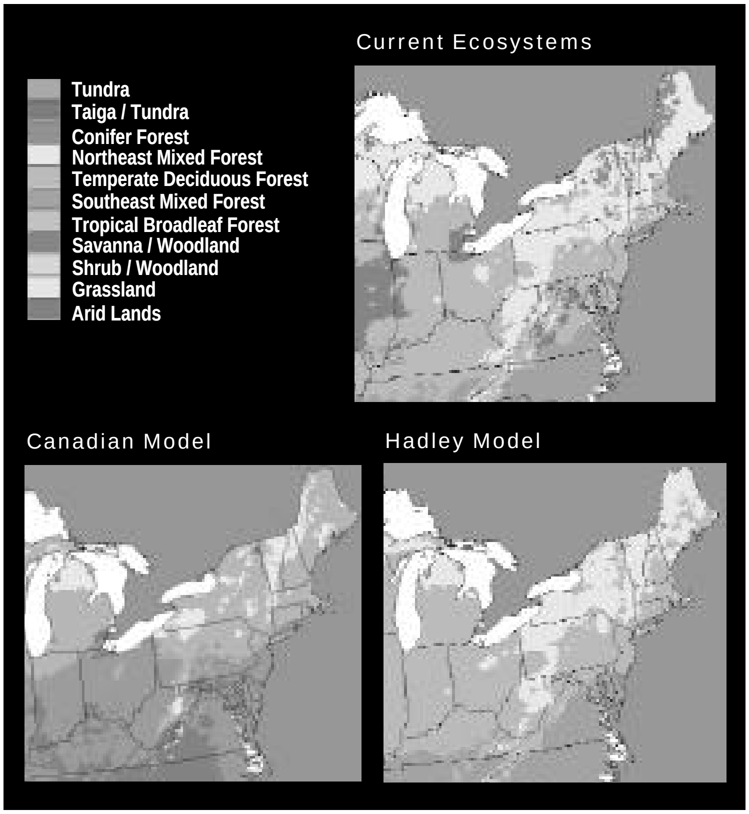

Figure 3. The projected changes in vegetation character using output of the Canadian (a) and the Hadley (b) models indicates a substantial northward shift in the vegetation types. These changes are significantly larger in the Canadian model scenario, which projects a greater warming trend with little change or a decrease in precipitation. Based on the model of Neilson and Drapek, (1998). See Color Plate Appendix.

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provides the basis for an assessment of changes in vegetation cover (VEMAP members,1995;Kittel et al.,1997) and primary productivity. The specific forest character is also projected using the MAPSS vegetation model (Neilson and Drapek,1998). Climate projections from the Canadian model yield substantial changes in the nature of the forests in the Northeast. The conifer forest of northern New England and much of the northeast mixed forest of New England,New York and Western Pennsylvania are projected to change to a temperate deciduous forest similar to southeastern Pennsylvania,Maryland,and northern Virginia today. The area of southeast mixed forest,today characteristic of the region south of Virginia, would become compressed into a small area of West Virginia,southern Pennsylvania,and the coastal plain of Virginia,Delaware,and New Jersey, while much of Virginia would become savanna/woodland.

The changes based on the Hadley model are less dramatic but still noteworthy. The conifer forest of northern New England is replaced by northeast mixed forest. The area of temperate deciduous forest in New England and Pennsylvania/West Virginia grows slightly. The area of southeast mixed forest grows in Virginia. The differences in vegetation projections are a strong reflection of the differences in moisture and temperature projections in the two climate model scenarios.

KEY ISSUES

Regional perspectives on the potential impacts of climate change are naturally influenced by personal experience related to historical weather and climate and their associated impacts. The key issues also reflect perceptions of current stresses and problems. In some cases,the issues are not directly related to climate change,but are likely to be exacerbated by climate change.

Four key issues are identified that are of major importance for the Northeastern US:

- Vulnerability to changes in extreme weather events;
- The compounding of climate change with other stresses for important ecosystems such as the Chesapeake Bay and other bays and estuaries;
- The impact of climate change on major urban environments;and
- The potential changes in recreation due to climate change.

Two additional issues are also noteworthy:

- Significant change in the character of forests in the Northeast;and
- Limited vulnerability in the agricultural sector

1. Vulnerability to Changes in Extreme Weather Events

The fact that the Northeast is prone to natural weather disasters and weather extremes figures strongly in the specific examples identified by stakeholders in each area of the Northeast. The reasoning is clear. Severe weather presents threats to both safety and property. During the period 1950-1989, storms caused more than $12 billion in damages in the Northeast (Changnon and Changnon,1992). Twenty-two events each caused more than $200 million in damages,with hurricanes causing the most damage, followed by thunderstorms, winter storms, and wind. A 1996 blizzard in the Mid-Atlantic and New England region, followed by flooding, caused an estimated $3 billion in damages and 187 deaths according to the National Oceanic and Atmospheric Administration. Changnon and Changnon (1992) and Agee (1991) note some correlation between higher historical temperatures and increased cyclonic and anticyclonic activity when five-year averages from 1950 to 1989 are analyzed. The strongest relationships were with thunderstorm activity and winter storms. The Northeast had relatively few "weather disasters" during the cooler 1960s, followed by increased numbers of events during the warming trend that followed. However, changes in severe weather are widely regarded as one of the most uncertain aspects of future climate projection (USGCRP, 1995; Barron, 1995). Further, the nature of these events is likely to change significantly as climate evolves over the 21st century. In other words, some of the tendencies for changes in severe weather are likely to be short term or transient features of a changing climate. Northeast stakeholders tend to focus attention on historical events with significant impacts, including ice storms, severe flooding, nor'easters, hurricanes and other tropical storms, and severe or persistent drought.

Ice storms. The ice storm of January 1998 caused substantial environmental, economic, and societal damage. This series of devastating ice storms hit northern New York and New England, along with portions of southeastern Canada, causing extensive damage to forests and energy and transportation infrastructure, as well as impacting human health. The magnitude of the storm in terms of measurements of the number of hours of persistent freezing precipitation was unprecedented (DeGaetano, 2000). While a number of significant ice storm events have occurred over the 20th century, the extensive area of impact (37 counties were declared Federal disaster areas) was also unusual.

A conservative estimate of the damage approaches 1 billion dollars for the US, with insured losses exceeding 200 million dollars (DeGaetano, 2000). Many people across the region were without power for up to three weeks in mid-winter. Seventeen deaths occurred, primarily associated with carbon monoxide poisoning and hypothermia associated with the power failure. In Maine, 70% of the state's population of 1.2 million people were without power for at least some period of time. Over the entire region (portions of New York, Vermont, New Hampshire, and Maine) approximately 1.5 million people were without electricity for up to three weeks. In addition, nearly 17 million acres of rural forests and urban trees were affected, with five million acres classified as severely damaged. Hardwood species were most heavily damaged with trees bent and limbs and branches broken under the weight of the ice coating. The longer-term ecological impacts of severe tree damage from the storm are not yet clear, especially as the ice storm was followed by the 1998-1999 drought.

Figure 4. The Northeast is prone to a wide variety of natural weather disasters and weather extremes including the 1998 ice storm illustrated.

Although the 1998 storm was extreme in terms of persistence and extent, other severe events have occurred in the 20th century. Changes in the frequency, intensity, or path of ice storms are not evident in the historical record. A primary concern is the potential for such storms to become more frequent. Ice storms occur when warm moist air masses are uplifted over cold polar air masses or move over cold surfaces. Such conditions will possibly become more common if the milder winters projected by the climate models increase the frequency of northern displacement of warm moist air masses as occurred in 1998. However, these effects, if they do occur, are likely to be transitory. In the Canadian scenario, winter precipitation decreases over much of the region and minimum winter temperatures eventually increase significantly (by 7 to more than 10˚F above present values), reducing the occurrence of subfreezing temperatures.

Severe flooding. The impacts of severe flooding (such as occurred during tropical storm Agnes in 1972 and Floyd in 1999) are amply demonstrated by the historical record from the Northeast. Records of severe floods reveal a diverse set of responsible meteorological conditions, including:

- rapid melting of snow with warming events following a major nor'easter;
- spring snow melt following heavy winter snowfall;
- heavy rainfall (as opposed to snow) as warm air masses move over a frozen ground that limits percolation and drainage;
- major summer thunderstorm systems;and
- major precipitation events associated with hurricanes or tropical depressions.

The frequency and occurrence of future flooding in the Northeast will depend on how this diverse set of meteorological conditions changes. Several elements of the historical and model-derived future climate projections raise flooding as an increased concern. These elements are:

- the historical trends that illustrate increases in extreme precipitation events through the latter half of the 20th century (Groisman et al.,2000),
- the Hadley model's tendency to simulate wetter conditions in summer and winter, and
- the uncertainties associated with projecting how the intensity and frequency of major hurricanes may change in the future.

Other elements of model-derived future climate projections suggest that winter and spring flooding increases are possibly transient in nature,or are likely to decline in the future. These elements are:

- the Canadian model's tendency to simulate drier conditions in summer and winter,
- the model simulations indicating milder winters and hence the potential for northward movement of warm air masses in winter producing rainfall over frozen ground as the climate warms, then with decreased flooding as continued warming substantially reduces the length of time the ground is frozen,and
- the potential for warming events during winter with associated higher snowfall creating rapid melting periods as a transient effect as the climate warms, followed by decreased snowmelt events as the climate continues to warm and precipitation tends to fall increasingly as rain.

Nationally, annual flood damages increased steadily over the period 1903 to 1997,and flood-related fatalities have been high since the 1970s (Kunkel et al.,1999b). Although societal growth is certainly a factor in the increase in flood damages,it is an insufficient explanation. More heavy precipitation events (Karl and Knight,1998) have also been suggested as a factor in this increase. Since 1983, flood damages in the river-rich Mid-Atlantic states total 4.7 billion dollars (US Army Corp of Engineers,1998). Flooding also disrupts water supplies and is a significant health risk (Solley et al.,1998;Yarnal et al.,1997). Several water-borne diseases present risks even in wealthier countries when flood waters compromise water systems. These include viruses (e.g., rotovirus), and bacteria-borne (e.g., *Salmonella*) or protozoan-borne (e.g., *Giardia* and *Cryptosporidium*) diseases.

Nor'easters. Major nor'easters produce significant precipitation accumulations and cause significant coastal damage,in terms of beach erosion and structural damage,and thus are of major interest to the Northeast. This is particularly true because five states of the Northeast (New York,Massachusetts, Connecticut,New Jersey, and Maryland,in respective order) represent five of the top six states along the Atlantic and Gulf coasts in terms of value of insured coastal property (Insurance Research Council,1995). The climate model projections are divergent with regard to nor'easters. The shift to deeper winter cyclones in the western North Atlantic with stronger winds for doubled carbon dioxide concentrations found by Carnell et al.(1996) indicates the potential for increased property damage. In contrast, Stephenson and Held (1993) found little change in the North Atlantic using the NOAA Geophysical Fluid Dynamics Laboratory model,and thus future increases in storm damages would more reflect development of coastal property rather than climate change.

The climate models used in this Assessment also provide different scenarios. The Mid-Atlantic region is the only area of the east coast in which both the Canadian and the Hadley climate models indicate slight increases in the frequency and intensity of winter storms with little change in storm track. The increases are more significant in the Hadley model with the north-south shift of the jet stream under future carbon dioxide conditions,while the Canadian model suggests decreases in storm counts with the exception of the Mid-Atlantic region.

A significant hazard to coastal areas stems from changes in flood levels superimposed on a more gradual rise in sea level. Return periods of coastal flood events will shorten considerably, even in the absence of any change in storm climatology. For example, by 2100,the 100-year flood event (the flood height that occurs on average once every 100 years) in New York City is likely to occur much more frequently (e.g., every 19 years in the Hadley model scenario) because of the sea-level increase (Rosenzweig and Solecki et al.,2000).

Interestingly, many of the severe winter weather conditions predicted for the Northeast may seem counter-intuitive. For example,the Great Lakes are very likely to experience decreased ice cover or a shorter season of ice cover with climate warming, yet a transient increase in the frequency and intensity of lake effect snows is possible. Specifically, the lack of ice cover allows increased lake effect snows as cold polar air masses move southward. Hence, the lake effect snows in areas such as Buffalo,NY could break records even though the climate warms. This result depends on the nature of cold air outbreaks that initially may not be substantially different from today. The effect is likely to be temporary or transient however, because as climate warms substantially, the precipitation increasingly falls as rain according to both climate model scenarios.

Hurricanes. Major tropical storms also remain a significant concern for several reasons:

- Hurricanes moving inland across the southern states have produced historically high precipitation extremes in the Northeast,and both wind and rainfall damage in New England and Long Island. Hurricanes rank first in terms of severe weather damage in the Northeast (Changnon and Changnon,1992).
- Considerable debate is on-going as to whether hurricane intensity may increase with warmer tropical and extra-tropical temperatures,particularly resulting in greater precipitation,higher winds,or both (see for example Emanuel,1988; Idso et al.,1990;Lighthill et al.,1994;Bengtsson et al.,1996;Knutsen et al.,1998).
- The debate about potential increases in the frequency of Atlantic hurricanes is also tied to whether warming will result in an increase or decrease in the tendency for El Niño-like conditions. Historically, during El Niño events,the probability of US land-falling hurricanes is reduced,while during La Niña events,the probability of US land-falling hurricanes increases (Bove et al.,1998). One modeling study, by Timmermann et al.(1999),suggests more frequent El Niño-like conditions and stronger La Niña events as climate warms.
- East Coast population growth substantially increases the potential health effects and property damage associated with hurricane events.

In 1995,the Insurance Research Council estimated that a category 4 hurricane making land-fall in Asbury Park,NJ, New York City, or Long Island had the potential to cause insurance losses of $40 to $52 billion. Conservatively, total damages can easily exceed twice the level of insured damages. In short,the potential for hurricane damage in the Northeast from a single storm far exceeds the region's total damages from hurricanes over the last 40 years. Much of the vulnerability stems from a remarkable increase in coastal property values. A comparison of storm intensity, frequency, and damages during this century (Kunkel et al.,1999b) indicate that large increases in damages are associated with increasing value of property exposed to weather risk. For example,the value of New York insured property doubled from 1988 to 1993. Unfortunately, hurricanes'spatial scales prevent their simulation as features of most global climate models. The Assessment climate models do not indicate any systematic change in the steering forces that might govern the path of future hurricanes compared to the present. Potential changes in intensity and frequency remain highly uncertain.

Drought. The differences in precipitation and temperature projected for the Northeast indicate substantial difficulty in determining how drought tendencies may change in the future. There are significant reasons for concern,but also the potential for little change from present conditions. Although the Northeast is on average "water-rich"in comparison with precipitation levels for the rest of the nation, drought is a significant concern for three reasons:

- Six of the last 20 years were characterized by drought in some part of the region and even a single year drought can result in water restrictions in many counties.
- The increased warming associated with smaller precipitation changes in the Canadian model provides a scenario for the Northeast characterized by a strong tendency toward frequent extreme droughts.
- The lack of water storage in the Northeast is a significant factor in creating vulnerability. In addition,the regions water withdrawals are highly dependent on surface flow. For example,in the Mid-Atlantic region 95% of the water withdrawals are from surface flows (Neff, 2000). Drought is a frequently cited potential impact of global warming because of increased evaporation rates associated with rising air temperatures.

In contrast,drought tendencies could change very little or decrease given that:

- The Hadley model,with a smaller temperature increase and increases in precipitation,yields a tendency toward neutral changes in drought

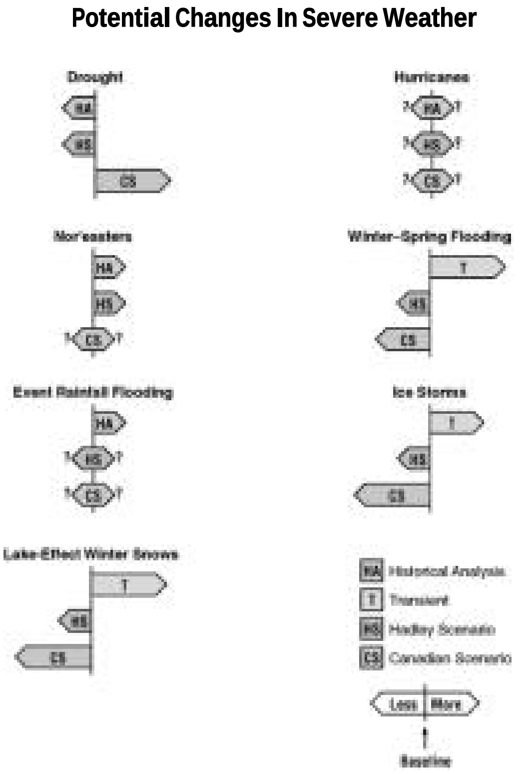
Potential Changes In Severe Weather

Figure 5. Schematic of the potential changes in severe weather for the Northeast based on historical data (H), the Hadley model scenario (HS), the Canadian model scenario (CS) or an assessment of possible transient effects (T). See Color Plate Appendix.

Figure 6. The coastal regions of the Northeast are dominated by extensive estuaries and bays.

severity or slightly decreased drought tendencies,
- Historical analyses indicate that the extent of area experiencing drought in the Northeast declined somewhat.

The Northeast is currently prone to weather-related natural disasters. However, historical analysis and climate model projections present a range of possibilities, including the potential that such weather disasters could increase in both summer and winter. The historical cases of large-scale damages associated with these events even under current climate conditions add a perspective of significant vulnerability. Many human structures are designed based on historical climate records. If these structures are already vulnerable, then this argues for adaptation strategies that focus on "over-designing" critical structures to add margins of safety and more frequent design-criteria review based on updated climate projections. The potential for changes in frequency, path, and intensity of hurricanes, and in the nature of severe winter storms, becomes a key uncertainty in assessing climate impacts. Coping with substantial increases in severe storms, or even repeat of historical events coupled with higher sea level, might necessitate relocation of infrastructure away from high-risk zones. Historically, negative economic impacts of severe weather on forestry and agriculture resulted in different planting and harvesting methods. The impact of changes in severe weather on ecosystems is a significant unknown.

2. Compounding Stresses on Major Estuaries and Bays

Major estuaries and bays, such as the Long Island Sound, Delaware Bay, and the Chesapeake Bay, characterize the coastal regions of the Northeast. These coastal embayments represent unique ecosystems and unique resources for fisheries and recreation (Fisher et al., 2000). Importantly, these geographically defined features are unable to "migrate" in response to climate change. In addition, growth in coastal populations has added substantial stresses to these environments. The Chesapeake Bay, the nation's largest estuary, is a key example.

Chesapeake Bay is characterized by multiple stresses with significant combined impact on water characteristics and ecosystems (Funderbunk et al., 1991; Kearney and Stevenson, 1991; Drake et al., 1996; Perry and Deller, 1995; 1996; Jones et al., 1997; Abler and Shortle, 2000; Walker et al., 2000). Human land-use practices and upstream industry have a marked impact on water quality and pollutant levels. High nutrient and particulate loading from agricultural and urban runoff and air-borne pollutants reduces oxygen levels, which reduces productivity and organism habitat area. High nutrient loading is very likely to increase algal blooms, shading deeper water and limiting submerged aquatic vegetation. Increased land use and growth in the area covered by impervious surfaces has resulted in "flashier" streams, meaning that any rainfall causes a rapid peak flow response. In naturally vegetated areas such as forests, a significant fraction of the rain percolates into the ground. As the soil becomes saturated, more water flows into the streams. It thus takes some time for rainfall to cause stream levels to rise. When land uses cover much of the ground with streets, buildings, and parking lots, less rainfall can percolate into the ground; thus it runs off quickly, causing the streams to "flash." Increased population pressure has also altered the boundary between the land environment and the Bay, providing fixed or "hardened" margins and decreasing the area of wetlands.

Climate change adds an additional stress. The most important influences reflect the potential to change water temperatures and freshwater inputs (hence salinity). Warming of the atmosphere is very likely to have a direct impact on Bay temperatures. Changes in the frequency and intensity of precipitation events, changes in frequency and strength of hurricanes, and any change in the strength and frequency of droughts would substantially influence freshwater inputs. With "flashier" streams, any increase in high precipitation events is very likely to have a marked impact. These changes would then influence salinity in the Bay and stratification of the water mass. Sea-level rise is likely to contribute to these changes. Local rates of sea-level rise in the Chesapeake (close to 4mm/year, or 0.16 inches per year yielding 16 inches in 100 years) are anomalously high for the Atlantic Coast, due to regional subsidence and other factors (Gornitz, 1999). The global average increase in sea level is closer to 1.2mm/year (0.048 inches per year) according to Gornitz and Lebedoff (1987). Both temperature and salinity are significant environmental controls on organism character, influencing fish populations, productivity, and human and ecosystem health. For example, cholera bacteria are present in the Chesapeake Bay. Increased cholera risk is associated with rising water temperatures, however water and waste treatment practices should prevent US epidemics (Colwell et al., 1998).

Gibson (1999) and Najjar et al. (2000) used a water balance model to project a 24% increase in runoff in the Susquehanna River Basin under the Hadley model scenario and a 4% decrease for the Canadian model scenario. Gibson and Najjar (2000) then analyzed changes in Chesapeake salinity as a function of these changes in runoff. The increased runoff in the Hadley model resulted in a 20% decrease in the surface salinity within the northern segment of the Chesapeake, with as much as a 4% change penetrating to deeper waters within the southern segment of the Bay. The Canadian model scenario results in changes of 3% or less.

The potential for significant changes in temperature and salinity raises several important concerns about species composition in the Chesapeake and other bays. Any significant changes in salinity and temperature are very likely to result in the migration or loss of key species. The introduction of opportunistic invasive species during changing conditions is also very likely to change predator-prey relationships influencing the character of ecosystems, or result in elimination of key species that may not be vulnerable to the direct effects of climate change. This type of indirect change is already evident in Chesapeake waterfowl populations in which declines of submerged aquatic vegetation, attributed to excessive nutrients and sedimentation, are associated with dramatic declines in some species of waterfowl unable to adapt to changing food sources (Perry and Uhler, 1988). The Chesapeake and Delaware Bays are stopover points for millions of bird species. Numerous waterfowl (the eight most dominant species have been numbered at 700,000) winter in the Chesapeake. If affected species have economic significance or if they are connected to the uniqueness of a region, the impact is very likely to be significant.

Sea-level change substantially influences wetlands through inundation, saltwater intrusion into fresh and brackish marshes, and erosion. Marshes are already estimated to have lost one-third of their original area.

Percent Salinity Change in the Chesapeake Bay

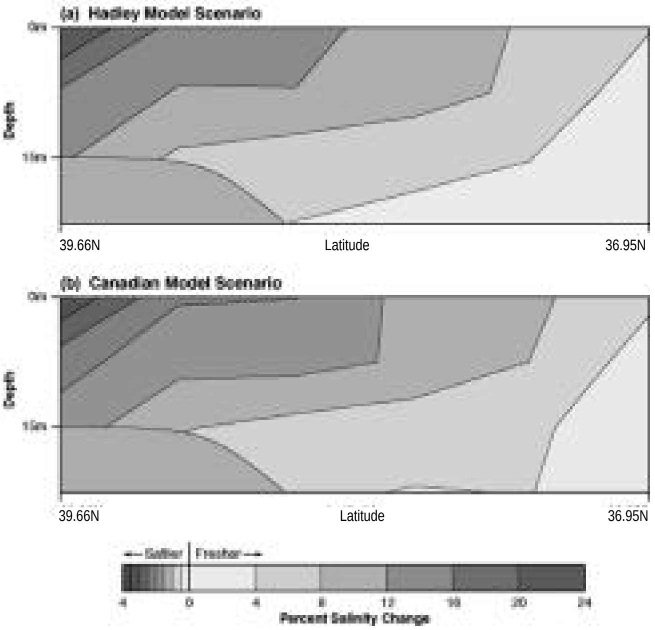

Figure 7. Calculated salinity within the Chesapeake given the runoff calculated from the Hadley (top) and Canadian (bottom) climate scenarios by Gibson and Najjar (2000). The distribution of salinities ranges from the upper reaches of the Bay (39.66N) to the Lower Chesapeake near its Atlantic opening (36.95N). See Color Plate Appendix.

Sea-level rise can also submerge protective barrier islands or cause them to retreat landward onto marsh and lagoonal areas.The hardening of the bay boundaries (through construction of impoundments, retaining walls,dockage,etc.) adds an additional limitation to the landward movement of wetlands as sea level rises. Marshes and lagoons are significant stopover habitats for migratory birds.

Adaptation strategies are governed by three factors. First,estuaries and bays are characterized by a number of compounding stresses. Second,there are limited avenues for protecting critical ecosystems that are geographically fixed and therefore cannot "migrate." Third,the uncertainties in projecting the water balance for the Northeast region under future climate conditions results in substantial uncertainty in determining the future water properties of the Bay and other estuaries in the region. One of the few adaptation strategies available may be to limit the non-climate stresses on the region in order to minimize any climatic impacts. This may argue for greater control of land-use at the boundaries of estuaries and increased concern over nutrient and pollutant fluxes into estuaries and bays. Humans are also gaining some experience in constructing artificial wetlands. However, we know little about the long-term viability of these constructed wetlands.

3. Multiple Stresses on Major

Urban Areas

The major urban areas of the Northeast are stressed even without climate change (Rosenzweig and Solecki et al.,2000). In the Northeast,there have been major investments in the infrastructures of system elements such as roads, water supply, communication,energy delivery, and waste disposal. Still, for many large urban areas this infrastructure is characterized by aging,problems with under-capacity, overuse,and deferred maintenance. Cities are associated with a host of continuing problems,some related to climate like air quality, and others that are non-climate related such as crime and poverty. The complex web of institutional relationships among communities, municipalities, regions,states,the federal government,and the public,private,and non-profit sectors often make consideration of overarching issues,such as the environment, problematic. Scenarios from climate models suggest that climate change intersects with a significant number of other stresses,all with implications for overall quality of life.

Sea Level and Storm Surge. One of the more significant potential climate change impacts in urban coastal communities is rising sea level (Bloomfield, 1999) and elevated storm surge levels. For example, historical events suggest that the metropolitan areas are particularly vulnerable. By using daily tide gauge data and statistics on extreme events (Ebersole,

Nor'easter of December 1992

The December 11-12,1992 nor'easter produced some of the worst flooding and strongest winds on record for the area. It resulted in a near shutdown of the New York metropolitan transportation system and evacuation of many seaside communities in New Jersey and Long Island. This storm should have provided a "wake-up"call,heralding the vulnerability of the transportation system to major nor'easters and hurricanes. Had flood levels been only 1 to 2 feet above the actual high water level of 8.5-foot above mean sea level,massive inundation of rail and subway tunnels could have resulted in loss of life. With rising sea levels, even a weaker storm would produce comparable damage. While hurricanes are much less frequent than nor'easters in this area, they can be even more destructive because the geometry of the New Jersey and Long Island coasts amplifies surge levels toward the New York City harbor. For a worst-case scenario category 3 hurricane, surge levels could rise 25 feet above mean sea level at JFK airport and 21 feet at the Lincoln tunnel entrance.

Figure 8. Vulnerable coastal areas for Manhattan, based on a 20 foot high flooding zone for the year 2100, derived by Klaus Jacob of Lamont-Doherty Earth Observatory for the Metroeast workshop. See Color Plate Appendix.

1982), the Metro-East Assessment team (Rosenzweig and Solecki et al., 2000) calculated a range of scenarios delineating significant coastal vulnerability, particularly in urban areas. Critical points for flooding for many of the region's vital transportation systems (including airports, subways, highways, and major road and railroad tunnels) are located at elevations between 7 and 20 feet above current sea level and are very likely to be inundated by coastal storm surges with estimated recurrence periods of about 100 years. Taking into account models of sea-level rise (IPCC, 1996) of 9 inches to 3 feet (23 to 96 cm) in the next 100 years, these current recurrence periods are likely to be shortened by factors of 3 to 10 before the year 2100.

Water Supply. Water supply systems in the major northeastern cities also exhibit substantial vulnerability to climate change. For example, the New York City water system is large and relatively inflexible in terms of demands on the system, and therefore susceptible to large changes in the water balance. A few key examples illustrate the nature of the problem. New York City's water supply is derived from water collected from a 2,000 square mile area, stored in three upland reservoir systems. This is an ecosystem service that the City has secured by making a capital investment of about $1 billion in the surrounding communities. The City's water supply is sensitive to climate variability and change given the demands on the current system, and its dependence on annual precipitation levels. Even with increased winter precipitation, rapid run-off (rather than accumulation as snow) has resulted in significant regional water supply problems in recent decades (McCabe and Ayers, 1989). The climate stresses from current conditions are already evident. The climate vulnerability is compounded by two factors. First, the upstate communities have experienced substantial growth. Second, these upstate communities have a legal right to water in times of low supply. In addition, New York City has a legal obligation to provide water to the Delaware Basin because it has access to water in the river headlands. In the Delaware Basin, additional water releases from the reservoir systems might be required if sea-level rise advances the salt water front up the Delaware and Hudson rivers (Alpern, 1996). A prolonged drought is likely to force the city to seek alternative water sources.

Soil Moisture. The combination of future precipitation changes and an increase in evaporation associated with higher future temperatures is expected to produce a decrease in summer soil moisture (Broccoli, 1996). The climate model scenarios used in this Assessment both project little trend in soil moisture in the region immediately adjacent to the city. However, significant climate change is likely to result in the need for new large-scale investments in order to replace the current ecosystem service from the growing surrounding communities.

Heat-related Illness and Death. Warmer summers are likely to be associated with higher maximum temperatures and then with increased heat-related morbidity and mortality in major cities of the Northeast (Kalkstein and Greene, 1997; Chestnut et al., 1998; Kilbourne et al., 1982). By 2090, increases in maximum temperatures from 1-2˚F to 5˚F are projected for the coastal Northeast. An associated increase from the current 13 days to a projected 16-32 days above 90˚F might result in a five-fold increase in heat-related mortality in New York City according to the Metroeast regional assessment, if no adaptation occurs. Kalkstein and Greene (1997) and Kalkstein and Swift (1998) utilized three different climate models to examine winter and summer mortality for 2020 and 2050. In all three models, increases in summer mortality exceeded decreases in winter mortality for Baltimore, Philadelphia, Pittsburgh, and Washington D.C.

Air Pollution. Higher summer temperatures also increase photochemical reaction rates leading to an increase in ground-level ozone (smog) and other pollutants. The New York City area already has one of the nation's highest rates of respiratory disease associated with airborne pollutants. This is likely to be exacerbated by increases in the urban heat island effect and conditions of persistent elevated summer

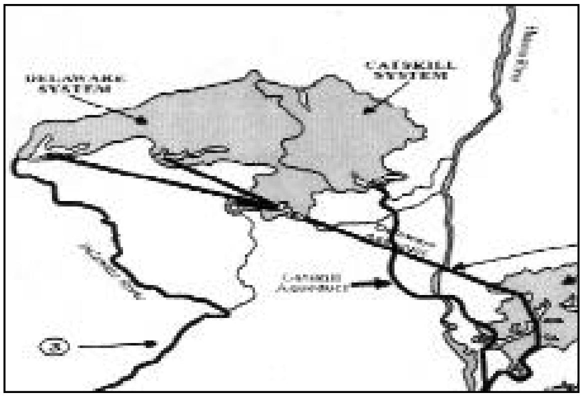

Figure 9. Water is one of the major ecosystem services provided to New York City by the surrounding land areas (Metroeast Workshop). Population growth in the region, and legal rights to the water by upstate communities, place the adequacy of the water supply at greater risk under some scenarios of future climate change.

temperatures.

In summary, the major urban areas of the Northeast are characterized by multiple stresses. Climate change has the potential to exacerbate many of these problems. The most significant climate-related stresses in the urban regions of the Northeast are increased heat mortality, greater ozone pollution associated with higher temperatures,infrastructure risk due to higher sea level, water availability problems associated with significant changes in regional water balance,and increased vulnerability to severe storms.

The addition of significant multiple stresses to the urban environment argues for a variety of adaptation strategies. Some of the direct health effects of heat can be mitigated with active warning systems (heat alerts,opening of shelters,spraying water on dark building tops) such as those currently in place in Philadelphia,structural adaptations (construction that promotes air-flow, reduction in area of black roofing,etc.) and "cool community"measures such as increased planting of trees. Some of the projected mortality studies do not reflect potential changes in air conditioning use or other adaptations,which offer substantial protection against heat waves. Indirect air pollution problems can be addressed through stricter controls on pollutants and ozone precursors. Construction of dike systems or relocation of critical infrastructure can reduce some of the vulnerability to sea-level rise.

Figure 10. Outdoor recreation is of major economic importance in the Northeast, and it is tightly coupled to climatic conditions.

Significant financial investment would be required to produce an urban system that is more robust under conditions of higher storm surges or increased tendency toward drought. Increased flooding and a significant increase in severe storms would argue for establishment of set back zones, rezoning,buyouts of high risk areas, relocation of structures at risk,or altered management. Investing in new reservoirs,limiting growth in water source regions,and increasing water costs to promote conservation are the primary coping strategies for water-related problems,but major reservoir construction projects have associated environmental consequences. A more comprehensive regional water management strategy with increased emphasis on safe water supplies could substantially mitigate major water supply and quality problems.

4. Recreation Shifts

Changes in warmth and the seasonal characteristics of precipitation are likely to have substantial impacts on recreation in the Northeast. In particular, this has been identified as a key issue for New England (Rock and Moore,2000). These impacts differ widely with the type of recreation and season. The winter ski industry is particularly vulnerable. Increases in minimum nighttime temperatures,periodic warm spells,and increased occurrence of winter precipitation as rain are likely to limit the ability of ski areas to maintain adequate snow pack. Current skiing locations with marginal climate characteristics are likely to become untenable.

The recent tendency for mild winters in the Northeast,coupled with climate model projections indicating significant increases in winter minimum temperatures,points to possible benefits. Mild winters and extended periods of warmth in fall and spring may encourage new recreational activities in the forested mountains of the region.

Higher sea level coupled with increased winter storms is likely to result in loss of beachfront property and destruction of barrier islands,decreasing the opportunities for beach recreation during warm months. In highly populated areas,prime recreational beaches can probably be maintained by more frequent episodes of beach nourishment,but costs could increase substantially (Valverde et al.,1999). Wet springs and mild winters are likely to lead to increased populations of insects and high pollen counts. Increases in disease-bearing vectors, such as mosquitoes and ticks, add increased health risks. For example, mosquito populations are tightly connected to minimum temperature characteristics and water availability. Increases in pest populations are likely to adversely impact recreation. The climate model projections offer different scenarios; the increased drought frequency in the Canadian model yields a different pest population than the warmer and wetter projection from the Hadley model.

The New England region currently experiences summer air quality and ozone pollution problems, both of which are exacerbated by warming. Ground-level ozone across New England may reach unhealthful levels during summer months, especially during humid periods when maximum temperatures exceed 90˚F. The combination of high temperatures and full sunlight, coupled with nitrogen oxides generated primarily by automobile traffic, and volatile organic compounds from both natural and human sources, result in elevated levels of ground-level ozone, a form of air pollution often called smog. Exposure to elevated levels of ozone has a negative impact on both forest health and human health. Due to the topographic variability typical of New England and upstate New York, and the fact that the region is typically downwind from major urban centers, high-elevation areas (above 3,000 feet) are likely to have unhealthful levels of ozone. The prospect of air quality alerts for hikers in the mountains of New England is likely to have a negative effect on tourism.

In contrast, typical summer recreational activities involving beaches or freshwater reservoirs are very likely to experience extended seasons. However, sea-level rise is projected to lead to increased beach erosion and loss due to the impact of both storm surges and permanent inundation. Due to the large amount of human development abutting beach areas, establishment of new beaches further inland is difficult in many cases or could result in significant costs to land owners or both. Adaptation measures including beach replenishment or hard structures such as sea walls and groins are costly and often ineffective except in the short-term. The diverse waterways of the Northeast, including lakes, rivers, beaches, and estuaries, are likely to continue to be havens for escape from the summer heat.

In autumn, a major recreational draw for the Northeast is the display of fall foliage. However, increased autumn warmth is associated with muting of fall foliage colors. Drought decreases leaf color and changes the timing of leaf drop. Both factors detract from a major tourist attraction in the Northeast. The two climate models used in this Assessment offer different recreational scenarios as the Canadian model projects increased drought while the Hadley model projects little change in drought risk.

Figure 11. On warm humid days when temperatures exceed 90ºF, ozone problems are exacerbated across the region. The top figure shows the view on a clear day at the Great Gulf of Mount Washington, New Hampshire. The bottom figure shows the same view when temperatures exceed 90ºF and air quality problems occur.

The key outcome of an analysis of recreational activities is that the extent of potential impacts is highly dependent on the type of activity and on the differences between the model results. Many of the activities are likely to “migrate” out of portions of the Northeast or will move northward (such as the ski industry). Ski resorts are likely to be required to continue current trends toward development of year-round attractions. An extended warm weather season is very likely to make waterways, mountains, and forests greater attractions. Undoubtedly, humans will make trade-offs in terms of type and location of recreational activities. The uncertainties associated with the water balance projections for the Northeast contribute to uncertainties about the impact of climate change on recreation in the region.

A key uncertainty is whether climate change will

New England Maple Syrup

A successful maple syrup season in New England depends on the proper combination of freezing nights and warm daytime temperatures,along with prolonged cold temperatures (resulting in a recharge of sugar to the sap) during the months of February and March. When the right combination of these climatic conditions occurs,the sugar maple tree produces a sap containing 2-5% sugar. In addition,the first flow of sap in a given season generally produces the highest quality maple syrup. A sustained,early flow heralds a good year for the maple industry in an area. If the initial flow occurs too early, before many of the producers have tapped their trees,they will miss this profitable opportunity. The maple industry in New England depends to a large extent on the timing of these critical climate events. Due to changes in both technology (the advent of tubing) and climate (very early initial flows and a reduction in freeze/thaw cycles and cold recharge periods),the maple syrup industry is moving from New England into Canada.

In the past,the success of the maple syrup industry in Canada was limited by deep snow cover (limiting access to individual trees) and fewer freeze/thaw cycles due to prolonged periods of low nighttime and daytime temperatures. The development of tubing-based sap collection methods,which provide easier access to trees and eliminate the need to make frequent collections,has allowed the Canadians to become more competitive in the past several decades. Changes in climate over the past several decades also allowed the Canadians to collect more sap over a longer “sugar season”than in the past. Conditions for sustained sap flow now mark the Canadian season while higher temperatures have led to fewer freeze/thaw cycles and reduced cold recharge periods in New England. This,coupled with earlier and earlier initial flows over the past two decades,has resulted in a shift in the volume of syrup production from the US to the Gaspe Peninsula of Quebec. It is interesting to note that in 1928,the major syrup production center in the US was located in Garrett County, Maryland.

If wintertime minimum temperatures continue to increase more rapidly than the maximum temperatures (as indicated in the climate models used in this Assessment) then the current northward shift in maple syrup production is very likely to continue. In the long term, change in the range of the maple tree is very likely to completely dominate the ability to produce maple syrup. The climate model scenarios,when coupled with assessments of the species composition of forests under the Canadian and Hadley model climate projections, project a substantial northward displacement in the distribution of maple trees (see Chapter 17 on Forests). It is likely under these scenarios that maple syrup production will not be possible in many regions of the Northeast because conditions for tree growth are unsuitable.

yield an increased tendency toward drought,which will impact fall colors, forest health,and the nature of water-related recreational activities.

ADDITIONAL ISSUES

Two additional issues are likely to be of considerable significance for the Northeast:

Forests

The species composition of the forests of the Northeast is very likely to change dramatically under both the Hadley and Canadian climate scenarios. Two approaches are available for assessing the forest changes in the Northeast. The MAPSS vegetation analysis (Neilson and Drapek,1998) provides an analysis of the distribution changes in large-scale forest types (e.g.,the Northeast mixed forest or the conifer forests of New England). The model of Iverson and Prasad (1998) examines changes in dominant forest species (e.g.,maple-beech-birch, oak-hickory, elm-ash-cottonwood,and oak-gum-cypress). Although both vegetation models indicate substantial changes in forest character in response to the climate model scenarios,there are also some differences between the models as might be expected from two different approaches.

Based on the Canadian model scenario and the MAPSS vegetation analysis,the conifer forest of northern New England and much of the northeast mixed forest of New England,New York,and western Pennsylvania changes to a temperate deciduous forest similar to southeastern Pennsylvania and northern Virginia today. The area of southeast mixed forest,today characteristic of the region south of Virginia,becomes compressed into a small area of

West Virginia, southern Pennsylvania, and the coastal plain of Virginia, Delaware, and New Jersey, while much of Virginia becomes savanna/woodland. The Hadley model predicts less dramatic changes but still the conifer forest of northern New England is replaced by northeast mixed forest. The area of temperate deciduous forest in New England and Pennsylvania/West Virginia grows slightly. The area of southeast mixed forest grows in Virginia. The northeast mixed forest declines dramatically in total area (72% loss of area in the US according to the Forest Sector Foundation report) and specific species, for example the sugar maple (*Acer saccarum*), are lost entirely from the US (Watson et al., 1998).

An additional analysis by the Mid-Atlantic Assessment (Fisher et al., 2000) examined the distribution of dominant forest types based on the model of Iverson and Prasad (1998). Oak-hickory forests (46%) and maple-beech-birch (37%) dominate the region today. In both climate model scenarios, oak and hickory forests replace the maple-beech-birch forests of western and northern Pennsylvania, West Virginia, and southern New York. These large changes have significant potential to affect aesthetics, tourism, fall colors, and to cause people concern. Although in the short-term, forests are regarded as only moderately vulnerable to the specific climate changes projected, changes in timber, and non-timber values such as recreation, scenic views, and wildlife habitat may be long-term issues.

Forest issues extend well beyond the species composition of the forests. These issues include (a) the potential for alteration of tree resistance to insects associated with changes in temperature and water availability (Roth et al., 1997), (b) increased fire occurrence associated with increased tendency toward drought, (c) reduction in primary productivity and carbon storage despite carbon dioxide fertilization if drought becomes as significant as projected by the Canadian model, (d) changes in forest disturbance as a function of changes in hurricane frequency and intensity, or changes in wind, ice, or heavy precipitation events. Climate change can also compound the impacts of invasive species, as invasive species tend to have high reproductive rates, good dispersal ability, and rapid growth rates (Williamson, 1999). Many of these impacts are associated with aspects of climate model projections that are associated with uncertainty – e.g., changes in the character of extreme weather and the nature of the future water balance in the Northeast under climate change conditions.

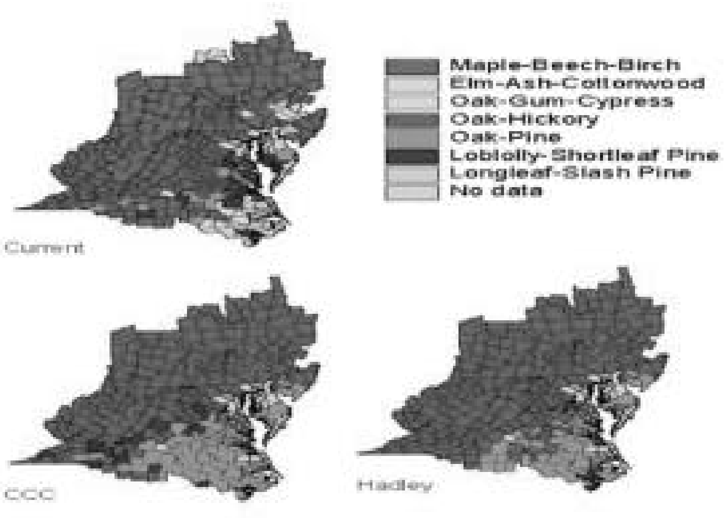

Figure 12. Dominant forest types for the mid-Atlantic region for current climate, and the potential distribution of these forest types for the Canadian and Hadley climate scenarios based on the Mid-Atlantic Assessment. Based on the model of Iverson and Prasad (1998). See Color Plate Appendix.

Agriculture

Although crop production is tied to climate, agriculture is a relatively small and declining fraction of economic output of the Northeast. Further, most studies indicate that the agriculture in the Northeast is relatively robust to climate change even though the crop mix may change (Abler et al., 1999). The ability to change crop types and to take advantage of hybrids limits vulnerability. The most frequently cited concern related to agriculture is associated with market forces, some of which are likely to be climate-related, generated by agricultural changes outside of the Northeast region. Some cool weather crops and many small family farms are exceptions to these conclusions. Farmers in the Northeast region make a significant contribution to the national supply of dairy products and food crops such as apples, grapes, potatoes, sweet corn, onions, cabbage, and maple syrup. In addition, small family farms throughout the Northeast are vital to the economy of rural areas, and they fill an important market niche for fresh, high quality, affordable local produce. These farms will be particularly sensitive to climate change due to the cost of adaptation, especially if compounded by other market forces. For example, the Northeast dairy industry is already quite fragile. Milk production by dairy cows is optimal at cool temperatures, so an increase in temperatures will require substantial increases in air conditioning costs. Most research on climate change impacts on agriculture has focused on major world trade crops such as wheat, soybeans, and corn.

Information from these studies has only very limited application to the Northeast where dairy and high value horticultural crops dominate the economy. Overall, agriculture in the Northeast is likely to survive a climate change,and may even benefit relative to some other regions of the US. However, the costs of adaptation could be high,and the vulnerability of small farms is likely to increase.

ADDED INSIGHTS

The results of assessment research in the Northeast yield several additional insights into the impacts of climate change on the region. Substantive issues include,but are not limited to the following:

Institutional Complexity. The complex institutional framework of community, municipal,county, regional,and statewide formal and informal governing bodies that characterize the Northeast have the potential to limit the region's ability to deal with extremes. For example,the complex array of watersheds,small management units,and urban dependencies on broad surrounding regions with different institutional characteristics all have the potential to limit drought planning and response management. Climate change is likely to cause a change in political focus and management of critical ecosystem services like water. Similar issues arise for weather disaster social services and energy distribution. There are signs of innovative management even with complex institutional structures in the Northeast transportation systems (e.g.,introduction of electronic fare collection systems and EZ Pass). The ability of the Northeast to adapt to extreme situations will depend upon the ability of institutions to identify and prioritize vulnerable facilities and populations. Targeting and flexibility in the use of resources among the many institutions is needed to adapt more effectively to climate change.

Infectious Diseases. Infectious disease vectors are often strongly influenced by climate. For example, the primary Lyme disease vector is the deer tick. The tick population is governed by the size of both mouse and deer populations. Increased acorn mast production directly influences rodent populations. Milder winters contribute to a larger survival rate for deer. Larger deer populations increase the human contact with deer and deer ticks,increasing the possibility of Lyme disease infections. Milder winters are projected by virtually all climate models (the two primary models used in this Assessment both indicate large increases in winter minimum temperatures). Although climate has a strong impact on Lyme disease vectors,the complexity of the relationships makes changes in the distribution and frequency of the disease under altered climate difficult to predict (Martens,1999). Changes in mosquito populations and survival are also possible with warmer and wetter conditions. Recent examples of outbreaks of West Nile Virus and equine encephalitis in Northeast urban areas have substantially raised concerns about vector-borne diseases and illustrate that improved monitoring and better understanding of these diseases are important to the region. Increased temperatures in coastal bays are likely to increase algal blooms,which have a chance of harboring cholera. Increased rainfall and flooding,if severe,have historically caused contamination of public and private water supplies (e.g., with *cryptosporidium*) and models project an increase in very heavy rainfall events and the potential for greater flood risks. However, in large measure,US public health infrastructure and response capabilities,if vigorously sustained,are likely to limit the potential impacts.

Species Changes. Although ecosystem character was not selected as one of the major topics for the first US National Assessment, regional assessment teams raised a significant number of issues concerning changes in species composition beyond forest character. Changes in temperature and precipitation will have direct impacts on species distribution as well as indirect impacts associated with changing predator-prey relationships and/or changes in pests and disease. In many cases,these species may be truly characteristic of a region or may be of economic significance. For example,lobster populations are associated with cooler waters and warming may promote northward migration of the population — a key issue for New England. Coastal population pressures combined with sea-level rise are very likely to limit habitat regions along the Atlantic Flyway for migratory birds. Warming is likely to substantially limit trout populations — a key issue for Pennsylvania. Changes in species mix and introduction of climate-driven invasive species are likely to also have unanticipated feedbacks on ecosystems.

Differential Human Impacts. The large differences in economic status and the aging of the population in the Northeast is likely to be associated with differential impacts based on the ability to respond to climate change. Where impacts are significant, climate change is likely to have greater impact on lower-income residents and the elderly, as well as children and the ill (e.g.,those with chronic respiratory ailments). The key concerns are heat mortality, susceptibility to disease, and changes in air quality factors such as ozone. For example, lower income residents, often including the elderly, may have additional burdens because of lack of air conditioning, poor housing conditions, and unsafe neighborhoods leading to unwillingness to open windows or seek relief out of doors or away from the city.

ADAPTATION STRATEGIES

The most important elements of adaptation strategies proposed for the Northeast include:

- relocating structures at risk from severe weather (e.g., hurricanes) and flooding (both in coastal regions and in river systems prone to high water levels);
- strengthening design criteria for critical infrastructure (e.g., power supply) to ensure robust operation under possible changes in weather and climate extremes;
- increasing reservoir construction and improving management of water supplies to increase robustness of the water systems under conditions of flooding or drought, recognizing the potential for other negative consequences;
- greater emphasis on water quality and air quality controls to minimize the compounding of climate impacts, including stricter adherence to existing regulations and potentially stricter controls on pollutants and their precursors;
- incorporating active warning systems (e.g., Philadelphia's heat wave warning system) and structural adaptations (e.g., construction that promotes air-flow, and reduction in area of black roofing) to limit the potential for increased heat mortality and morbidity;
- limiting the non-climate stresses in order to minimize impacts on critical regions that are geographically fixed and therefore can't "migrate" such as the Chesapeake Bay;
- limiting agricultural and forestry economic impacts by introducing different planting and harvesting methods based on historical responses to weather and climate; and
- limiting coastal development through existing regulatory frameworks to protect coastal regions, increasing the focus on "smart" land use to reduce vulnerability to floods and storm damage, and limiting pollution delivered to coastal regions by water run-off from the adjacent land area.

The social and economic framework of the future is likely to be substantially more advanced than at present. As a result, the adaptation strategies may become more numerous, more effective, and more easily implemented.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Seven critical factors limit our ability to assess the potential importance of climate change on the Northeast:

- For the Northeast, changes in extreme weather are viewed as a critical issue in assessing potential impacts. A key issue is an ability to assess the potential changes in severe storms, including hurricane intensity, path, and frequency and the character and frequency of nor'easters. Changes in the frequency and intensity of extreme weather events with climate change remain one of the most uncertain aspects of future climate.
- Improved projections of the spatial and temporal distribution of future temperature and precipitation would enable a more robust assessment. The difference in the projections of changes in the Palmer Drought Severity Index between the Canadian and Hadley models presents significantly different scenarios, with dramatically different implications for ecosystems, water, recreation, and agriculture.
- The ability to combine multiple stresses and to simulate the resultant effects on the environment is severely limited in many specific environments (e.g., the Chesapeake Bay). Fully integrated observational networks for multiple variables and comprehensive models will be required to address multiple stresses.
- Changes in population and land use patterns will have dramatic effects on ecosystems and on the nature and magnitude of climate impacts, yet the ability to project these changes is limited. Continued growth in coastal populations in conjunction with sea-level rise introduces substantial additional risk due to severe weather and greater concerns about habitat loss.
- Understanding of the potential change in species composition and character in response to climate change is in its infancy. This includes changes in economically important species, pests, invasive species, and predator-prey relations. Validation of biological response models is a major problem.
- Understanding of how people and societies will adapt, due to uncertainties in overall changes in

the economy, technology, and societal values, is a major area of uncertainty.

- Uncertainties in estimating sea-level rise substantially limit the ability to assess the height of storm surges and the recurrence interval of flooding events with substantial economic impacts.

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ACKNOWLEDGMENTS

Many of the materials for this chapter are based on contributions from participants on and those working with the

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