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CHAPTER 8
BIOLOGICAL DIVERSITY

by Lauretta M. Burke
and Ross A. Kiester

FINDINGS

Unlike most other impacts, loss of species and reduced biological diversity are irreversible. The ability of a natural community to adapt to changing climate conditions will depend on the rate of climate change, the size of species ranges, the dispersal rates of the individual species, and whether or not barriers to species migration are present. If climate changes rapidly, many species will be lost.

Species Diversity

- The effect of climate change on species and ecosystems will most likely vary, with some species benefiting and others facing extinction. The uncertainties surrounding the rate of warming, individual species response, and interspecies dynamics make impacts difficult to assess. However, climate change would alter competitive outcomes and destabilize natural ecosystems in unpredictable ways.

- In many cases, the indirect effects of climate change on a population, such as changes in habitat, in food availability, and in predator/prey relationships, may have a greater impact than the direct physiological effects of climate change.

- Natural and manmade barriers, including roads, cities, mountains, bodies of water, agricultural land, unsuitable soil types, and habitat fragmentation, may block migration of species in response to climate change and exacerbate losses.

- The areas within the United States that appear to be most sensitive to changes in climate are those that have a number of threatened and endangered species, species especially sensitive to heat or drought stress, and species inhabiting coastal areas.

- Rapid climate change would add to the already existing threats biodiversity, faces from anthropogenic activities, such as deforestation and habitat fragmentation.

Marine Ecosystems

- The loss of coastal wetlands and coastal habitat resulting from sea level rise and saltwater intrusion may profoundly affect the populations of all inhabitants of these ecosystems, including mollusks, shellfish, finfish, and waterfowl. However, there is no evidence to indicate these species would become extinct.

Freshwater Ecosystems

- Freshwater fish in large bodies of water, such as the Great Lakes, may increase in productivity, but some significant species could decline. Fish in smaller bodies of water may be more constrained in their ability to respond to climate change. They also may be harmed by reductions in water quality.

Migratory Birds

- Migratory birds are likely to experience mixed effects from climate change, with some arctic nesting herbivores benefiting and continental nesters and shorebirds suffering. The loss of wintering grounds due to sea level rise and changing climate could harm many species, as would the loss of inland prairie potholes due to potentially increased continental dryness.

Policy Implications

- Existing refuges, sited to protect a species or ecosystem under current climate, may not be properly located for this purpose if climate changes or as species migrate.

- Wildlife agencies such as the Department of the Interior, state government agencies, and conservation organizations may wish to assess the feasibility of establishing migratory corridors to facilitate species migration.

- Areas that may become suitable future habitat for threatened and endangered species, such as lowland areas adjacent to current wetlands, need to be identified and protected.

- The practice of restoration ecology may need to be broadened to rebuild parts of ecosystems in new areas as climates shift.

- The increase in the number of species at risk as a result of climate change may require new strategies for balancing ecosystem level concerns with single species concerns. Agency programs such as the Fish and Wildlife Service's Endangered Species Program, may wish to assess the relative risk of climate change and more current stresses on ecological systems.

VALUE OF BIOLOGICAL DIVERSITY

Maintaining the biological diversity of our natural resources is an important goal for the nation. The preamble to the Endangered Species Act of 1973 emphasizes the value of individual species, stating that endangered and threatened species of fish, wildlife, and plants "are of aesthetic, ecological, educational, historical, recreational and scientific value to the Nation and its people." We depend upon our nation's biological resources for food, medicine, energy, shelter, and other important products. In addition to species diversity, the genetic variability within a species and the wide variety of ecosystems add to biological diversity. Reduced biological diversity could have serious implications for mankind as untapped resources for research in agriculture, medicine, and industry are irretrievably lost.

The evolving biological diversity of this planet is inevitably affected by climate change. Historic climate changes have resulted in major changes in species diversity. This has been true for the millions of years life has existed on Earth. Now our planet may face a more rapid change in climate that may have important consequences for biological diversity.

The National Resource

Public and private lands in the United States provide sanctuary for an abundant diversity of plants and animals. About 650 species of birds reside in or pass through the United States annually. Over 400 species of mammals, 460 reptiles, 660 freshwater fishes, and tens of thousands of invertebrates can be found in this country, in addition to some 22,000 plants (U.S. Fish and Wildlife Service, 1981). These species compose a wide variety of ecosystem types within the United States, including coniferous and broad-leaf forest, grassland, desert, freshwater, marine, estuarine, inland wetland, and agricultural ecosystems. Figure 8-1 shows the major ranges of natural vegetation in the United States.

The U.S. national parks, forests, wilderness areas, and fish and wildlife refuges are among the public lands that provide sanctuary for wildlife resources, including many endangered species. U.S. public lands, which encompass over 700 million acres (about 32% of the land area of the United States), support about 700 rare species and communities (Roush, 1986). Over 45% of the lands held by the Forest Service, Fish and Wildlife Service, National Park Service, and Bureau of Land Management are in Alaska, and over 48% are located in the 11 most western states (U.S. Department of the Interior, 1987). However, much of the nation's biological diversity lies outside these areas.

Private land holdings also account for a great deal of this nation's biological endowment. Private groups, such as the Nature Conservancy and the Audubon Society, manage 500,000 acres and 86,000 acres, respectively, for biological diversity.

GENERAL COMPONENTS OF BIOLOGICAL DIVERSITY

Biological diversity can be broadly defined as the full range of variety and variability within and among living organisms. It includes species diversity, genetic diversity, and ecosystemic or community

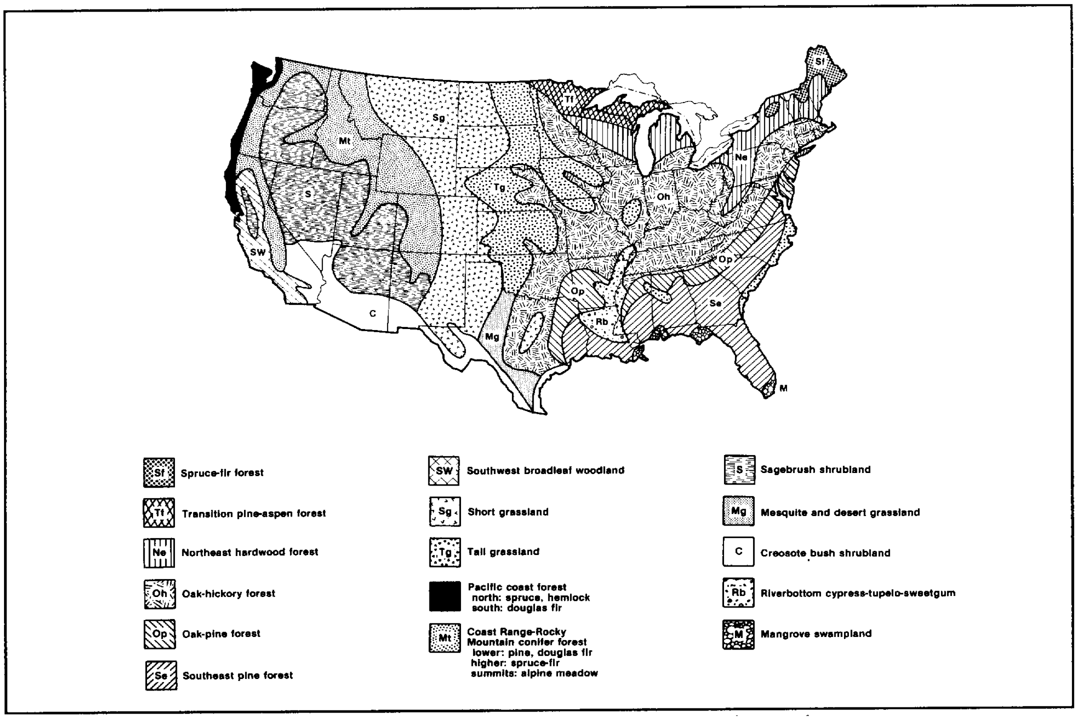


Figure 8-1. Natural vegetation in the United States (Hunt, 1972).

diversity. This report concentrates on species diversity, but only because it is better understood. Genetic and ecosystemic diversity are equally important.

Species Diversity

Each species occurs in a characteristic range or geographical area. The factors controlling species ranges are critical constraints on biological diversity. The presence of a species in an area suggests that the species must have successfully achieved the following: (1) dispersal into an area (no barriers to dispersal, such as the presense of bodies of water or unsuitable soil types); (2) survival in that area (the physical characteristics of the area were suited to the species' physiology, and food was available); and (3) establishment in the area (the organism found an appropriate place in the food web in the absence of excessive competition and predation, and was able to reproduce).

The stresses brought about by development, overuse, and alteration of habitat have fragmented much of the world's natural habitat and have created many new barriers. Consequently, for many species, dispersal has become much more difficult than it was in the past. For other species, humans have inadvertently aided dispersal and have caused rapid spread in recent years. Such practices as clearcut logging prevent the dispersal of species adapted to dense forest conditions (e.g., flying squirrels) and promote the dispersal of species suited to open areas (e.g., deer).

Currently, 495 species are listed as endangered within the United States, and over 2,500 species await consideration for that status by the Fish and Wildlife Service. The list of endangered species is dominated by plants, birds, fishes, and mammals but also includes insects, amphibians, reptiles, mollusks, and crustaceans (U.S. Fish and Wildlife Service, 1988).

New species are created through the evolutionary process of speciation, whereas existing species are lost through extinction. Speciation generally requires at least hundreds of thousands of years. However, extinction as a result of human activities, even without climate change, is occurring rapidly and at an increasing rate. Owing to its slowness, the process of speciation does little to offset species' loss to extinction.

Stressed Biological Diversity

Biological diversity continues to erode steadily around the globe as a result of human activities. Habitat destruction, degradation, and fragmentation have resulted in the loss of many species and have reduced the ranges and populations of others. These impacts affect all three levels of biological diversity. Through providing an additional pressure on ecological systems, climate change will further reduce the biological diversity in this nation and around the globe.

It is difficult to determine the exact rate of species extinction because the number of species on the Earth is known only to an order of magnitude. A recent estimate by Wilson (1988) places the total number of species between 5 and 30 million. Assuming 10 million species, Wilson made the rough calculation that one in every 1,000 species is lost each year. Wilson then compared this to estimates of extinction rates over geologic time, which ranged between 1 in every 1 million and 1 in every 10 million each year. Thus, human activities may be eliminating species at least 1,000 times faster than natural forces.

The significance of rare species should not be underestimated. A narrowly or sparsely distributed species may be a keystone in an ecosystem, controlling the structure and functioning of the community, or it may be a species of great and yet unknown value to humans.

Genetic Diversity

Each species that persists has a characteristic genetic diversity. The pool of genetic diversity within a species constitutes an adaptation to its present environment as well as a store of adaptive options for some possible changes in the environment. The loss of genetic diversity can contribute to the extinction of a species by reducing its ability to adapt to changing environmental conditions.

Generally, species with larger populations have greater genetic diversity. Species near extinction represented by few individuals in few populations have lower genetic diversity, a situation exacerbated by inbreeding. Additionally, extreme climatic events may cause bouts of natural selection that reduce genetic variability (Mayr, 1963).

Community and Ecosystemic Diversity

Ecosystemic diversity is the number of distinctive assemblages of species and biotic processes that occur in different physical settings. A long-leaf pine forest, a sand dune, and a small pond are all part of our diversity at this level. Ecosystems come into existence through complex physical and biological processes not now well understood. They may be lost by outright replacement of one by another (as in the desertification of a grassland) or by the gradual merging of two formerly separate ecosystems (as in the loss of some estuarine systems when they become saltier and take on more of the characteristics of a purely saltwater ecosystem). Ecosystems can also be eliminated because of human activities (as in the filling in of a wetland).

FACTORS AFFECTING THE RESPONSE OF BIOLOGICAL DIVERSITY TO CLIMATE CHANGE

Species respond to environmental change on a hierarchy of time scales. For relatively small changes occurring within the lifetime of an individual, each member of the species can respond through a variety of physiological adjustments. Individual species differ in their ability to adjust to change. Some can withstand a great deal of climate change, whereas others are restricted to a narrow range. Over several generations, natural selection can cause genetic adaptation and evolution in response to the change. Alternatively, a species can respond to climate change by moving into a new area through migration and dispersal. This can occur over a relatively short period of time if the species has the biological ability to move quickly. The discussion of response to climate change centers on migration as the response that could occur over a relatively short period of time.

The distributions of species are significant indicators of climate change. Local climate appears to be the primary factor defining an environmental setting and determining the species composition and spatial patterns of communities in terrestrial zones (Bolin et al., 1986). Temperature means, temperature extremes, and precipitation are the factors most often affecting the potential natural distributional limits of a species (Ford, 1982), while the actual distribution of a species is also affected by soil type, soil moisture, ecological dynamics, and regional isolation.

Rate of Climate Change

Predicting how a species or ecosystem might respond to a given environmental change is difficult. Adaptation to climate change will inextricably depend on the rate of climate change. For some species, migration rates may be inadequate to keep up.

The large number of combinations of dispersal range and age to reproduction make the potential rate of migration different for every species. Paleorecords suggest migration rates between 10 and 20 kilometers per century for chestnut, maple, and balsam fir, and between 30 and 40 kilometers per century for some oak and pine species (see Chapter 5: Forests). On the other hand, cattle egrets have shown a much quicker migration rate by colonizing all of the North American tropics within approximately 40 years.

As species shift at different rates in response to climate change, communities may disassociate into new arrangements of species. Local extinction can result either directly from physiological pressures or indirectly from changes in inter species dynamics. Hence, the effect of climate change on an area will be to cause sorting and separation of species as a result of the differential rate of migration and species retreat (Ford, 1982). Ecosystems, therefore, will not migrate as a unit.

Species do not immediately respond to changed and changing environmental conditions. A negative response, such as local extinction in an area, is usually quicker than the positive response of new species' colonization of a region (see Chapter 5: Forests). In the Arctics, the lag period between climate change and species response by migration and colonization may be several hundred years (Edlund, 1986). This lag period will leave areas open for weedy, opportunistic species that can quickly migrate and propagate in a region.

The rate of climate change will be crucial to the survival of the species in an ecosystem. A 3°C (5°F) increase in temperature, for example, would effect a several hundred kilometer poleward sluft in the temperate vegetation belts (Frye, 1983). If this change took place within a century, species would need to migrate several kilometers each year to adapt to this warming. Plants have a wide range of migration rates, and only some may be able to achieve this rate. Failure of a species to "keep up" with suitable environmental conditions would eventually result in extinction.

Many factors make evaluating the impact of climate change on ecosystems difficult. The great interdependencies among species in an ecosystem add considerable uncertainty to the effect that the various responses of individual species will have on the system. An impact upon a single species could profoundly affect the entire ecosystem. Certain species are vital to the workings of their ecosystems. Among them are large carnivores that regulate predator-prey relationships, large herbivores that significantly change vegetation, and organisms that pollinate plants (WRI, 1988). Plants can also be key species within an ecosystem. For example, elimination of a tree species in a region could have a significant effect on the whole forest ecosystem, including birds, insects, and mammals.

Animal populations are generally much more mobile than plants. But animal distributions heavily depend on vegetation for food, protection, and nesting habitat. Species not directly dependent on vegetation ultimately depend on some other species that is. The ranges of the fig wasp and the fig depend entirely upon one another. In this case, the plant species depends on a single pollinator, and the insect species relies upon a single species of plant for food (Kiester et al., 1984).

Effect on Genetic Diversity

With regard to genetic diversity, rapid climate change would select for those genotypes (combinations of genes) that were best suited to the new climate regime and would tend to eliminate others. This process of natural selection would usually decrease the genetic variability within a population. In the long term (evolutionary time), it is possible that greater climatic variability could select for greater genetic variability.

Barriers to Response

The rate of species migration is also affected by natural and manmade barriers and by competition. Peters and Darling (1985) examined the potential responses of species to climate change, ecological interactions, and barriers to adaptation. Physical barriers include mountains, bodies of water, roads, cities, agricultural land, inappropriate soil type, and habitat heterogeneity (landscape patchiness). A species whose migration rate is sufficient to keep up with changing conditions could become constrained by a physical barrier. Inability to cross the barrier could result in a reduction of the range of the species and its eventual extinction.

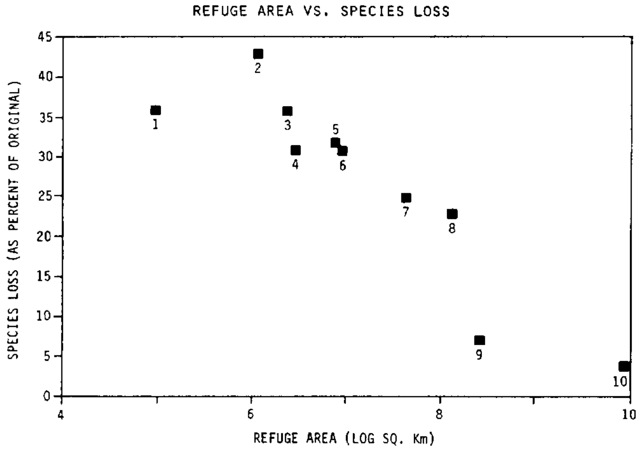
Reserve and Island Species

Additional constraints on the ability of populations living on reserves to respond to climate change frequently result from insufficient habitat area or isolation from other populations. The problem of isolation is similar to that of island species and has become known as the island dilemma. Species on reserves are often remnants of larger populations and are more susceptible to environmental stress and extinction.

Species on reserves are likely to be pressured from two directions as a result of climate change. A population isolated on a reserve surrounded by altered or unsuitable habitat receives little immigration from populations outside the reserve. Also, that population may not be able to colonize areas outside the reserve as these areas become suitable because of development or other alterations of habitat.

Even without the added pressure of climate change, reserve populations are vulnerable because many reserves are not large enough to support a self-sustaining population (Lovejoy, 1979). The predictive theory of island biogeography showed that, other factors being equal, small islands accommodate smaller numbers of species than do large islands (MacArthur and Wilson, 1967). This held true for other ecological "islands," such as mountaintops, woodlots, and lakes. Also, when large ecosystems become smaller through fragmentation, the number of species always declines. Figure 8-2 shows how mammalian extinctions have been inversely related to refuge area in North American parks.

Reserves that originally may have been well sited to protect a vulnerable population and its habitat may, after climate change and population response, exist outside the now suitable range. Figure 8-3 illustrates this problem. Large reserves and buffer zones around reserves help to lessen these problems. Corridors between reserves lessen the problem of spatial isolation by allowing for some migration between reserves.



	PARK	AREA (km^2)	PERCENT OF ORIGINAL SPECIES LOST
1)	Bryce Canyon	144	36
2)	Lassen Volcano	426	43
3)	Zion	588	36
4)	Crater Lake	641	31
5)	Mount Rainier	976	32
6)	Rocky Mountain	1,049	31
7)	Yosemite	2,083	25
8)	Sequoia-Kings Canyon	3,389	23
9)	Glacier-Waterton	4,627	7
10)	Grand Teton-Yellowstone	20,736	4

Figure 8-2. Habitat area and loss of large animal species in North American parks (1986) (Newmark, 1987).

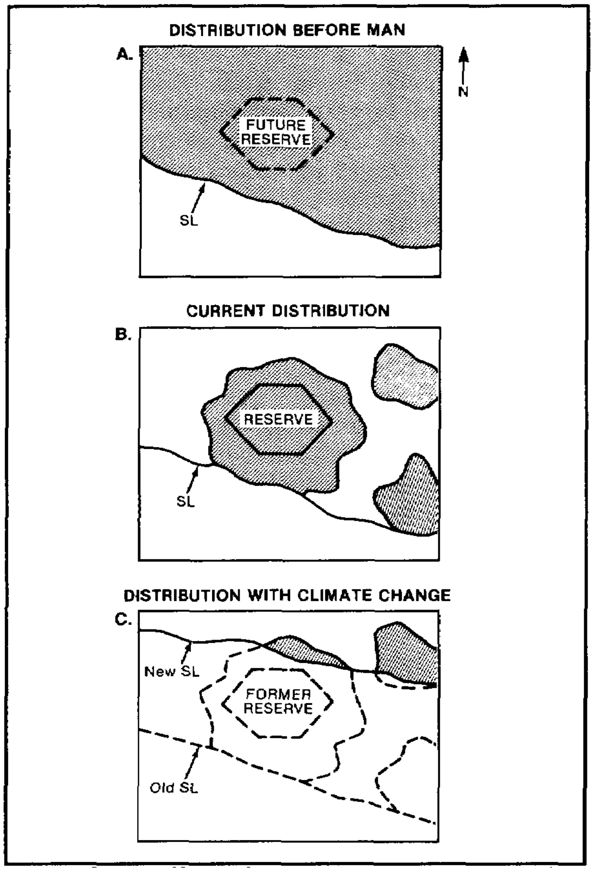


Figure 8-3. Effect of climate change on biological reserves. Hatching indicates the following: (A) species distribution before human habitation (SL indicates southern limit of species range); (B) fragmented species distribution after human habitation; (C) species distribution after warming (Peters and Darling, 1985).

Mountain Species

Just as species can migrate latitudinally, they can respond attitudinally to climate change by moving up or down a mountain slope. Species can often respond more easily to changing conditions on a slope because a shorter distance is required to migrate to achieve the same temperature change.

Among the problems associated with attitudinal migration are displacement of the species at the top (Peters and Darling, 1985). Also, with the increase in altitude, the area available for colonization usually becomes smaller, communities become isolated, and these smaller populations are more prone to extinction.

CLIMATE EFFECTS RESEARCH

This section reviews some previous studies of ecological response to past changes in climate, recent studies of potential response to climate change, and studies done for this report, which use climate change scenarios from general circulation models for a doubled CO_2 environment (see Table 8-1).

Forest Ecosystems

The tree species that make up any forest are major factors in determining the biological diversity found there. Trees provide a multitude of habitats and are the basis of much of the food web in a forest.

Changes in forest composition resulting from climate change (see Chapter 5: Forests) would have significant implications for biological diversity. Potential northerly range shifts of several hundred to a thousand kilometers may be limited by the tree species' ability to disperse. One possibility is that southern pine forests will move farther north into the regions currently occupied by mixed hardwood species. Some of these hardwood forests contain the highest tree species diversity found anywhere in the United States (Braun, 1950). If they migrated north, species would inevitably be lost, and overall biological diversity would substantially decrease.

If forests were disrupted by the extinction of the dominant tree species, the land would be invaded by weedy, opportunistic species. This would create a system with very low diversity, similar to that following logging. Ultimately, these new systems would not persist as succession took place, but the pattern of succession following the removal of a forest by rapid climate change is unknown.

Table 8-1. Studies Conducted for This Report and Cited in This Chapter

- Potential Responses of Great Lakes Fishes and Their Habitat to Global Climate Warming -Magnuson, Regier, Shuter, Hill, Holmer, and Meisner, University of Wisconsin (Volume E)
- The Effects of Global Climate Change on the Water Quality of Mountain Lakes and Streams - Byron, Jassby, and Goldman, University of California at Davis (Volume E)
- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, HydroQual, Inc. (Volume A)
- Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay -Josselyn and Callaway, San Francisco State University (Volume E)
- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration - Livingston, Florida State University (Volume E) Tropical Forest Ecosystems

Tropical Forest Ecosystems

The greatest concentration of biological diversity in the world is in the rain forests of the Tropics (Wilson, 1988). Besides reducing diversity, deforestation contributes to disruption of the global carbon cycle by releasing CO_2 into the atmosphere and will directly affect the rate of climate change (Prance, 1986). Indeed, on a global scale, the problems of tropical deforestation, rapid climate change through (among other factors) increased CO_2 production, and the loss of biological diversity cane seen as aspects of the same problem.

Tropical forests are also important as wintering grounds for migratory birds coming from the United States and as sources of new knowledge, because the patterns of interactions between species and climate are at their most sensitive and complex there (Robinson, 1978; Janzen, 1986). The Tropics may provide important leading indicators of the ecological effects of climate change.

Freshwater Ecosystems

A study conducted by Magnuson et al. (Volume E) concludes that in most areas of the Great Lakes, climate warming would increase the amount of optimal thermal habitat for warm-, cool and coldwater fishes (see Chapter 15: Great Lakes). Although overall productivity would increase, overall biological diversity could decrease through intensified species interactions.

A study by Byron et al. (Volume E) on mountain lakes suggests that climate change would cause a range of impacts, including higher productivity, changes in species composition, and decreased water quality resulting from an increase in algal growth (see Chapter 14: California). Blumberg (Volume A) found that thermal stratification in Lake Erie could decrease dissolved oxygen levels.

The combined pressures of warmer waters, saltwater intrusion, and a rising sea level would significantly affect estuaries. The regional studies suggest that coastal estuaries would see a growth in marine species and a loss of some estuarine species. A study by Josselyn (Volume E) on the San Francisco Bay estuary suggests a decline in species that use the delta for spawning (see Chapter 14: California). Livingston (Volume E) concluded that crabs, shrimp, oysters, and flounder in the Apalachicola estuary could not survive the warming in the GISS and GFDL scenarios (see Chapter 16: Southeast).

Saltwater Ecosystems

In general, a warmer global climate would increase productivity in ocean fisheries, but the location and relative abundance of species are likely to change (Sibley and Strickland, 1985). Up to some threshold temperatures, such as 2°C (4°F), warmer ocean temperatures would increase ocean productivity in many species, but beyond that threshold, productivity could decline (Glantz, Volume J). It is likely that as productivity decreases, biological diversity would decrease as well. Warmer temperatures would most likely cause fish to migrate poleward, although many other factors, such as shifts in upwelling, may affect this.

Coral Reef Ecosystems

Coral reefs provide the structural base for the very biologically diverse reef ecosystems. Coral reefs in the Caribbean and the Pacific may be severely stressed as a result of warmer water temperatures and the rising sea level associated with climate change. Extensive bleaching of coral (the expelling of symbiotic algae in response to environmental stress) occurred in the Pacific after the 1982-83 El Nino (Glynn, 1984) and in the Caribbean following a summer of elevated water temperatures in 1987 (Roberts, 1987). Loss of the algae, the primary food source of the coral, is thought to kill coral, making the reef ecosystem vulnerable to erosion and physical devastation.

Coral reefs also will very likely be affected by sea level rise. Studies by Buddemeier and Smith (1988) and Cubit (1985) suggest that vertical accretion of reef flats eventually may be unable to keep up with an accelerating rise in sea level. Reef flats also may be subject to the stress of increasingly large waves, erosion, and sedimentation, which can inhibit coral growth (Buddemeier, 1988).

Arctic Ecosystems

Within the North American Arctics, plant size, vigor, and reproduction could be expected to increase with higher temperatures in the near term (years to decades). Some low-lying plants would most likely become upright, and there would be a northerly movement of the tree line and all vegetative zones (Edlund, 1986).

Over the longer term, however, rising temperatures may be a mixed blessing. Overall biological productivity is likely to increase, and some species may be able to increase their range. However, some arctic plant species are likely to be out-competed by invading species, and many others would face the same type of problem that mountaintop species face: they would have nowhere to go once they reach the Arctic Ocean. Thus, native arctic species may be especially at risk. Other arctic species may face their own problems. For example, caribou would be severely harmed if rivers do not freeze for periods long enough to allow for migration.

Migratory Birds

Migratory waterfowl are likely to experience very mixed effects as a result of warmer temperatures (Boyd, 1988). Herbivorous, arctic nesting species, such as geese, could benefit from the shortened winter season and from the increases in vegetation, in nesting habitat, and in ecosystem productivity (Harington, 1987). Smaller arctic nesting shorebirds, on the other hand, would be harmed by the encroachment of taller vegetation, potentially eliminating the preferred low-lying tundra breeding ground. Other effects on shorebirds could result from changes in ecosystem predator-competitor relationships and changes in the seasonal timing of such events as larval blooms, upon which these birds depend for nourishment while they are in a flightless stage and during migration (Myers, 1988).

Waterfowl that breed in the continental interior may suffer more than arctic nesters. Over half of all waterfowl in North America originate in the prairie pothole region, a large agricultural area riddled with ecologically productive permanent and semipermanent wetlands. Increased temperature and changes in seasonal precipitation could reduce the highly variable number of potholes (wetlands) in the area and could significantly impair the productivity of breeding ducks.

Because of the drought of 1988, over 35% of the seasonal wetlands within the prairie pothole region were dry during the breeding season (U.S. Fish and Wildlife Service, 1988). The Fish and Wildlife Service forecast that only 66 million ducks would migrate during the fall of 1988, a total of 8 million fewer than in 1987 and the second-lowest migration on record (Irion, 1988). The productivity index for mallards (number of young per adult) was 0.8, which was down by over 20% from the historical average (U.S. Fish and Wildlife Service, 1988).

Waterfowl and other migratory birds are likely to be affected on both ends of their migratory journey and at staging areas along the way. The loss of coastal wetlands, already an area of great concern in the United States, reduces the amount of habitat available to waterfowl, creating population pressures on a limited resource. Of the 215 million acres of wetlands in the coterminous United States at the time of settlement, fewer than 99 million acres (46%) remain (U.S. Fish and Wildlife Service, 1988). Loss of an additional 26 to 82% of existing coastal wetlands could occur over the next century as a result of a 1-meter rise in sea level, saltwater intrusion, and human development (see Chapter 7: Sea Level Rise). Loss of wintering habitat along the Gulf of Mexico would affect many waterfowl, including mallards, pintails, and snow geese.

The Tropics, the winter home for many species of migratory birds, may be significantly altered by rapid climate change. The need to protect a species in all parts of its range underscores the truly global nature of the effects of rapid climate change on biological diversity (Terborgh, 1974).

Endangered Species

Hundreds of species are currently listed as endangered in the United States, and several thousand await consideration for that status. These species are likely to be stressed further as a result of climate change.

Threatened and endangered species of the Southeast would be very susceptible to the impacts of sea level rise. Some species potentially at risk in that region include the Key deer, manatee, Florida panther, and Everglades kite (Breckenridge, 1988). Climate change could also greatly increase the number of rare, threatened, and endangered species in the United States.

Other Direct and Indirect Stresses

As plant and animal species experience increasing pressures from changes in temperature, precipitation, and soil moisture, so too will agriculture and urban water supplies. The changes that result from the human response to climate change may have the greatest impact on biological diversity. If the continental interior of North America dries, for example, wetlands that dry out may be cultivated, and our current uses of water resources may change. These secondary effects may significantly compound the loss of biological diversity.

NATIONAL POLICY IMPLICATIONS

Climate change presents new challenges for policymakers, regulators, and resource managers. Planning for climate change may help to minimize the disruption to natural systems and facilitate adaptation under changing conditions. Decisions will need to be made in an environment of increased pressure on many other resources.

Policies regarding rare and endangered species are likely to change as the number of species at risk greatly increases. As more species become stressed and potentially threatened by climate change, reevaluation of protection policies may be required. The tradeoffs between protection of individual species and species' habitats and the broader protection of biodiversity at the level of ecosystems may need to be reexamined. As a part of this question, decisions concerning whether to protect existing communities or to foster establishment of new communities may need to be made.

Management Options to Maintain Biological Diversity

Only a limited number of techniques are available for maintaining biological diversity. However, these techniques can be adapted and intensified to meet the potentially great impacts of rapid climate change.

Maintenance of Native Habitats

The most direct way to maintain biological diversity is to manage land to retain ecosystems, communities, and habitats. This already has been successfully undertaken on a broad scale by federal and state governments and by private organizations. Ecosystem conservation, especially as represented by the national parks and other large reserves, maintains much of our national biological diversity. These ongoing efforts will be the crucial first step for maintaining biological diversity in the face of climate change.

Land acquisition and management policies should take climate change into account. Climate change and the future requirements of whole ecosystems should be considered in siting and managing reserves. To preserve functioning ecosystems, large areas of land will be required. Preserves would need to be at least large enough to support self-sustaining populations. Lands that could be more important as future plant and animal habitats need to be identified and evaluated. Land managers should consider whether these lands should be set aside.

Although identification of appropriate future habitats is difficult and highly dependent on the future rate and extent of climate change, some areas, such as lowland areas adjacent to current wetlands, hold good potential for habitat protection.

To protect a species, alternative sites should be considered with regard to the ecological needs of target species under changing conditions. Siting reserves in mountainous areas is beneficial because it allows for the shorter-distance altitudinal shifts of adjustment to changing climate. Stream corridors, which can be effective avenues of dispersal for terrestrial as well as aquatic organisms, should be protected wherever possible. Providing corridors for migration between reserves also should enhance the ability of wildlife to adapt to climate change. Ideally, these corridors should be wide enough to maintain the ecosystem characteristics of the reserve in their center. Some species do not find the habitat conditions of narrow corridors suitable for migration.

The pressures caused by changing climate are likely to exacerbate competing land-use demands. Acquisition of land for preserving biological diversity will often be difficult, especially in areas where agriculture or forestry may be expanding. Flexible management strategies that reserve the possibility of land management for biological diversity in the future, while allowing for other use in the interim, hold potential for reducing resource conflicts and maintaining biological diversity. Creative approaches such as encouraging hedgerows, which may serve as migratory corridors, should also be considered.

Maintenance of Species in Artificial Conditions

When individual species are threatened with extinction, a possible option is to ensure that the species is propagated in captivity. Indeed, some rare species, such as the Pere David deer and the California condor, now exist only in captivity. This technique can be made to work for a variety of species, depending on their biology and the degree to which they successfully adapt to captive conditions. As more species become threatened with extinction due to climate change, the effort applied in this area may have to increase dramatically. However, only a tiny fraction of the nation's species can be maintained in this way. Existing seed bank programs also provide an important method for conserving plant genetic diversity.

Restoration of Habitat

Restoration ecology is a new discipline whose goal is to develop methods to restore damaged ecological communities to their prior unaltered state. Except in forestry, where reforestation has a longer tradition, restoration ecology has been in existence for only a few years. Nonetheless, it offers some real promise for ameliorating the effects of rapid climate change.

Normally, restoration is done at the site where the community previously existed and was altered or damaged. Historical and baseline information is used to manage the species in such a way as to eliminate unwanted new species and to encourage and possibly reintroduce native species.

Perhaps the theory and practice of restoration ecology could be expanded to include rebuilding natural communities on sites where they have not previously existed. This activity has not yet been attempted but may be necessary to save communities displaced by climate change. If the climate changes so that many of the key species of a community can no longer survive in their original range, and if the species are incapable of dispersing and establishing themselves elsewhere, then the artificial transplantation of components of entire communities may become necessary. This transplantation of communities would be a monumental task and could help to save much biological diversity, but it cannot possibly be undertaken on the scale necessary to preserve all species threatened by climate change. Restoration ecology can be useful for extending reserve boundaries and for providing migratory corridors.

Planning Options

While there are only a few management techniques to maintain biological diversity, many different groups in our society can implement them. These groups can be divided into the private and public sectors.

Many different groups in the private sector, ranging from private individuals to large conservation organizations, will have an interest in maintaining biological diversity. However, all would need information about the current and probable future state of biological diversity. The federal government may be able to play a role here by providing information on the state of biological diversity, including the systematics and distribution of species; on the genetic variability of species; and on the distribution of communities and ecosystems.

The four major federal land management agencies develop plans intended to lay out a comprehensive framework and direction for managing federal land. Land Resource Management Plans, required for each national forest, define the direction of management in the forest for the next 10 to 15 years. In addition, the Forest Service prepares 50-year plans, as required by the Resource Conservation Act. The National Park Service prepares a General Management Plan for each unit in the system that defines a strategy for achieving management objectives within a 10year time frame. A Statement for Management is also prepared for each national park and is evaluated every 2 years; this includes a determination of information needs. The Bureau of Land Management's (BLM) Resource Management Plans and the Fish and Wildlife Service's Refuge Master Plans are prepared and revised as needed for BLM resource areas and wildlife refuges (U.S. Department of the Interior, 1987). These periodic reviews of the management plans for public lands should include consideration of the possible effect of climate change on biodiversity.

Some federal land management agencies are beginning to devote resources to the climate change issue. The Forest Service, for example, has begun planning the Forest Atmosphere Interaction (FAI), which will be concerned with the relationship between the atmosphere and our national forests. The FAI has been designated a priority research program for the Forest Service.

The federal government manages an enormous amount of land and should consider management options to preserve biological diversity on much of that land. The major management techniques of habitat maintenance and restoration ecology could be applied by the agencies actively responsible for managing the nation's public lands.

RESEARCH NEEDS

The ability to protect biological diversity is severely restricted by a lack of knowledge regarding the rate of climate change, the precise nature of the change, how individual species will respond, and how ecological balances will shift. Research should be expanded in two areas: identification of biological diversity, and species interactions and biological diversity. New management options for biological diversity should be derived from these studies.

Identification of Biological Diversity

First and most important, an intensified, better coordinated research effort, involving both systematics (organism classification) and ecology, is required to identify the biologically diverse resources of our country. There should be more coordination to identify U.S. plants and animals, range maps, and habitat requirement information for those species.

The apparently simple task of identifying the species of plants and animals that exist in a given area is actually a major barrier to further understanding. Although common species are usually easy to identify, serious problems are often encountered in attempts to determine whether a widespread group is, for example, one or two species. For example, there is currently no federally sponsored Flora (listing of all known plants) of the United States.

Although it is necessary to describe the genetic diversity of our nation's species, it is difficult to do so in a direct fashion. What may be feasible is the further development of population genetic theory and of data that would predict the genetic diversity of a species based on species' properties, such as population size and habitat range variability.

The challenge in describing ecosystem diversity is to find the system of classification that best helps make decisions intended to minimize the loss of biological diversity. Such a system will most likely only be found through experience. For now, we should continue with the many different approaches of ecosystem classification, and we should look for the strengths of each.

Species Interactions and Biological Diversity

The second area to which research should be devoted is the direct effects of climate on species and the indirect interactions of species with other species dependent on climate. Comprehensive mapping of species' ranges along temperature and moisture gradients would provide valuable information. The direct effect of climate change on vegetation needs to be better assessed, and more estimates of species' dispersal rates would significantly improve our ability to identify species at greatest risk.

A variety of ecosystems within a diversity of climatic regions and terrains should be intensively studied using analog climate regions under changed climate conditions. Although an ecosystem's response under changing climate conditions will not be wholly predictable, modeling individual ecosystemic responses would enhance knowledge of the likely effects. Further research on how species interact and how trophic structures might change with climate would help predictive capabilities.

There should be further study on the question of the relationship between ecosystem function and species diversity to resolve the uncertainty in this area. Modeling the effect of climate change on ecosystem function and its relationship to diversity would help with predictive capabilities.

It will be impossible to study in detail even a fraction of the nation's species. The groups chosen for study either must be representative of many species or must possess some special properties (such as extreme sensitivity to climate change). The method of deciding which group to study is itself a major outstanding research question.

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CHAPTER 9
WATER RESOURCES

by Mark W. Mugler and Michael C. Rubino

FINDINGS

Higher temperatures will most likely result in greater evaporation and precipitation; earlier snowmelt and reduced water availability in summer; and, during dry periods, more rapid declines in soil moisture and water levels, volumes, and flows. Although a general warming and global increase in precipitation are likely, the distribution of precipitation is highly uncertain and may change in unexpected ways. As a result, the frequency, seasonality, variability, and spatial distribution of droughts, water availability constraints, floods, and water quality problems will very likely change. Some regions could benefit from changing precipitation patterns, while others could experience great losses.

Although great uncertainty is associated with the projection of future hydrologic conditions and their water-use implications, we must be most concerned about current vulnerabilities to climate extremes that could become exacerbated under climate change. For instance, certain dry regions could become more vulnerable to drought as a result of higher temperatures, earlier snowmelt, and/or shifts in precipitation.

Impacts on Water Uses

- If climate in a given region were to become warmer and drier, water availability would decrease and water demand would increase, especially demand for irrigation and electric power production.

- Lower riverflows resulting from drier conditions could adversely affect instream uses such as hydropower production, navigation, aquatic ecosystems, wildlife habitat, and recreation.

- Lower streamflow and lower lake levels could cause powerplants to shift from once-through to evaporative cooling. New plants may also locate in coastal areas to obtain a water source that is reliable and that may be used without violation of thermal restrictions, although sea level rise could be a problem. This would have important implications for land use, transmission lines, and the costs of power.

- Where water availability is reduced, conflicts among users could increase. These include conflicts over the use of reservoir systems for flood control storage, water supply, or flow regulation; and conflicts over water rights among agricultural, municipal, and industrial users of water supply.

- Should extreme flood events become more frequent in a river basin as a result of earlier snowmelt and increased precipitation, activities located in the floodplain would endure more damages or could require more storage capacity (whether by construction, reallocation, or changes in operating procedures), often at the expense of other water uses.

Policy Implications

Water management responses to current vulnerabilities are available and in use, and can appropriately be brought into play to respond to changing hydrologic conditions. These responses include the following:

- Build new storage capacity, provided that the structures show positive net benefits under a variety of possible climatic conditions;

- Modify water system operations to improve performance under extreme conditions, to enhance recovery from extreme conditions, and to accept greater risk to low-valued uses to protect high-valued uses; and

- Encourage a reduction in water demand and an increase in water-use efficiency through conservation, water markets, water quality control, drought contingency planning, and coordinated uses of regional and interstate water resources, provided that such measures do not reduce the performance and recovery capabilities of supply systems.

IMPACTS OF CLIMATE CHANGE ON THE WATER RESOURCES IN THE UNITED STATES

Current Status of Water Resources

The potential effects of climate change on water resources must be examined within the context of the existing and projected supply of, and demands for, water.

The United States is endowed with a bountiful supply of water, but the water is not always in the right place at the right time, or of the right quality. On the average, 4,200 billion gallons per day (bgd) of precipitation fall on the lower 48 states. However, a large portion of this water (66%) evaporates, leaving 1,435 bgd (34%) for surface water runoff and groundwater recharge. Largely owing to weather variability, 675 bgd of the 1,435 bgd of runoff water in the coterminous United States is considered to be available for use in 95 years out of 100 (Figure 9-1).

Surface and groundwaters are managed by controlling and diverting flows through impoundments and aqueducts; by withdrawing water for such "offstream" applications as irrigation and municipal use; by regulating flows to maintain "instream" water quality and such uses as navigation, hydropower, and recreation; and by controlling flows under flood conditions to avoid loss of life, damage to property, or inconvenience to the public. Water may be "withdrawn" and returned to the source more than once, or "consumed" and not returned to the source.

In 1985, freshwater withdrawals for offstream uses totaled 338 bgd. Of the withdrawals, 92 bgd were consumed, mostly for irrigation. Withdrawals and consumption of freshwater by major offstream uses in 1985 are summarized in Figure 9-1.

Our investment in water infrastructure is substantial. Water supply for municipal and industrial use represented a $108 billion national investment in infrastructure in 1984 (National Council on Public Works Improvement, 1988). Government agencies and industries spent $336 billion (in constant 1982 dollars) from 1972 to 1985 (Farber and Rutledge, 1987) on water pollution abatement and control activities. In other areas, excess water periodically floods agricultural and urban areas, causing annual average damages valued at $3 billion (in constant 1984 dollars) during the past decade (National Council on Public Works Improvement, 1988).

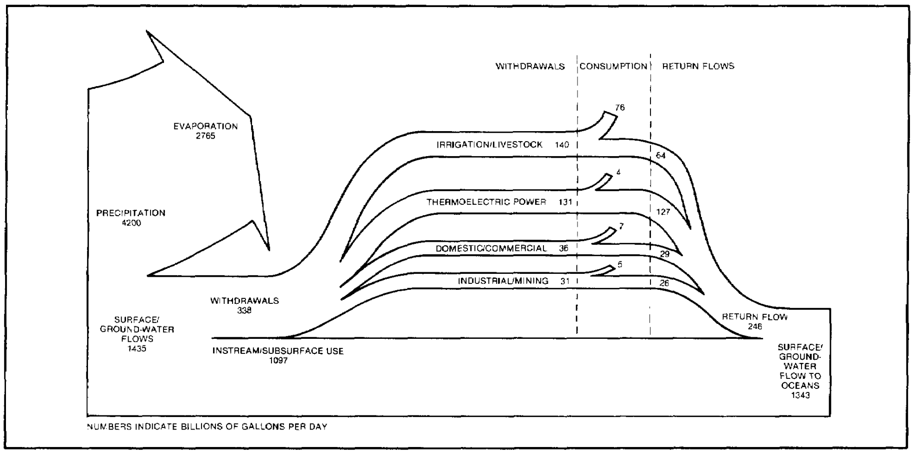


Figure 9-1. Water withdrawals and consumption by offstream uses, coterminous United States, 1985 (Solley et al., 1988).

On a national scale, water supplies are adequate, and water availability exceeds withdrawals and consumption. However, in some regions, the gap between demand for water and available supply is narrow, or the variability in water supply is high, or both. For example, average surface water withdrawal exceeds average streamflow in the Great Basin, Rio Grande, and Colorado River Basins. In these water-short basins, offstream water uses often conflict with instream uses, such as recreation and maintenance of environmental quality. Degraded water quality further limits water availability in many regions. Table 9-1 summarizes the current status of water supply by major river basin. The regions are delineated in Figure 9-2.

Table 9-1. Current Status of the Water Supply

River Basin	Average renewable supply (bgd)[a]	Withdrawal[b] (1985)	Consumption[b] (1985)	Reservoir storage[b]	Stream-flow exceeded 95% of time[c]	Ground-water overdraft
New England	78.4	11.7	0.9	15	62.4	0
Mid-Atlantic	80.7	29.5	2.1	11	62.2	1.2
South Atlantic- Gulf	233.5	13.5	2.1	15	55.5	6.2
Great Lakes	74.3	42.9	2.9	8	62.6	2.2
Ohio (exclusive of TN region)	139.5	22.3	1.5	13	59.0	0
Tennessee	41.2	22.3	0.8	24	77.0	0
Upper Mississippi (exclusive of MO region)	77.2	21.9	2.3	14	54.0	0
Mississippi (entire basin)	464.3	3.7	1.2	32	46.7	0.5
Souris-Red Rainy	6.5	4.3	1.9	110	32.1	0
Missouri	62.5	55.2	20.3	120	40.7	24.6
Arkansas-White-Red	68.6	22.3	11.7	41	36.5	61.7
Texas-Gulf	33.1	41.4	18.2	67	27.5	77.2
Rio Grande	5.1	109.8	43.7	182	33.3	28.1
Upper Colorado	14.7	51.4	16.3	229	39.0	0
Colorado (entire basin)	15.6	47.4	27.2	403	75.0	48.2
Great Basin	9.9	81.8	36.4	30	50.0	41.5
Pacific Northwest	276.2	12.9	4.5	20	70.7	8.5
California	70.2	53.6	29.9	49	44.0	11.5
Alaska	975.5	0.4	0.0	0.1	78.5	0
Hawaii	7.4	17.2	1.8	0.1	60.3	0
Caribbean	5.1	11.9	3.2	5	35.6	5.1

[a] Average renewable supply is defined as the average flow potentially or theoretically available for use in the region; units = billion gallons per day.

[b] Withdrawals, consumption, and reservoir storage are expressed as a percentage of the average renewable supply.

[c] As a percentage of average streamflow.

Source: U.S. Water Resources Council (1978); U.S. Geological Survey (1984); Solley et al. (1988).

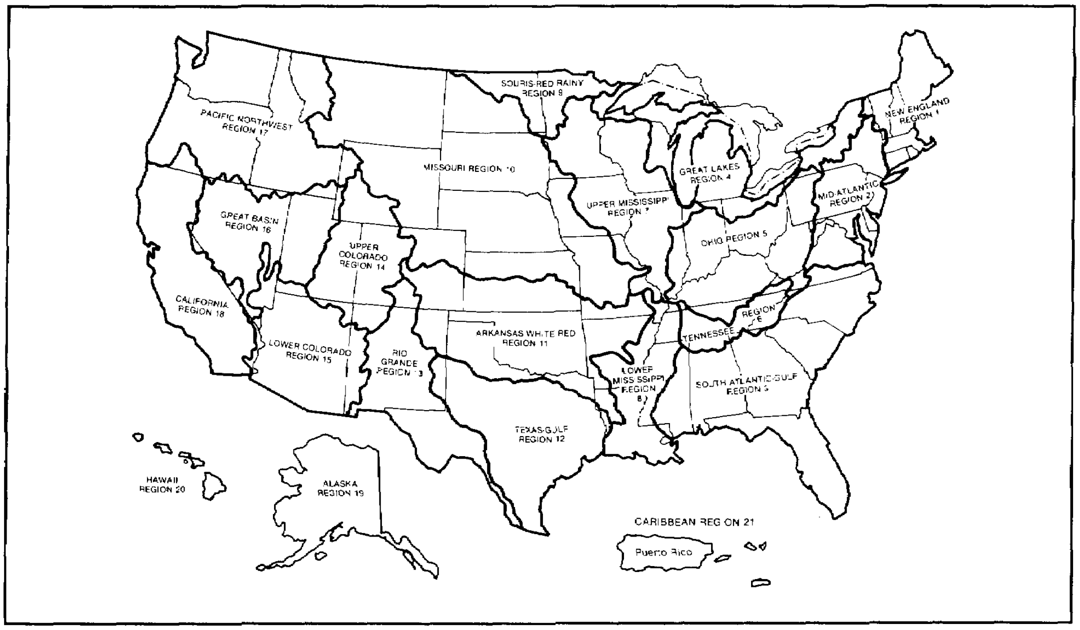


Figure 9-2. Water resources regions (U.S. Geological Survey, 1985).

Water supply and use have changed significantly during the past decade. For the first time since 1950, when the United States Geological Survey began recording water withdrawals, national total fresh and saline water withdrawals dropped 10% from 1980 to 1985 (from 443 billion gallons to 399 billion gallons, of which 338 billion gallons were freshwater) (Solley et al., 1988). Increased conservation and water recycling in agriculture, industry, and energy production, slower growth in energy demand, and decline in availability of new water supply reduced or tempered water use in all sectors (Solley et al., 1988). Withdrawals declined by 7% in irrigation, by 33% in industry, and by 13% in thermal power during the same period. Of the major users, only municipal /domestic water supply increased (by 7%).

The value of instream uses has risen relative to that of offstream uses. Navigation and hydropower have retained their importance as society has begun to place greater value on wastewater dilution, ambient water quality, fish and wildlife habitats, and recreation. Higher values on instream uses have made diversion of water for such applications as agriculture in the West and for powerplant cooling in the East more difficult.

Climate Change, Hydrologic Conditions, and Water Resources

As shown in Figure 9-3, weather controls hydrologic conditions through precipitation (mean and frequency), runoff, snowmelt, transpiration and evaporation, soil moisture, and the variability of storms and drought. In turn, the ability to use water resources is greatly influenced by variability in hydrologic conditions.

Climate change will affect both the supply of and demand for water. Figure 9-4 outlines the major potential impacts of global warming and changes in precipitation on water resources.

If climate warms in the United States, there will likely be greater evaporation and, in turn, greater precipitation; earlier snowmelt and, in turn, reduced water availability in summer; and, during dry periods, more rapid declines in soil moisture and water levels, volumes, and flows. Over the very long term, groundwater availability may be affected by altered recharge rates. Transpiration may not increase as much because increased levels of carbon dioxide may shrink the stoma or pores of plants (Rosenberg, 1988).

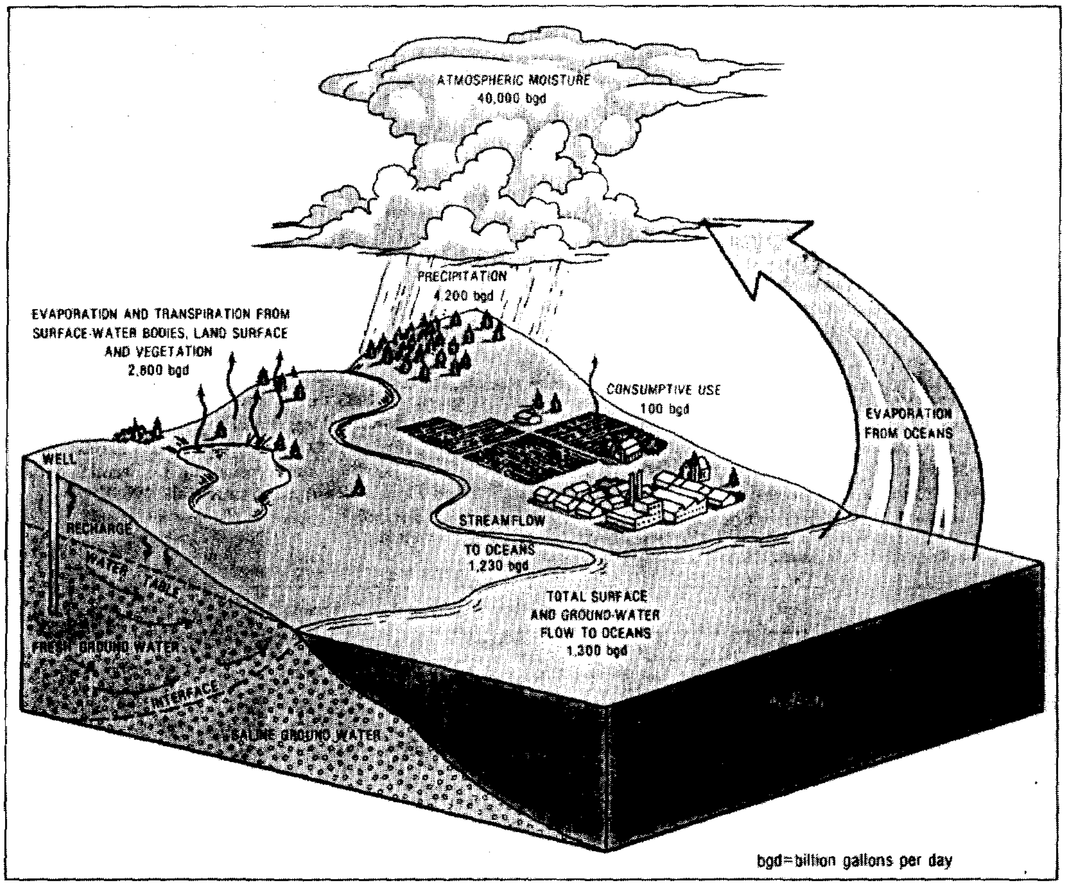
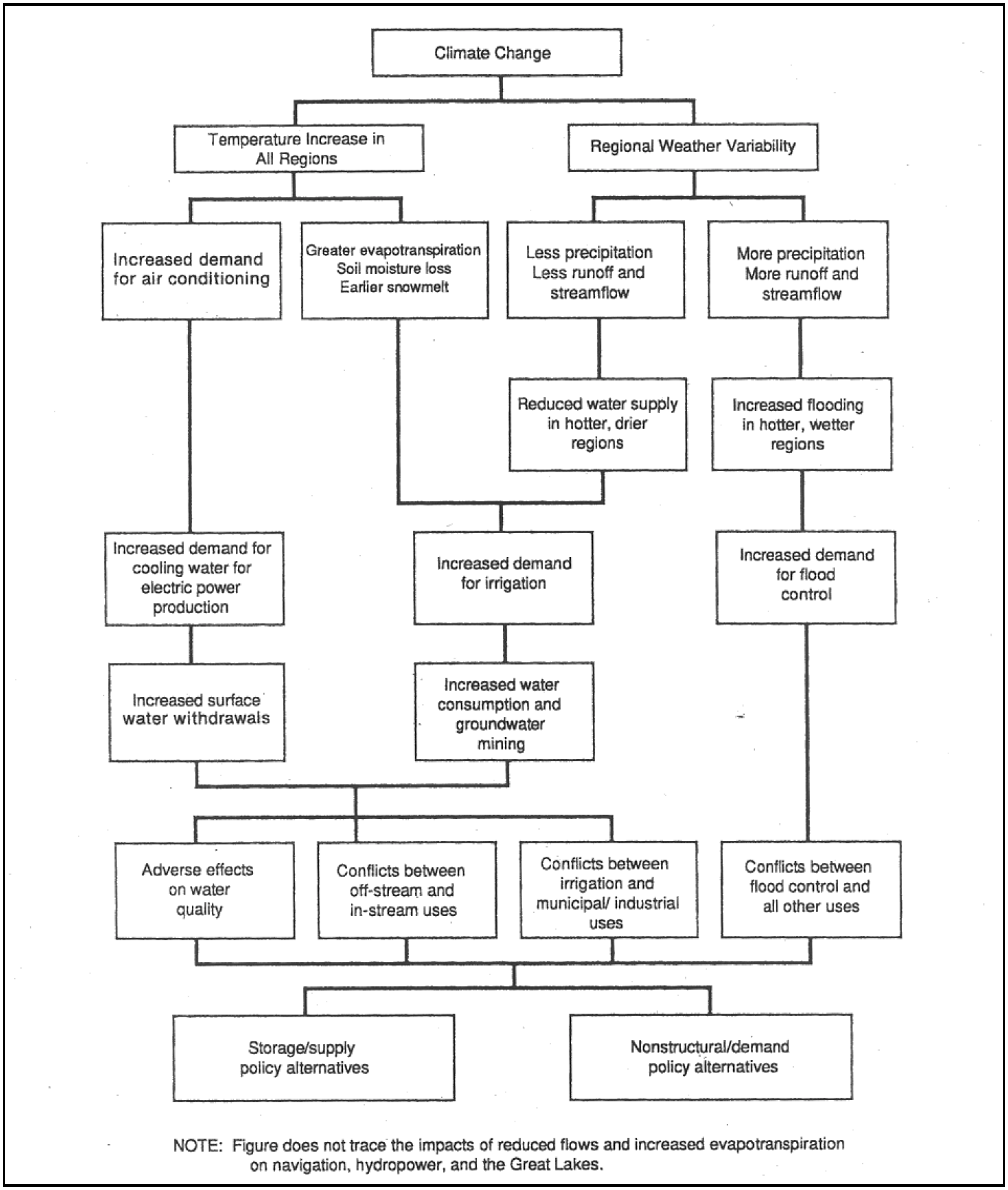


Figure 9-3. Hydrologic cycle showing the gross water budget of the coterminous United States (Langbein et al., 1949; Solley et al., 1983).

Although general warming is likely to occur, the distribution of precipitation is highly uncertain and may change in unexpected ways.

Earlier studies have shown that small changes in regional temperature, precipitation, and evaporation patterns can cause significant changes in water availability, especially in arid areas (see Nemec and Shaake,1982; Klemes and Nemec, 1985; Beran, 1986). Precipitation is more variable in arid than in humid areas. In addition, each degree of temperature increase causes a relatively greater decline in runoff and water availability in arid regions as compared with humid regions. If regional climate becomes warmer and drier, more vulnerability to interruptions in water availability may be observed.

As a result, the frequency, seasonality, variability, and spatial distribution of droughts, water availability constraints, floods, and water quality problems would probably change. In many locations, extreme events of dryness and flooding could become more frequent. Some regions may experience more drought conditions, others more flooding, others degraded water quality, and others a combination.



NOTE: Figure does not trace the impacts of reduced flows and increased evapotranspiration on navigation, hydropower, and the Great Lakes.

Figure 9-4. National impacts of climate change on water supply and demand.

Global warming may have a significant impact on the demand for water in some regions. Warmer temperatures may raise the demand for air conditioning in the South without a proportionate decrease in demand for electric heat. Increased demand for cooling water for electricity powerplants would result (see Chapter 10: Electricity Demand). Warmer temperatures may also prompt more farmers to irrigate crops (see Chapter 6: Agriculture).

Impacts of Climate Change on Water Uses

Models of global climate change do not yet provide reliable data to predict regional changes in the water supplies; however, we can indicate possible directions of impacts and the water uses and sectors affected. The following sections outline the potential impacts of climate change on offstream and instream water uses. The uses most likely to be affected are those currently vulnerable to water quantity and quality constraints:

- irrigation, the major source of withdrawals and consumption in the West;
- thermal power production, a major source of heat effluent and evaporative consumption, especially in the East;
- instream uses that depend on levels and flows; and
- domestic supplies that are vulnerable to hazardous and toxic substances in ground and surface water.

Table 9-2 highlights the vulnerability of major water uses in each region to climate change.

<u>Irrigation</u>

Irrigation accounts for 42% of freshwater withdrawals and 82% of freshwater consumption in the United States. Although irrigated land comprises about 10% of harvested cropland acreage nationwide, it contributes 30% of the value of cropland production. Many of these crops are fruits, vegetables, and specialty crops (U.S. Water Resources Council, 1978; Bajwa et al., 1987). The 17 western states account for 85% of the irrigated lands in the country (Bajwa et al., 1987).

Water-short western states are exploring numerous options for minimizing water requirements. Because of depleted groundwater supplies, the rising cost of obtaining groundwater, and the high cost and limited availability of sites for new surface water developments, irrigated acreage has stabilized or is declining in some areas of the West (Solley et al., 1988). Groundwater pumping for irrigation has already started to decline in the southern Great Plains States and in Arizona, although the impacts on production have been mitigated by the adoption of more efficient irrigation systems and by a switch to crops offering higher returns to wafer (Frederick and Kneese, 1989). In contrast, supplemental irrigation is rising in the Southeast, largely because of expansion in Georgia (Bajwa et al., 1987).

Table 9-2. Potential Regional Impacts of Climate Change on Water Uses: Areas of Vulnerability

Use	Pacific Northwest	California	Arid Western River Basins	Great Plains	Great Lakes	Mississippi	Southeast	Northeast
Irrigation	X	X	X	X			X	
Thermal power							X	X
Industrial		X	X					X
Municipal/domestic		X	X					X
Water quality			X	X	X	X	X	X
Navigation					X	X	X	
Flood control	X	X		X		X	X	
Hydropower	X	X			X		X	
Recreation					X		X	

Climate change may significantly affect agriculture. Summer drought and earlier runoff are likely to change agricultural practices and increase demands for irrigation in most areas east of the Rocky Mountains.

Thermal Power Generation

Thermal Power Generation Steam electric powerplants withdraw almost as much freshwater as irrigation but consume much less than irrigation. Although the freshwater withdrawn to produce the nation's electricity totals 131 bgd, only 4.35 bgd are actually consumed (Solley et al., 1988).

Future demand for water for power production will depend on energy demand, technology, and on federal and state regulations governing instream water quality, instream flow, and thermal pollution. Although a large amount of installed capacity exists along eastern rivers, freshwater withdrawals by powerplants in the East have decreased, and siting of plants in coastal areas has increased, so that by 1987, 30% of installed capacity in coastal areas used saline surface water (Solley et al., 1988). In addition, the thermal regulations have caused a shift in the design of new cooling systems from once- through cooling, which discharges heat back into the water sources, to evaporative cooling with towers and ponds (Breitstein and Tucker, 1986). Although evaporative cooling alleviates thermal pollution, it increases water consumption.

During droughts, federal and state regulations protecting instream uses and limiting thermal discharges may constrain withdrawals for powerplant cooling. In addition, powerplant water needs on some eastern rivers are so large that insufficient water may be available to dissipate heat during low-flow conditions (Hobbs and Meier, 1979).

Demand for electric power and construction of new generating capacity may increase as warmer temperatures raise air-conditioning use (see Chapter 10: Electricity Demand). If streamflows are reduced as a result of climate change, powerplants using once-through cooling could be adversely affected. Increased demand for power may reinforce existing trends in powerplant design toward evaporative cooling, and in powerplant siting toward coastal locations. With less water available, low- flow conditions may interrupt power production and may increase power production costs and consumer electricity prices.

Industrial Uses

Since 1954, self-supplied industry steadily used less and less water per unit of production (Solley et al., 1988). This decline was partly due to efficiencies achieved to comply with federal and state water pollution legislation that restricts the discharge of untreated water. The trend toward more efficient industrial water uses is continue.

In regions where flows are reduced, there could be a reduction in both the quantity and the quality of water available for industrial production. In addition, if the climate becomes drier, the potential for interruption of industrial supply will be increased.

Domestic Water Uses

Domestic uses account for 10% of total water withdrawn and 11% of consumption. Over the past 20 years, domestic water use has increased from 16 to 25 bgd owing to growth in the number of households, with little change in usage per household (Solley et al., 1988).

Most municipal water supply systems are designed to provide reliable water at all times (safe yield). However, urban growth depends upon developed water supply, which is approaching exhaustion in some areas. For instance, in the Southeast and parts of the West, a large percentage of municipal water supply comes from groundwater (U.S. Water Resources Council, 1978; Solley et al., 1988). These regions withdraw more groundwater than can be recharged; consequently, any increased drought caused by climate change could accelerate groundwater mining (see Chapter 14: California and Chapter 16: Southeast).

Municipalities in the West are purchasing irrigators' water rights to ensure adequate water supplies for urban growth. If climate change results in reduced municipal supply, this trend will continue or accelerate, leading to the loss of irrigated acreage.

In the East, Midwest, and Southeast, municipalities may be able to increase safe yield by repairing and replacing existing leaking water delivery systems and by consolidating fragmented water supply districts. These actions could provide the margins of safety necessary to accommodate climate change.

Navigation

If riverflow and lake levels became lower, navigation would be impeded. Systems that are particularly vulnerable are those with unregulated flows or levels and high traffic, such as the Mississippi River and the Great Lakes. The effects of dry conditions and reduced water levels on barge traffic on the Mississippi in 1988 illustrate the potential impacts of climate change.

Hydropower

Because of the decline in water availability that could result from climate change, hydropower output and reliability, which depend on flows, could decline in the West and the Great Lakes. If the Southeast became drier, it could face the same problems unless it sacrificed water supply reliability to maintain hydropower production.

Recreation

If the Southeast becomes drier, there may be an increase in the conflict among water uses, especially over reservoir releases and levels in the Tennessee Valley and the Lake Lanier, Georgia, system. The conflicts are among flood control, which relies on storage; recreation, which depends on stable reservoir pool elevations; and downstream uses and water supply, which depend on flows.

Climate Change and Water Quality

Water quality directly affects the availability of water for human and environmental uses, since water of unsuitable quality is not really "available." Likewise, water quality in the nation's rivers, lakes, and streams depends in part on water quantity. Water supply is needed for dilution of wastewaters that flow into surface and groundwater sources. Freshwater inflows are needed to repel saline waters in estuaries and to regulate water temperatures in order to forestall changes in the thermal stratification, aquatic biota, and ecosystems of lakes, streams, and rivers.

The Federal Clean Water Act of 1972 and subsequent amendments ushered in a new era of water pollution control. Massive expenditures for treatment facilities and changes in water-use practices by government and industry have decreased the amount of "conventional" water pollutants, such as organic waste, sediment, oil, grease, and heat, that enters water supplies. Total public and private, point and nonpoint, and capital and operating water pollution abatement and control expenditures from 1972 to 1985 totaled $336 billion in 1982 dollars (Farber and Rutledge, 1987).

Nevertheless, serious surface water quality problems remain. Groundwater pollution problems, especially toxic contamination and nonpoint source pollution, are receiving increased recognition (U.S. EPA, 1987b).

One-third of municipal sewage treatment plants have yet to complete actions to be in full compliance with the provisions of the Clean Water Act (U.S. EPA, 1987a). Federal and state regulation of previously unregulated toxic and hazardous water pollutants has just begun. In the West, irrigation has increased the salinity levels in the return water and soils of several river basins (the lower Colorado, the Rio Grande, and the San Joaquin) to an extent that threatens the viability of irrigation (Frederick and Kneese, 1989).

Should climate change involve reduced flows, less freshwater may be available in some regions for diluting wastewater salt and heat, especially in lowflow periods (Jacoby, 1989). Dissolved oxygen levels in the water would decline while temperature and salinity levels would increase, affecting the viability of existing fish and wildlife. Increased thermal stratification and enhanced algal production due to higher temperatures may degrade the water quality of many lakes (see Chapter 15: Great Lakes; Blumberg and DiToro, Volume A). Finally, the combination of declining freshwater availability and rising sea level would move salt wedges up estuaries, changing estuarine ecology and threatening municipal and industrial water supplies. On the other hand, should climate change involve increased flows, greater dilution of pollutants would be possible in some regions.

Groundwater is the source for over 63% of domestic and commercial use (Solley et al., 1988). Although only a small portion of the nation's groundwater is thought to be contaminated, the potential consequences may be significant and may include cancer, damage to human organs, and other health effects (U.S. Congress, 1984).

Adequate recharge of aquifers is needed not only to perpetuate supplies but also to flush contaminants. Should climate change result in reduced flows and reduced recharge, the quality as well as the available quantity of groundwater could be adversely affected.

Climate Change and Flood Hazards

Because of the buffering and redundancy designed into large structures, major federal flood control projects may be able to contain or mitigate the impacts of more frequent severe floods. However, continued performance for flood control may come at the expense of other uses. For example, drawing down the levels of reservoirs to contain floodwaters from anticipated increases in precipitation or earlier snowmelt may curtail water availability for water supply. (This aggravated conflict is a distinct possibility in California, for example; see Chapter 14: California.)

The major concern with existing dams and levees is the consequence of failure under extreme conditions. For instance, an increased probability of great floods, whether due to urbanization of upstream watersheds or to climate change, would cause dams with inadequate spillways to fail. (Spillways are designed to prevent dam failure through overtopping.)

The majority of large dams that provide substantial flood storage are in good condition. The National Dam Safety Inventory shows that the overall condition of the U.S. Army Corps of Engineers' more than 300 flood control reservoirs is sound (National Council on Public Works Improvement, 1988). In addition, the spillways of many large dams are designed to pass a "probable maximum flood" (an extreme flood event much greater than the 100-year flood).

Smaller structures, such as urban drainage culverts and sewers and local flood protection projects, are currently more susceptible to failure and are in poorer condition than large structures (National Council on Public Works Improvement, 1988). One-third of the non-federal flood control dams inspected under the national non-federal dam program were found to be unsafe, mostly owing to inadequate spillways (National Council on Public Works Improvement, 1988). The capacity of these non-federal, smaller, mostly urban flood control and stormwater structures is more likely to be exceeded. Urbanization upstream from many dams and water control structures is already resulting in increased impervious surfaces (such as pavement) and increased peak runoff, making some structures increasingly vulnerable to failure.

Climate Change and Conflicts Among Water Uses

There is no doubt that climate change has the potential to exacerbate water availability and quality problems and to increase conflicts between regional water uses as a result. The foregoing discussion has highlighted a number of such conflicts:

- conflicts between instream and offstream uses;
- conflicts among offstrearn uses, such as agriculture, domestic use, and thermal power production;
- conflicts between water supply and flood control in the West;
- conflicts between all uses and recreation in the Southeast; and
- conflicts between thermal power production and instream uses, especially in the East.

In some areas, increased precipitation due to climate change could alleviate water quality/quantity problems and conflicts, but only after water infrastructure is modified to accommodate the increased probability of extreme events.

REGIONAL IMPACTS OF CLIMATE CHANGE

Water resources supply and management occurs at the regional, river basin, state, and local levels. To be of use to water resources decisionmakers, climate change models and forecasts need to address regional impacts.

The regional studies conducted by the U.S. Environmental Protection Agency for this document (see Table 9-3) examine the potential regional impacts

Table 9-3. Regional Water Resource Studies

California

- Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California - Lettenmaier, University of Washington (Volume A)
- Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)
- The Impacts of Climate Change on the Salinity of San Francisco Bay - Williams, Philip Williams & Associates (Volume A)

Great Lakes

- Effects of Climate Changes on the Laurentian Great Lakes Levels - Croley, Great Lakes Environment Research Laboratory (Volume A)
- Impact of Global Warming on Great Lakes Ice Cycles - Assel, Great Lakes Environment Research Laboratory (Volume A)
- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, HydroQual, Inc. (Volume A)
- Potential Climatic Chances to the Lake Michigan Thermal Structure - McCormick, Great Lakes Environment Research Laboratory (Volume A)

Great Plains

- Effects of Projected CO_2 -Induced Climate Changes on Irrigation Water Requirements in the Great Plains States - Allen and Gichuki, Utah State University (Volume C)

Southeast

- Potential Impacts of Climatic Change on the Tennessee Valley Authority Reservoir System - Miller and Brock, Tennessee Valley Authority (Volume A)
- Impacts on Runoff in the Upper Chattahoochee River Basin - Hains, C.F. Hydrologist, Inc. (Volume A)
- Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)

of climate change. (With the exception of Allan and Gichuki (Volume C), all studies listed in Table 9-3 are found in Volume A.) The studies use scenarios generated from up to four global circulation models (GCMs) as their starting points (see Chapter 4: Methodology) and match them with regional or subregional water resource models. This section reviews the findings from the studies on California, the Great Plains, the Great Lakes, and the Southeast; from previous studies of the impacts of climate change on these and other regions; and from previous hydrologic studies and models of individual river basins.

The GCMs do not yet provide definitive forecasts concerning the frequency, amount, and seasonality of precipitation and the regional distribution of these hydrologic effects (see Chapter 2: Climate Change; Chapter 3: Variability; Chapter 4: Methodology; Rind and Lebedeff, 1984; Hansen et al., 1986; Gleick, 1987; Rosenberg, 1988). The uncertainty of the forecasts is partially due to the limitations and simplifications inherent in modeling complex natural and manmade phenomena. Modeling efforts are made more difficult by the feedbacks and interconnections between changes in temperature; and the amount and frequency of precipitation, runoff, carbon dioxide, growth and transpiration of foliage, cloud cover, ocean circulation, and windspeed.

However, the regional studies commissioned for this report are a significant step in the effort to bring GCM and regional water resources models together to examine the regional impacts of climate change.

The West

The arid and semiarid river basins west of the Mississippi River have significant surface and groundwater quantity and quality problems and are vulnerable to restricted water availability. Total water use exceeds average streamflow in 24 of 53 western water resource regions (U.S. Water Resources Council, 1978), with the majority of the West's water withdrawals going to irrigation. Surface and groundwater quality in the West have deteriorated as a result of low flow, salts concentrated by irrigation, and pesticide use. The West also depends upon nonrenewable groundwater supplies for irrigation (Solley et al., 1988).

Climate change may exacerbate water shortage and quality problems in the West. Higher temperatures could cause earlier snowmelt and runoff, resulting in lower water availability in the summer. Some GCM scenarios predict midsummer drought and heat, less groundwater recharge, and less groundwater and surface water availability for irrigation in the middle latitudes of the country. The sensitivity analyses conducted by Stockton and Boggess (1979) indicated that a warmer and drier climate would severely reduce the quantity and quality of water in arid western river basins (Rio Grande, Colorado, Missouri, California) by increasing water shortages. Water shortages and associated conflicts between instream and offstream uses, between agricultural and urban/industrial water uses, and between flood control and other water uses of reservoirs may be expected under these scenarios. Hydropower output also would decline as a result of lower riverflow.

Pacific Northwest

The competition for water for irrigation, hydropower, and fisheries habitat is increasing in the Pacific Northwest (Butcher and Whittlesey, 1986). Climate change may alter the seasonality and volume of precipitation and snowmelt, increasing the risk of flooding, changing reservoir management practices, and affecting the output and reliability of hydroelectric power production and the availability of water for irrigation.

California

The diversion of water from water-rich northern California and from the Colorado River to southern California via federal and state systems of dams, aqueducts, and pumping stations has transformed California into the nation's leading agricultural state and has made possible the urbanization of southern California. Irrigation accounted for 83% of the total value of California's agricultural output in 1982 (Bajwa et al.,1987). Because of this high economic dependence on water in an arid area, southern California is vulnerable to droughts and any altered temporal pattern of runoff that may be caused by atmospheric warming.

Total annual runoff from the mountains surrounding the Central Valley is estimated to increase slightly under GCM scenarios, but runoff in the late spring and summer maybe much less than today because higher temperatures cause earlier snowmelt (Lettenmaier, Volume A). The volume of water from the State Water Project may decrease by 7 to 16% (see Chapter 14: California; Sheer, Volume A). Existing reservoirs do not have the capacity to increase storage of winter runoff and at the same time to retain flood control capabilities. In addition, flows required to repel saline water near the major freshwater pumping facilities in the upper Sacramento-San Joaquin River Delta may have to be doubled as a result of sea level rise, further reducing water available to southern California (Williams, Volume A).

Decreases in water availability may also reduce hydroelectric power produced in California. In the 1976- 77 drought, hydroelectric production in northern California dropped to less than 50% of normal, a deficiency relieved by importing surplus power from the Pacific Northwest and by burning additional fossil fuels at an approximate cost of $500 million (Gleick, 1989).

Colorado, Rio Grande, and Great Basins

Total consumption is more than 40% of renewable supply in these river basins. The Colorado River Basin has huge reservoir storage, but demand exceeds supply in the lower half of the basin. Ordinarily all of the Colorado River's water is consumed before it reaches the Gulf of California in Mexico. The Colorado River Compact of 1922, the 1963 Supreme Court decision in Arizona v. Califomia, the treaties with Mexico of 1944 and 1973, and other agreements allocate Colorado River water to seven states and Mexico (Dracup, 1977). Some studies show that the Upper Colorado region will use all of its allocation by the year 2000, reducing water hitherto available to lower Colorado and California (Kneese and Bonem, 1986).

Climate change may further reduce the availability of water in these basins. A model by Stockton and Boggess (1979) of a 2 C temperature increase and a 10% precipitation decrease shows decreases in the water supply in the upper Colorado and the Rio Grande of 40 and 76%, respectively.

Great Plains

The southern Great Plains States of Kansas, Nebraska, Oklahoma, and Texas produce almost 40% of the nation's wheat, 15% of its corn, and 50% of its fattened cattle (see Chapter 17: Great Plains). The region heavily depends on groundwater mining (when pumping exceeds aquifer recharge) for irrigation. The region was severely affected during the "Dust Bowl" years of the 1930s and suffered from severe drought in 1988.

Because of the greater reliability in irrigated yields relative to dryland yields, the demand for irrigation could rise (Allen and Gichuki, Volume C; Adams et al., Volume C). Thus, while total agricultural acreage could decrease, irrigated acreage and groundwater mining may increase in the southern Great Plains. Greater demand may be placed on the Ogallala Aquifer, which underlies much of the region, causing further mining of the aquifer.

Great Lakes

Based on analyses for this report (Croley and Hartmann, Volume A), higher temperatures may overwhelm any increase in precipitation and may evaporate lakes to below the lowest levels on record. However, changes in Great Lakes evaporation under climate change are highly uncertain and depend on such variables as basinwide precipitation, humidity, cloud cover, and windspeed. Under a possible set of conditions, lake levels could rise. The winter ice cover would be reduced but would still be present, especially in shallow areas and northern lakes (Assel, Volume A). Navigation depths, hydropower output, and water quality all would be adversely affected, but losses of existing shorelands from erosion would be reduced as a result of lower lake levels (see Chapter 15: Great Lakes).

Mississippi River

The Mississippi River historically has been affected by both spring floods and drought. In 1988, low flows due to drought received national attention. Low flows disrupt navigation, permit saltwater intrusion into the drinking water of southern Louisiana cities, reduce the dilution of contaminants transported from upstream locations, and reduce the inflow of water to the vast Mississippi Delta wetlands (see Glantz, Volume J).

Northeast

Although the Northeast is humid, cities and powerplants demand large amounts of water at localized points in a watershed, necessitating storage and interbasin transfers. Because of the small amount of storage in the Northeast, the region is vulnerable to prolonged drought. No new major storage has been built in the Northeast during the past 20 years, except the Bloomington Dam on the Potomac River. Water supply in lower New England, New York, and Pennsylvania, and power production in the Northeast, remain vulnerable to drought, which may occur more frequently (Schwartz, 1977; Kaplan et al., 1981). During periodic droughts in the Northeast, such as those in 1962-65 and 1980-81, instream flow regulations ration water and threaten shutdowns of electrical powerplants (U.S. Army Corps of Engineers, 1977; Schwartz, 1977; Kaplan et al., 1981).

Southeast

In the Southeast, the experience with drought in recent years is increasing the use of groundwater and surface water for irrigation and is prompting farmers to consider shifting crops. In Georgia, for instance, the use of groundwater for irrigation has grown quite rapidly. However, the GCMs disagree on whether the Southeast may become wetter or drier (see Haines, Volume A; Miller and Brock, Volume A). Most reservoirs in the area have sufficient capacity to retain flood surges and to maintain navigation, hydropower, water supply, and instream uses (e.g., dilution, wildlife) under both wetter and drier conditions (see Chapter 16: Southeast; Sheer and Randall, Volume A). However, drier conditions would pose conflicts between recreational uses (which would be hurt by changes in reservoir levels) and all other instream and offstream uses.

Should the Southeast become drier, a decline in the inflow of freshwater could alter the estuarine ecology of the gulf coast, which may be most vulnerable to sea level rise (see Chapter 16: Southeast).

POLICY IMPLICATIONS

Decreases in water availability and quality, increased risk of flood damages, and the exacerbation of conflicts between water users competing for an increasingly scarce or difficult to manage resource are the major potential impacts of a global warming trend on the nation's water resources. How will we manage water resources given the possibility of change and uncertainties about its nature and timing?

Policy approaches to water resources may be grouped under supply (or structural) approaches and demand (or nonstructural) approaches. Supply approaches mitigate hydrologic variability and climate change; demand approaches modify behaviors that create vulnerability to such change. For example, water shortages may be addressed either by developing surface water storage capacity and improving the quality of water from available sources (supply approaches), or by decreasing water use and consumption (a demand approach).

Many of the policy approaches discussed below have been recommended by water resource experts for 20 years and are in use to address existing water problems and vulnerabilities. The potential of climate change provides another reason for expanded use of these approaches.

Supply and Structural Policy Approaches

The supply-related policy approaches to water resources include design for uncertainty, surface water development, and optimization of water resource systems.

Design for Uncertainty

Most water resource decisions in the past have been based on the assumption that the climate of a region varies predictably around a stationary mean. Water managers develop water resources plans based on statistical analyses of historical climatological and hydrologic data. However, the frequency of extreme events, which has been assumed to be fixed or to be modified only by the urbanization of watersheds, may be changed significantly by altered climatic conditions.

In addition to being uncertain about hydrologic conditions, we are uncertain about future demographic, economic, and institutional factors that affect offstream water uses and social and economic values attached to instream uses. As an example, water withdrawals in 1985 declined overall from 1980, falling far short of projections made starting in 1960 and as recently as 1978 (Solley et al., 1988).

Finally, we are uncertain about how our economic, regulatory, and institutional systems will respond to climate change in the absence of concerted governmental action. It would be a mistake to attempt to project the impacts of climate change simply by superimposing projected future hydrologic conditions on today's social systems.

The planners and designers of water resources must address such uncertainties. Three types of response are often used to address conditions of great uncertainty:

- Avoid inflexible, large-scale, irreversible, and high-cost measures; opt for shorter term, less capital-intensive, smaller scale, and incremental measures.

- Conduct sensitivity analysis and risk-cost exercises in the design of structural and management systems to address the potential range of climate change impacts. Sensitivity analysis describes the sensitivity of projections to variables affecting their accuracy; risk-cost analysis identifies the costs, for various conditions other than those projected, associated with underdesign or overdesign of a structure. The consideration of hydrologic extremes and the use of risk analysis in the design of specific projects to mitigate the adverse consequences of hydrologic variability may incidentally mitigate many of the physical impacts of climate change (Hanchey et al., 1988).

- Design structures and systems for rare events. Matalas and Fiering (1977) found that many large systems have substantial redundancy (margins of safety) and robustness (ability to perform under a variety of conditions) that enable them to adapt technologically and institutionally to large stresses and uncertain future events.

Although the principle of design for rare extremes may provide robustness, it has a cost and may conflict with the principle of maximizing the economic return from a project. Most public and private water developers subject projects to "net present value" or "internal rate or return" analyses. These analyses discount future benefits relative to present benefits. If a high discount rate is used in decisionmaking, conditions beyond 10 or 20 years may have little impact on design and investment decisions (see Chapter 19: Preparing for a Global Warming; Hanchey et al., 1988).

Surface Water Development

Surface water structures increase developed or available water supply, provide for the regulation of flows for instream uses, prevent flooding, or perform some combination of these functions. These structures include dams, reservoirs, levees, and aqueducts. Because of high costs of construction, adverse impacts on the environment, the limited number of sites available for new structures, and opposition by citizen groups, the trend during the past decade has been away from large excess-capacity, capital- intensive projects. Only the Central Utah Project and the Central Arizona Project have gone forward in recent years. Only one major project in the Northeast has been completed in past 20 years: the Bloomington Dam on the Potomac River. In 1982, California citizens voted down funds for the proposed Peripheral Canal that would have permitted increased diversion of water from north to south in the state. In addition, the national trend toward increased local/state financing and reduced federal fmancing for projects has reduced funds available for large projects (National Council on Public Works Improvement, 1988).

These current trends in water resources management may be reevaluated in light of possible new demands for developed water caused by climate changes. Pressure to build proposed projects such as the Narrows Project in Colorado, the Garrison Diversion in North Dakota, the Peripheral Canal in California, and structures to divert water from northern New England to southeastern Massachusetts may be renewed if droughts reoccur or demand increases. The pace at which existing projects are upgraded, modified, or expanded may also accelerate.

Optimization of Water Resource Systems

Water resources can be managed to maximize the water availability from a given resource base such as a dam, watershed, or aquifer. Adoption of systemwide strategies for a large-scale water system may allow for substantial operating flexibility related to releases of stored water. This flexibility can have an enormous influence on the overall performance and resilience (recovery abilities) of the system, and may provide additional yields that mitigate the impacts of climate change. For example, the U.S. Department of the Interior's Bureau of Reclamation (1987) is adopting operational, management, or physical changes to gain more output from the same resources. Water management agencies nationwide are implementing methods to protect groundwater recharge areas and to use ground and surface waters conjunctively (U.S. EPA, 1987b). Watershed management practices also affect water supply; for example, water yields can be significantly affected by timber harvest practices.

In the East, consolidation of or coordination among fragmented urban water supply authorities can achieve economies of scale in water delivery, decrease the risk of shortage in any one subsystem within a region, increase yields, and provide effective drought management procedures. Sheer (1985) estimated that coordinated water authority activities in the Potomac River basin eliminated the need for new reservoirs, saving from $200 million to $1 billion.

River basin and aquifer boundaries in many cases traverse or underlie portions of several states. Regional and interstate cooperation to manage water resources has a long tradition in some U.S. river basins. Although numerous opportunities exist for additional coordination of water management between states, within basins, or between basins, the agreements required for regional compacts and operating procedures and sharing of water supplies may require substantial and lengthy negotiations.

Several interstate water authorities have significant water allocation authority. For example, the Delaware River Basin Commission allocates water to users in the Delaware Basin and transfers it to New York City under authority of a 1954 Supreme Court ruling (347 U.S. 995) and federal legislation, which established the Commission in 1961 and granted it regulatory, licensing, and project construction powers. Similarly, water authorities in the Washington, D.C., metropolitan area operate Potomac River water supply projects as integrated systems under a 1982 agreement. Both the Delaware and Potomac regional compacts include provisions for drought allocations. (See Harkness et al., 1985, for management actions taken by the Delaware River Basin Commission during a 1984-85 drought.)

Demand Management and Nonstructural Policy Approaches

Demand-related adaptations encourage a reduction in water demand and an increase in water use efficiency through pricing, market exchange of water rights, conservation, protection of water quality, education and extension service assistance, technological innovation, and drought management planning. Policies that discourage activities in floodprone areas are the nonstructural counterparts for reducing flood damage.

Water Pricing, Water Markets, and Water Conservation

In the past, many people considered that water was too essential a resource or too insensitive to price to allow market forces to allocate its use, especially during shortages. Policy took the form of direct controls and appeals to conserve (Hrezo et al., 1986). In recent years, greater attention has been given to market-based policies and mechanisms that allocate limited water supplies among competing uses and promote water conservation.

Water prices that reflect real or replacement costs and the exchange of water rights by market mechanisms can promote conservation and efficient use. Since water use is sensitive to price (Gibbons, 1986) water users faced with higher prices will conserve water and modify their technologies and crop selection to use less without substantial reduction in output. If there is a market for water rights, those willing to pay more may purchase rights from those less willing to pay. As a consequence, water will be transferred out of marginal uses and will be conserved.

Three related pricing and conservation approaches are irrigation conservation, municipal and industrial water use, and water markets and transfers.

Irrigation Conservation

Relatively small reductions in irrigation demand can make large amounts of water available for urban and industrial uses. For instance, nearly 83% of the withdrawals and 90% of the consumptive use of western water is for irrigation. A 10% reduction in irrigation use would save 20 million acre-feet (maf) in water withdrawn and 10 maf in water consumed annually, effectively doubling the water available for municipal and industrial uses in the West (Frederick, 1986). (For comparison, the average annual flow of the Upper Colorado River Basin is 15 maf.)

Inexpensive water was a key factor in the settlement of the West and the expansion of agriculture (Frederick, 1986). The Bureau of Reclamation was established early in this century to promote the development of irrigation in the West. The Bureau provides irrigation for about 11 million acres, more than one-fifth of the total irrigated acreage. Since the Bureau accounts for nearly one-third of all surface water deliveries and about one-fifth of total water deliveries in the 17 western states, actions by the Bureau to use this water more efficiently have an impact throughout the West (Frederick, 1986).

In the past, demand for Bureau water was not based on the real cost of the water, because more than 90% of the Bureau's irrigation projects have been subsidized, and payments on some projects no longer even pay for operation and maintenance (Frederick and Hansen, 1982). Irrigators fortunate enough to receive such inexpensive water may have little or no incentive to conserve. However, the Bureau's more recently stated objectives include revising their water marketing policy, promoting conservation, and pricing water to reflect its real cost (U.S. Department of the Interior, 1987).

Municipal and Industrial Water Use

Municipalities throughout the country are finding it difficult and expensive to augment their supplies to meet the demands of population and economic growth and are finding that users would rather use less than pay more (Gibbons, 1986). Traditional average-cost pricing provides adequate service to customers and adequate returns to water companies, but is being reevaluated because it tends to cause overinvestment in system capacity (U.S. Congress, 1987). Marginal-cost pricing (charging for the cost of the last-added and most expensive increment of supply) or progressive-rate pricing (charging more per unit to users of large amounts) can reduce domestic and industrial water consumption because water use is sensitive to price (Gibbons, 1986).

Water Markets and Transfers

The "first in time, first in right" appropriation doctrine, which favors the longest standing water rights, governs much of the West's surface water and some groundwater. The appropriation doctrine has the potential to establish clear, transferable property rights to water -- a precondition for effective operation of water markets. The potential for water transfers to the highest value users has not yet been fully realized because the nature and transferability of the rights are obscured by legal and administrative factors (Trelease, 1977; Frederick, 1986; Saliba et al., 1987). Following are some examples:

- Rather than grant absolute ownership, states with prior appropriation rules grant rights to use water for beneficial purposes. Water rights not put to beneficial use may be forfeited. This encourages a use-it-or-lose-it attitude.

- Federal and Native American water rights remain unquantified in some areas such as the Colorado River Basin.

- The emergence in law of the "public trust doctrine," which states that all uses are subject to the public interest, has cast a cloud over some water rights. This has been true in California, where the public interest has driven a reexamination of withdrawals from Mono Lake, and where existing permits have been modified to protect the Sacramento-San Joaquin Delta from saltwater intrusion. Montana is increasingly basing water management plans on its instream flow requirements and is exploring ways to have these requirements for all future beneficial instream uses count as a bona fide use of the Missouri River to slow the growth rate of water diversion for offstream uses (Tarlock, 1987).

- In resolving interstate water disputes, a federal common law of "equitable apportionment" has developed under which an informed judgment, based on consideration of many factors, secures a "just and equitable" water allocation (see Strock, 1987). The Supreme Court decided in Colorado v. New Mexico (456 U.S. 176, 1982) that equitable apportionment may be used to override prior appropriation priorities in cases of major flow reductions. The Supreme Court specifically mentioned climatic conditions in ruling that prior appropriation systems would otherwise protect arguably wasteful and inefficient uses of water at the expense of other uses (see Strock, 1987).

- Because of imperfect competition, third-party effects, uncertainty over administrative rules, and equity considerations, water market prices may not appropriately measure water values according to economic efficiency criteria (Gibbons, 1986; Saliba et al., 1987).

- It is possible to control groundwater withdrawals, but for a number of reasons it is difficult to establish market mechanisms for groundwater allocation. Because all groundwater users essentially draw from a shared pool, groundwater resources are treated as "common property." As a result, property rights are difficult to define, third-party impacts of transfers of groundwater rights are significant, and interstate agreements concerning allocation of interstate aquifer water are difficult to attain (Emel, 1987).

Despite the obstacles, transfer of water rights among users -- especially from irrigators to municipalities and power companies seeking water for urban expansion and electricity production -- is becoming common in many western states (Wahl and Osterhoudt, 1986; Frederick, 1986). Methods include negotiated purchases, short-term exchanges during droughts, and water banks and markets (Wahl and Osterhoudt, 1985; Saliba et al., 1987; Wahl and Davis, 1986).

Legislation in many western states has facilitated water transfers (Frederick, 1986; Frederick and Kneese, 1989). For instance, Arizona's new water law facilitates the purchase of agricultural land for water rights, and the use of that water for urban development. Strict technical standards imposing conservation on municipal and industrial water uses, such as watering golf courses with wastewater, are also part of Arizona's laws (Saliba et al., 1987).

Frederick and Kneese (1989) caution that water transfers occur gradually and are not likely to affect more than a small percentage of agricultural water rights for the foreseeable future. However, legal and institutional changes facilitating water markets and demand for water by high-value users may be accelerated under the stress of climate change (Trelease, 1977).

Drought Management Policies

Integrating drought planning into water resource management may assume greater priority if climate change aggravates water shortages. The Model Water Use Act (Hrezo et al., 1986) advocates that states or water supply authorities integrate drought management and advance planning into their policies by designating a governmental authority for drought response and by adopting mechanisms for automatically implementing and enforcing water-use restrictions. In 1986, only seven states had comprehensive management plans for water shortages (Hrezo et al., 1986). Most states rely on water rights appropriations, emergency conservation programs, and litigation to allocate water during shortages. Improved capabilities in surface hydrology and in water system modeling and monitoring would be required to support broadened drought contingency planning.

Water Quality

Federal and state legislation and regulations for control of instream water quality have had a dramatic effect on reducing conventional water pollutants since the enactment of the 1972 Clean Water Act. The reduced riverflows and lake levels that are possible under altered climate conditions could necessitate more stringent controls on point and nonpoint sources to meet water quality standards. Promotion of nonpolluting products, waste minimization, and agricultural practices that reduce the application of chemicals will also enhance water quality, making more water of suitable quality available for use.

Many states have adopted measures to protect instream water uses. These include reserving flows or granting rights for particular instream uses and directing agencies to review impacts before granting new rights (U.S. Water Resources Council, 1980; Frederick and Kneese, 1989). Regulations limiting water use may have to be modified where climate change has resulted in reduced flows during droughts.

Policies for Floodplains

The National Flood Insurance Program was enacted in 1968, with major amendments in 1973. The program provides subsidized flood insurance for existing structures in flood-prone areas, provided that the community with jurisdiction regulates the location and construction of new buildings to minimize future flood losses. New structures that comply with the restrictions are eligible for insurance at full actuarial rates.

In 1979, the program took in $140 million in premiums and paid $480 million in claims. Recently, the program was authorized to relocate structures exposed to repeated flood or erosion damage rather than pay claims for such structures.

Where rainfall and flooding increase, the 100-year floodplain would expand, and rate maps would need revision. Premium payments and claims would rise.

RESEARCH NEEDS

Water is the principal medium by which changes in atmospheric conditions are transmitted to the environment, the economy, and society. Hydrology is the key discipline that enables us to understand and project these effects. Improvements in both the GCMs and regional hydrologic models are needed so that we may understand the impacts of climate change and devise appropriate water resources management strategies. Specifically, GCMs do not yet provide regional forecasts at the level of certainty and temporal and spatial resolution required for decisionmakers. To be more helpful, the GCMs should provide forecasts specific to individual river basins or demand centers, and should describe hydrologic conditions over the typical design-life of water resource structures.

Research activities should include the following:

- Monitor atmospheric, oceanic, and hydrologic conditions to detect evidence of water resources impacts of climate change.
- Continue to develop and refine regional hydrologic models that are capable of modeling the changes in runoff, water availability, water use, and evapotranspiration induced by changes in temperature and atmospheric conditions. This research should focus on vulnerable river basins where demand approaches or exceeds safe yield or where hydrologic variability is high.
- Refine global climate change models and link them to regional hydrologic models so that regional water resource planners, engineers, and managers can use their projections more confidently.
- Study the sensitivity of existing water systems to possible changes in climate conditions.

At the same time, the following research is needed to identify opportunities for adopting measures to adjust and adapt to climate change.

- Quantify federal and Native American water rights in the West.
- Examine how present institutions and markets can better allocate water among users and provide incentives to conserve water.
- Assess the extent to which laws and regulations may exacerbate the effects of climate change. (Examples include thermal controls for rivers and federal pricing and reallocation policies for irrigation water.)
- Identify, project, and quantify the demographic and institutional adjustments that may occur in the absence of public action in response to climate-induced impacts on water resources. This research will reduce uncertainty for policymakers regarding where concerted public action may be or not be needed.

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CHAPTER 1O
ELECTRICITY DEMAND

by Kenneth P. Linder

FINDINGS

Global warming would increase electricity demand, generating capacity requirements, annual generation, and fuel costs nationally. The impacts could be significant within a few decades and would increase substantially over time if global warming continues.

- The new generating capacity requirements induced by climate change effects on electricity demand estimated for 2010 show an increase of 25 to 55 gigawatts (GW), or 9 to 19% above estimated new capacity requirements assuming no change in climate. Between 2010 and 2055, climate change impacts on electricity demand could accelerate, increasing new capacity requirements by 200 to 400 GW (14 to 23%) above what would be needed in the absence of climate change. These capacity increases would require investments of approximately $200 to $300 billion (in 1986 dollars). In the absence of climate change, population and economic growth may require investments of approximately $2.4 to 3.3 trillion through 2055.

- Estimated increases in annual electricity generation and fuel use induced by climate change represent several thousand gigawatthours by 2055. The estimated increases are 1 to 2% in 2010 and 4 to 6% in 2055. Annual fuel, operation, and maintenance cost to meet increased electricity demand would be several hundred million dollars in 2010 and several billion dollars in 2055. Without climate change, these annual costs would be $475 to 655 billion in 2055.

- Estimated regional impacts differ substantially. The largest increases could occur in the Southeast and Southwest, where air-conditioning demands are large relative to heating. Northern border states may have a net reduction in electricity generation relative to base case requirements assuming no change in climate. These changes could be exacerbated by reductions in hydropower production and increases in demand for electricity to run irrigation equipment.

- These results are sensitive to assumptions about the rates of economic growth, technological improvements, and the relationship between electricity use and climate. The potential savings in other energy sources (gas and oil) used for space heating and other end uses sensitive to climate and the potentially significant impacts on hydroelectric supplies and other utility operations were not analyzed.

Policy Implications

- Utility executives and planners should begin to consider climate change as a factor in planning new capacity and future operations. The estimated impacts of climate change in some regions are similar to the range of other uncertainties and issues utility planners need to consider over the 20- to 30-year period. Additional climate and utility analyses are needed to develop refined risk assessments and risk management strategies.

- The increased demand for electricity induced by climate change also could exacerbate other environmental problems, such as the implementation of "acid rain" strategies, adherence to the international nitrogen oxide treaty, state implementation plans for ozone control, and thermal pollution control permit requirements. The Environmental Protection Agency should analyze the impacts of climate change on long-range policies and should include climate change as an explicit criterion in making risk management decisions when appropriate.

- The increased demand for electricity could make policies to stabilize the atmosphere through energy conservation more difficult to achieve. The estimated increases in electricity generation induced by climate change could increase annual CO_2 emissions, depending upon future utility technology and fuel choice decisions. Assuming no change in efficiency of energy production and demand, reliance on coal-based technologies to meet the increased demands could increase CO_2 emissions by 40 to 65 million tons in 2010 and by 250 to 500 million tons in 2055. Use of other, lower CO_2 emitting technologies and fuels (e.g., efficient conversion technologies and nuclear and renewable resources) would reduce these incremental additions. In addition, warmer winter temperatures could reduce the demand for oil and gas in end uses such as residential furnaces for heating, thereby lowering CO_2 emissions from these sources. Future analyses of national and international strategies to limit greenhouse gases should include the changes in energy demand created by global warming as a positive feedback.

CLIMATE CHANGE AND ELECTRICITY DEMAND

Climate change could affect a wide range of energy sources and uses. In the near term, policies aimed at reducing emissions of greenhouse gases from fossil fuel combustion could affect the level and mix of fuel consumption in various end-use technologies and in the generation of electric power. In the longer term, changes in temperature, precipitation, and other climatic conditions also could affect energy resources. For example, warmer temperatures likely would reduce the demand for fuels used in the winter for space heating and increase the demand for fuels used in the summer for air-conditioning; and reduced precipitation and soil moisture in some regions could increase the use of energy to pump water for irrigation. These effects could be particularly significant for planning in the electric utility industry based upon the substantial amount of electric load accounted for by weather-sensitive end uses, the variety of resources used to generate electric power, and the capital-intensivity of the industry. One major consideration is the potential impact of climate change on the demand for electricity and the implications of changes in demand on utility capacity and generation requirements.

Many electrical end uses vary with weather conditions. The principal weather-sensitive end uses are space heating, cooling, and irrigation pumping and -- to a lesser degree -- water heating, cooking, and refrigeration. These applications of electricity may account for up to a third of total sales for some utilities and may contribute an even larger portion of seasonal and daily peak demands.

Changes in weather-sensitive demands for electricity can affect both the amount and the characteristics of generating capacity that a utility must build and maintain to ensure reliable service. These changes also can affect fuel requirements and the characteristics of efficient utility system operations, particularly the scheduling and dispatching of the utility's generating capacity. For example, electric energy used for air-conditioning exceeds that used for space heating nationwide, and the temperature sensitivity associated with cooling is higher than that associated with heating. This implies not only changes in seasonal electricity demands but also increases in annual electricity demands as a result of higher temperatures.

Similarly, utilities in most regions experience their peak demands in the summer. A rise in air conditioning and other temperature-sensitive summer loads would significantly increase peak loads and, as a result, would step up utility investments in new generating capacity needed to meet additional demands and to maintain system reliability.

Examples of other ways in which climate could affect electric utilities include the following. Changes in precipitation, evaporation, and runoff from mountain snowpack as well as changes in water management practices in response to climate change could affect the annual and seasonal availability of streamflow to generate hydropower. Reductions in hydropower would require utilities to rely upon other, possibly more costly and less environmentally benign generation sources to meet customer needs. Furthermore, reductions in water resources would adversely affect the availability and/or cost of water for powerplant cooling.

Other direct impacts of climate change on electric utilities include the effects of temperatures on powerplant operating efficiencies, the effects of sea level rise on the protection and siting of coastal facilities, and the effects of changes in various climate conditions on the supply of renewable energy resources such as solar and wind power. Also, legislation and regulations designed to limit greenhouse gas emissions from utility sources could significantly affect the supply and cost of electricity generation.

Although some of these impacts could significantly affect utility planning and operations (particularly on a regional basis), they have not been analyzed in detail and are not addressed in this report. Further research and analysis are needed to develop a more complete assessment of utility impacts.

PREVIOUS CLIMATE CHANGE STUDIES

A number of utilities conduct analyses relating short-term variations in weather conditions with a need to "weather-normalize" historical demand data and to test the sensitivity of system reliability and operations to these short-term variations. Furthermore, some researchers have speculated regarding the potential effects of longer term climate changes on electricity demand (e.g., Stokoe et al., 1987).

However, only one previous study has estimated the potential implications of longer term, global warming-associated temperature changes on electricity demands and the effects of changes in demand on utility investment and operating plans. Linder et al. (1987) used general circulation model (GCM) results to estimate the potential impacts of temperature change on electricity demand (and on the supply of hydropower) for selected case study utility systems in two geographical areas: a utility located in the southeastern United States and the major utilities in New York State, disaggregated into upstate and downstate systems.

Linder et al. found that temperature increase could significantly heighten annual and peak electricity demands by 2015, and that a temperature rise would require construction of new generating capacity and increases in annual generation. The southeastern utility had higher estimated increases in electricity demand, generation, and production costs than the New York utilities because of greater electricity demands for air-conditioning. In addition, streamflow used to generate hydropower in New York could be reduced, requiring increased use of fossil fuel generation to meet customer demands for electricity.

CLIMATE CHANGE STUDY IN THIS REPORT

Study Design

Linder and Inglis (Volume H) expanded the case studies (Linder et al., 1987) of the sensitivity of electricity demand to climate change and conducted a national analysis of electricity demand. Relevant regional results from the national studies of Linder and Inglis are discussed in the regional chapters of this report.

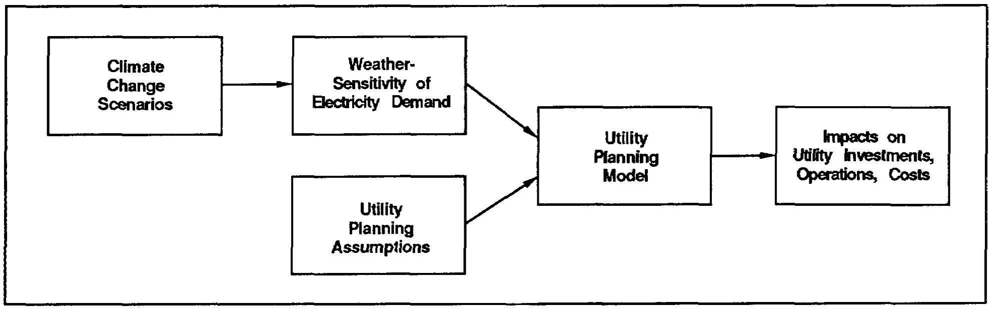

Figure 10-1. Analytic approach (Linder and Inglis, Volume H).

The analytic approach developed by Linder et al. (1987) formed the basis for estimating the regional and national impacts described in this report. The principal steps in the approach are summarized in Figure 10-1(see Volume H for more details). Estimated impacts were developed for the relatively near term (from the present to 2010, within electric utility long-range resource planning horizons of 20 to 30 years) and over the longer term (to 2055), when the magnitude of temperature changes is expected to approach equilibrium levels representative of a doubling of atmospheric concentrations of CO . Linder and Inglis used Goddard Institute for pace Studies (GISS) A and B transient estimates of temperature change in 2010 and GISS A estimates for 2055 in their calculations. The scenario changes in annual temperatures for the United States range from about 1.0 to 1.4 C in 2010 and are approximately 3.7 C by 2055. Regional temperature scenarios show greater variation.

Linder and Inglis used actual utility demand and temperature data from the case study utilities, and from five other large, geographically dispersed utility systems, to develop a set of weather-sensitivity parameters for utility areas. On a weighted-average basis (weighted by electricity sales), utility peak demands were estimated to increase by about 3.1% per change in degree Celsius (ranging from -1.35 to 5.40% across utility areas), and annual energy demands were estimated to increase by about 1.0% per change in degree Celsius (ranging from -0.54 to 2.70%).

A number of uncertainties associated with the data and assumptions used to develop these weather-sensitivity relationships suggested that the relationships may understate customer response to climate change, particularly at higher temperature change levels occurring in the future. For example, the approach did not explicitly account for probable increases in the market saturation of air conditioning equipment as temperatures rise over time. To address this possibility, an alternative case was designed in which the estimated weather sensitivity values were increased by 50%. This was designated as the "higher sensitivity" case.

Since this study is focused on estimating how climate change may affect key utility planning factors, Linder and Inglis used a planning scenario assuming no change in climate (a "base case") to serve as a basis for comparison with planning scenarios under alternative assumptions of climate change for 2010 and 2055. Thus, base case utility plans were developed for 2010 and 2055, using assumptions regarding future demands for electricity in the absence of climate change (reflecting population and economic growth), generating technology option performance and costs, fuel costs, and other utility characteristics. [1]Linder and Inglis assumed that future capacity and generation requirements will be met by investments either in new coal-fired baseload capacity or in oil- and natural gas-fired peaking capacity. Other sources, such as nuclear energy and renewables or innovative fossil fuel-fired technologies (e.g., fluidized bed combustion), were not considered (for further details, see Linder et al., 1987).

Demands for electricity in the absence of climate change can be related to the overall level of economic activity as represented by the gross national product (GNP). Because economic growth assumptions are critical to estimates of future electricity demands, alternative GNP growth rates were assumed in developing the base cases; these ranged from 1.2 to 2.1% per year.[2] These alternative assumptions are referred to as "lower growth" and "higher growth," respectively.

These assumptions served as inputs to a regional planning model called the Coal and Electric Utilities Model (CEUM). CEUM outputs include the amount and characteristics of new generating capacity additions, electricity generation by fuel type, and electricity production costs.

Limitations

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[1] Note that the development and use of a base case reflecting changes in non-climate-related conditions over time was undertaken only for the electricity demand study, not for other areas in the report. Changes in population and technology are considered in Chapter 6: Agriculture.

[2] These GNP growth rates are relatively conservative, but they are comparable with GNP growth rates used by EPA in its report to Congress on Policy Options for Stabilizing Global Climate.

The study extrapolated temperature-sensitivity findings for some regions and did not include specific analyses of temperature sensitivity for all utility regions of the United States. It focused narrowly on impact pathways, considering only the potential effects of temperature change on changes in electricity demand. Neither the potentially significant impacts of climate change on hydropower availability nor the impacts of reduced water supplies for powerplant cooling were included.

Furthermore, the study did not evaluate the sensitivity of the results to different, doubled-CO_2 GCM climate scenarios (GFDL and OSU), although the use of the GISS transient experiment results for 2010 and 2055 indicates relative sensitivities to small and large temperature changes.

The study did not consider variations in temperature changes and the occurrence of extreme events, which affect powerplant dispatch and determinations of peak demands, respectively, and are important for utility planning.

Many uncertainties exist regarding the concepts, methods, and assumptions involved in developing and applying estimates of the temperature sensitivity of demand. For example, a key assumption is that the estimated sensitivities of demand to historical, short-term variations in temperature are adequate representations of future relationships between electricity demand and long-term changes in mean temperatures.

Uncertainties also exist regarding market, regulatory, technological, and other conditions that will face the utility industry in the future. For example, technological changes that improve the energy efficiency of weather-sensitive end-use equipment or electricity-generating equipment will continue to evolve. These changes would likely lead to lower climate change impacts than estimated in this report. On the other hand, regulatory changes aimed at reducing the emissions of greenhouse gases from electricity generation could limit a utility's future fuel and technology investment options, leading to higher estimates of cost impacts than reported here. Because of these limitations, it is important to recall that the results presented in the next section should not be considered as projections of actual powerplant investments and utility operations, but rather as comparisons providing estimates of the magnitude of sensitivities to alternative climate change assumptions.

Results

The potential national impacts for 2010 and 2055 are summarized in Table 10-1. The table presents base case values (i.e., assuming no change in climate) for each year and estimated impacts represented by changes from the base case values. The impacts for 2055 are presented for both the lower growth GNP and the higher growth GNP cases. Also, where ranges of impacts are presented, they summarize the estimates under alternative climate change scenarios (GISS A and GISS B) and assumptions of the weather sensitivity of demand ("estimated sensitivity" and "higher sensitivity").

Estimated increases in peak demand over the base case on a national basis range from 2 to 6% by 2010. Changes in estimated annual energy requirements by 2010 are more modest, ranging from 1 to 2%. In 2055, peak national demands are estimated to increase by 13 to 20% above base case values, and annual energy requirements are estimated to increase by 4 to 6%.

By 2010, new climate change-induced generating capacity requirements increase by 6 to 19%, or about 24 to 55 GW, representing an average increase of up to 1 GW per state (approximately the capacity of one to two large nuclear or coal-fired baseload powerplants). The majority of the capacity increase is for peaking capacity rather than baseload capacity. The investment associated with these capacity increases is several billion dollars (in constant 1986 dollars). By 2055, the change in new capacity requirements increases in percentage terms and represents several hundred GW. Under high GNP and higher weather-sensitivity assumptions, the estimated increase attributable to climate change is almost 400 GW, or 23%. To put these results into perspective, it should be noted that current generating capacity in the United States is about 700 GW. The increase in new capacity requirements under the base case is 1,350 to 1,780 GW.

Annual generation increases for the United States are not as large in percentage terms as those estimated for new generating capacity requirements, but

Table 10-1. The Potential National Impacts of Climate Change on Electric Utilities

	2010		2055			
			Lower GNP		Higher GNP	
	Base	Increase	Base	Increase	Base	Increase
Peak Demand (GW)	774	20-44	1,355	181	1,780	238-357
New capacity requirements (GW)[a]						
Peaking	50	13-33	176	118	254	182-286
Baseload	226	11-22	1,011	67	1,423	74-98
Total	276	24-55	1,187	185	1,677	227-384
Annual sales (bkWh)	3,847	39-67	6,732	281	8,848	370-555
Annual generation[b] (bkWh)						
Oil/gas	287	(12)-(29)	221	2	308	27-51
Coal	2,798	54-103	6,242	305	8,295	381-560
Other	1,092	1-(1)	846	(2)	1,003	(7)-0
Total	4,177	43-72	7,309	305	9,607	401-611
Cumulative capital costs[c,d]	669	25-48	1,765	173	2,650	222-328
Annual costs[d]	162	3-6	474	33	655	48-73

[a] Includes reserve margin requirements; does not include "firm scheduled" capacity.

[b] Includes transmission and distribution losses.

[c] "Base" values include regional capital expenditures for utility-related equipment in addition to new generating capacity (e.g., new transmission facilities).

[d] In billions of 1986 dollars.

Abbreviations: GW = gigawatts; bkWh = billion killowatthours.

Source: Linder and Inglis (Volume H).

nonetheless, they account for several hundred billion kWh by 2055. In the near term (i.e., to 2010), increased levels and changing patterns of climate change-induced electricity demand permit utilities in some areas having excess generating capacity to serve the growing needs of utilities in other areas through substitution of lower cost baseload generation for higher cost peaking generation. On net, peaking generation would be lower as a result of climate change in 2010(see Linder et al., 1987, for further detail). In 2055, peaking generation is projected to increase along with baseload generation, because all the excess capacity that had existed in 2010 either would have been fully used by growing demands to 2055 or would have been retired. The estimated impacts of climate change on national new generating capacity requirements and annual generation are illustrated in Figure 10-2.

Table 10-1 also indicates that the increase in annual costs for capital, fuel, and operation and maintenance associated with climate change-induced modifications in utility investments and operations are a few billion dollars in 2010 and are $33 to $73 billion by 2055, a 7 to 15% increase over base case values of $475 to $655 billion for 2055.

Figures 10-3 and 10-4 illustrate the diversity of the estimated results for generating capacity on a state-by-state basis. The state and regional differences reflect differences in current climate conditions (e.g., seasonal temperature patterns), assumed future climate changes, and electricity enduse and utility system characteristics (e.g., market saturation of weather-sensitive appliances and equipment).

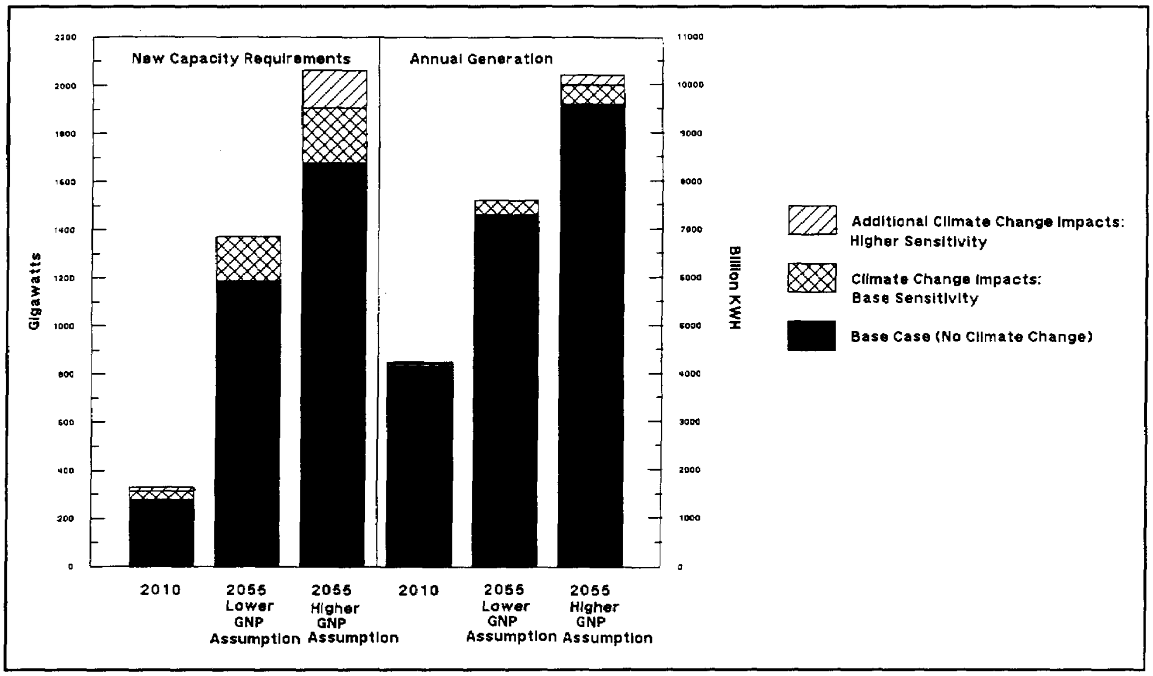

Figure 10-2. Potential impacts of climate change on electric utilities, United States (Linder and Inglis, Volume H).

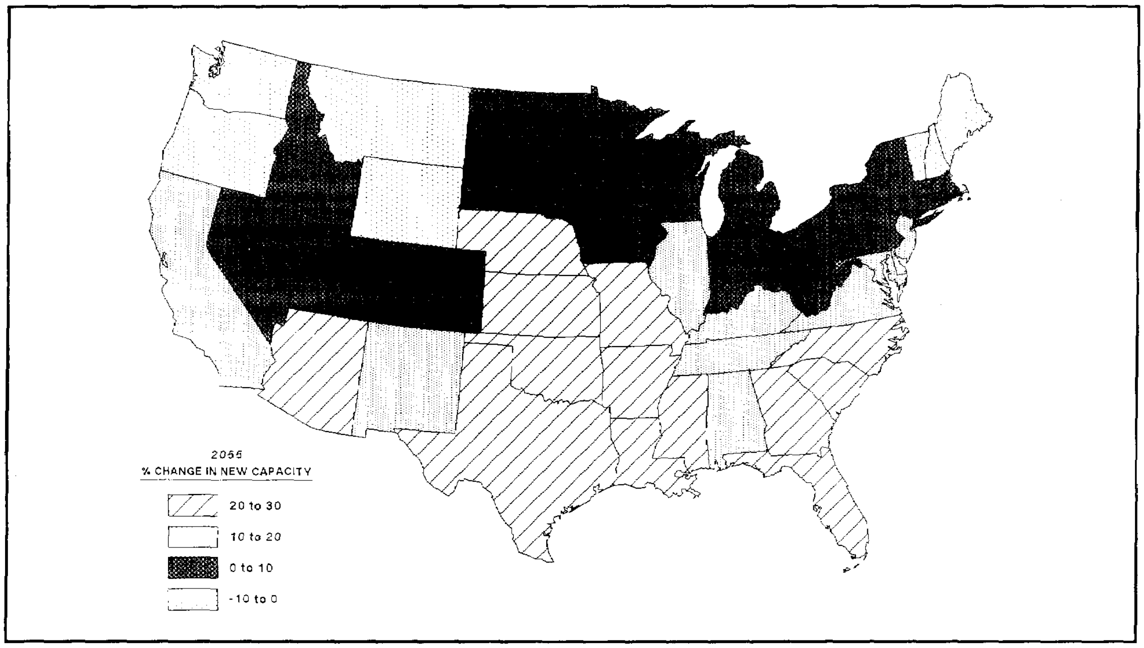

Figure 10-3. Changes in electric utility capacity additions by state, induced by climate change in 2055 (derived from Linder and Inglis, Volume H).

Figure 10-3 shows that estimated reductions in new capacity requirements induced by climate change are limited to the winter-peaking regions of the extreme Northeast and Northwest. The Great Lakes, northern Great Plains, and Mountain States are estimated to experience increased new capacity requirements by 2055 in the range of 0 to 10%. Increases greater than 20% are concentrated in the Southeast, southern Great Plains, and Southwest.

Figure 10-4 shows a somewhat similar geographic pattern of impacts for electricity generation in 2055. Reductions in generation are estimated in the North, and the greatest increases are concentrated in the Southwest. Despite substantial use of air-conditioning in the Southeast, the estimated increases in generation are only in the 5 to 10% range. There is a relatively high market saturation of electric heat in the region, and the increase in cooling is partly offset by a decrease in heating as a result of warmer winters.

Because regions are affected differently, the results indicate potential changes in the patterns of interregional bulk power exchanges and capacity sales over time and as climate changes. For example, under the assumption of increasing temperatures, some regions may require significant amounts of additional generating capacity to reliably meet increased demands during peak (cooling) seasons, but may experience lower demands in other (heating) seasons. As a result, the region's needs may be for powerplants that are utilized heavily during only part of the year. Low annual utilization in the region would not justify construction of highcapital and low-fuel cost baseload powerplants that can produce electricity more cheaply (per kWh) than low-capital and high-fuel-cost peaking units. However, when considered across several regions, the least-cost plan may be to construct baseload powerplants in certain regions, utilize them to an extent greater than required by the region, and sell the "excess" electricity from these plants into other regions. The location and amount of these interregional sales would be subject to the transfer capabilities of transmission capacity in place. An alternative to increased interregional bulk power sales would be the development and application of efficient and effective energy storage technologies.

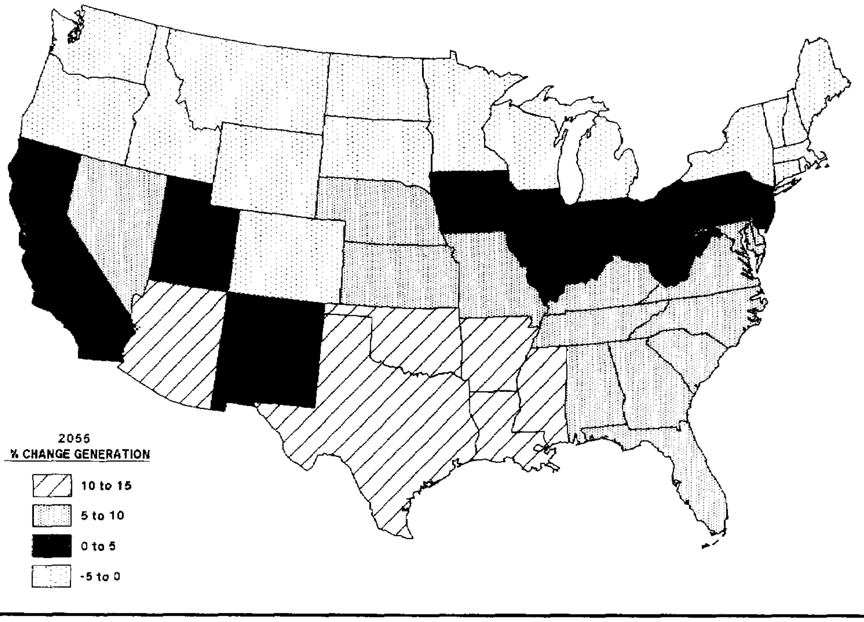

Figure 10-4. Changes in electricity generation by state, induced by climate change in 2055 (derived from Linder and Inglis, Volume H).

SOCIOECONOMIC AND ENVIRONMENTAL IMPLICATIONS

Despite the limitations of the analysis and the need for more research to refine the data and methods used, the results are judged to be reasonable estimates of the sensitivity of electricity demand to potential climate change. Key socioeconomic and environmental implications of the results stem from the increases in electric generating capacity and generation requirements associated with climate-induced changes in demand. The implications include the following:

- Climate change could result in overall fuel mixes for electricity generation that differ from those expected in the absence of climate change.
- Climate change would not evenly affect regional demands for electricity. Greater impacts would occur in regions where weather-sensitive end uses (particularly airconditioning) are important sources of electricity demand. Substantially greater climate change impacts were estimated for the Southeast and Southwest than for other regions, especially the northern tier of states. Other impacts not addressed in this study, such as the availability of water for hydropower generation and powerplant cooling, also would be more important in some regions (e.g., the West) than in others.
- Regional differences in capacity and generation requirements suggest that important new opportunities for interregional bulk power exchanges or capacity sales may arise as a result of climate change.
- The impacts of uncertain climate conditions over the long term could pose significant planning and economic risks. Because of long lead times required to plan and build economic baseload generating capacity, the ability of utility planners to correctly anticipate climate change could result in lower electricity production costs. The magnitude of these risks in some regions (e.g., the Southeast and the southern Great Plains) could be similar to other uncertainties that utility planners and decisionmakers must face.
- If the result is confirmed that the majority of new capacity requirements in response to climate change are for peaking capacity, a new technological and market focus would be directed toward this type of generating plant. Related to this would be increased research and development on electricity storage technologies, which would allow lower cost, more efficient powerplants to generate, at off-peak times, electricity for use during peak periods.
- Because increases in customer demands for electricity may be particularly concentrated in certain seasons and at peak periods, conservation and especially load management programs that improve the efficiency or change the patterns of customer uses of electricity could be more cost-effective when considered in the context of potential changes in climate.
- Increased electricity generation implies the potential for increased adverse environmental impacts depending upon generating technology and fuel-use assumptions. Potential adverse impacts compared with the base case are associated with the following:

  – air quality (e.g., emissions of sulfur dioxide, NOW and other pollutants);
  – land use for new powerplant sites, fuel extraction, fuel storage, and solid waste disposal;
  – water quality and use (e.g., for powerplant cooling and fuel processing); and
  – resource depletion, especially of nonrenewable fuels such as natural gas.

  Of particular concern would be additional water withdrawal and consumption requirements in areas where water supplies may be reduced by climate change.[3]

- Increased electricity generation also implies increased emissions of CO. and other greenhouse gases compared with base case emissions. For example, if the estimated increases in climate change-induced generation reported in Table 10-1 were met by conventional technologies, CO_2 emissions could increase by 40 to 65 million tons per year by 2010 and by 250 to 500 million tons per year by 2055.[4] Use of lower CO_2-emitting technologies and fuels -- such as efficient conversion technologies and nuclear or renewable resources -would lower these estimated impacts.

POLICY IMPLICATIONS

In general, the study results suggest that utility planners and policymakers should begin now to assess more fully and to consider climate change as a factor affecting their planning analyses and decisions. If more complete and more detailed analyses support the socioeconomic and environmental implications of the climate change effects described above, they should be explicitly addressed in planning analyses and decisions. Specific policy implications related to the findings include the following:

- In formulating future National Energy Plans, the Department of Energy may wish to consider the potential impacts of climate change on utility demands.

- The interactions of climate change and the current efforts of the Federal Energy Regulatory Commission (FERC) to restructure the electric utility industry are difficult to assess. For example, the industry's response to FERC policies could either accelerate or reduce the rate of emissions of greenhouse gases, depending upon changes in the mix of generating fuels and effects on the efficiency of electricity production. The possible alternative responses should be assessed, and FERC policies should be considered with respect to their potential implications related to climate change issues.

- Increases in electricity demands induced by climate change will make achievement of energy conservation goals more difficult. For example, the conference statement from "The Changing Atmosphere: Implications for Global Strategy" (Environment Canada, 1988) calls for reductions in CO_2 emissions to be achieved in part through increased efforts in energy efficiency and other conservation measures. An initial goal for wealthy, industrialized nations set by the conference is a reduction in CO_2 emissions through conservation of approximately 10% of 1988 emissions levels by 2005. The impacts of climate change to increase electricity demand should be factored into the policies and plans designed to achieve this conservation goal.

- Similarly, climate change impacts may exacerbate the difficulties or costs associated with implementing acid rain mitigation strategies being considered by the Congress. However, these strategies center primarily on near-term solutions focusing on emissions reductions from existing powerplants, and the impacts of climate change may not be large within that time frame.

- Although not addressed directly in the analyses underlying this report, state and federal agencies should consider mitigation strategies that include energy conservation; increased efficiency in the production, conversion, and use of energy; and the development and reliance on fuel sources with

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[3] For example, increased electricity generation induced by climate change in northern California could increase requirements for water withdrawal by 600 to 1,200 million cubic feet and for water consumption by 200 to 400 million cubic feet in 2055. Comparable figures for the southern Great Plains in 2055 would be water withdrawal of 5,800 to 11,500 million cubic feet and consumption of 1,800 to 3,500 million cubic feet.

[4] Note, however, that these increases in emissions from electricity production could be offset, at least in part, by reduced demand for space heating provided by natural gas and oil furnaces or by other direct uses of fossil fuels.

low CO_2 emissions.

RESEARCH NEEDS

Important areas for further climate change research include improved methods for developing and disseminating climate change scenarios, with particular emphasis on (1) improved estimates of climate variables (in addition to temperature) relevant to utility impact assessment (e.g., hydrologic factors, winds); (2) estimates of the possible impacts of global warming on variations in weather conditions and the occurrence of extreme events; (3) continued attention to estimates of the rate of climate change over time; and (4) estimates of climate change at a more disaggregated regional or local level.

Follow-on research suggestions on the utility side include (1) refinement of the analytical approach, in part through lessons learned from additional utility-specific analyses; (2) more detailed and complete analyses of the weather sensitivity of customer demand for electricity; (3) extension of the approach to consider other pathways (including indirect and secondary effects) through which climate change could affect utility investments and operations; and (4) an assessment of the value of improved climate change information to utility planners and managers.

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CHAPTER 11
AIR QUALITY

by Joseph J. Bufalini, Peter L. Finkelstein and Eugene C. Durman

FINDINGS

- Potential changes in regional temperatures, precipitation patterns, clouds, windspeed and direction, and atmospheric water vapor that will accompany global climate change will affect future air pollution levels and episodes in the United States.

- While uncertainties remain, it is likely that an increase in global temperatures would have the following effects on air quality, if other variables remain constant. These potential impacts should be interpreted as relative changes as compared with air quality levels without climate change. This chapter does not predict what will happen to air quality without climate change and does not consider changes in anthropogenic emissions or technology.

  - Ozone levels in many urban areas would increase because higher global temperatures would speed the reaction rates producing ozone in the atmosphere.

  - Natural emissions of hydrocarbons would increase with a temperature rise. Natural emissions of sulfur would also change, but the direction is uncertain. The hydrocarbons and nitrogen oxides participate in reactions that produce ozone.

  - Manmade emissions of hydrocarbons, nitrogen oxides, and sulfur oxides may rise if more fossil fuel is used to meet higher electricity needs (see Chapter 10: Electricity Demand) and if technology does not improve.

  - The formation of acidic materials (such as sulfates) would increase with warmer temperatures because sulfur and nitrogen oxides would oxidize more rapidly. The ultimate effect on acid deposition is difficult to assess because of changes in clouds, winds, and precipitation.

  - Visibility may decrease because of the increase in hydrocarbon emissions and the rate at which sulfur dioxide is oxidized to sulfate.

  - The small increase in temperature will not significantly affect carbon monoxide emissions.

- Preliminary analyses of the effects of a scenario of a 4 C temperature increase in the San Francisco Bay area, with no change in emissions or other climate variables, on ozone concentrations suggest that maximum ozone concentrations could increase by approximately 20%, that the area in which the National Ambient Air Quality Standard (NAAQS) would be exceeded would almost double, and that the number of people-hours of exposure would triple. The Midwest and Southeast also could incur high concentrations and an increase in the area of high ozone by a factor of three.

- Increases in ambient ozone levels resulting from climate change could increase the number of nonattainment areas and make attainment more expensive in many regions. Preliminary estimates suggest that an expenditure of several million dollars per year may be necessary for volatile organic compound (VOC) controls above those needed to meet standards without climate change. The total costs for additional air pollution controls that may be needed because of global warming cannot be estimated at this time.

- Because of the close relationship between air pollution policies and global climate change, it is appropriate for EPA to review the impact of global climate change on air policies and the impact of air pollution regulations on global climate change.

RELATIONSHIP BETWEEN CLIMATE AND AIR QUALITY

The summer of 1988 provided direct evidence of the importance of weather to pollution episodes in the United States. Despite significant progress in reducing emissions of many pollutants over the last decade, the extended stagnation periods and high temperatures caused ozone levels in 76 cities across the country to exceed the national standard by at least 25%. Whether this recent summer is an appropriate analog for the future cannot be determined with certainty, but scientists have recognized for some time that air pollution does vary with seasons and is directly affected by ventilation, circulation, and precipitation, all of which could be affected by future global climate changes.

Ventilation

Two major factors, referred to as "ventilation" when considered together, control the dilution of pollutants by the atmosphere: windspeed and the depth of the atmospheric mixing layer (frequently called the mixing depth). If windspeed is high, more air is available to dilute pollutants, thus lowering pollutant concentrations. The mixing layer (the distance between the ground and the first upper-layer inversion) tends to trap pollutants because the inversion above it acts as a barrier to vertical pollutant movement. Thus, pollutant concentrations decrease as mixing depth increases, providing greater dilution.

The ventilation characteristics of an area change, depending on whether a high- or low-pressure system is present. Low-pressure systems usually produce good ventilation because they normally have greater mixing depths and windspeeds, and precipitation is often associated with them. High-pressure systems, on the other hand, generally produce poor ventilation conditions because they frequently have smaller mixing depths on their western sides and lower windspeeds. They also tend to move more slowly than lows, so more emissions can enter their circulation patterns. In addition, they are frequently free of clouds, resulting in maximum sunlight and therefore more photochemical ozone production during the day. Also, during the evenings, the clear skies allow surface-based (see below) inversion layers to form, concentrating pollutants in a small volume of air and often creating very high air pollution levels.

Climatologically, certain places in the country, such as the Great Plains and the Northeast (Figure 11-1A), are frequently windy, and others, such as the Southwest (Figure 11-1B), frequently have large mixing depths. These areas will have cleaner-than-average air if they do not contain too many pollutant sources. Areas, such as California, that are frequently affected by high-pressure systems -causing lower windspeeds and smaller mixing depths -- will have more major air pollution episodes.

Circulation

Two semipermanent high-pressure systems are important to the global circulation pattern and greatly influence U.S. air pollution climatology. the large Pacific high, which is often situated between the Hawaiian Islands and the west coast of North America, and the Bermuda high, located over the western Atlantic Ocean.

The Pacific high often results in extended periods of air stagnation over the western United States from Oregon and California to over the Rockies, and is responsible for many severe ozone episodes in southern California. Air stagnation associated with the westward extension of the Bermuda high occurs most often during the summer months and affects the eastern United States from southern Appalachia northward to New England. Within the Bermuda high, pollutants are slowly transported from the industrial areas of the Ohio River Valley into the populated areas of the Northeast. The Bermuda high is also responsible for the general southwest-to-northeast airflow in the summer, carrying pollutants along the metropolitan corridor from Richmond to Boston and exacerbating the ozone problem in the Northeast.

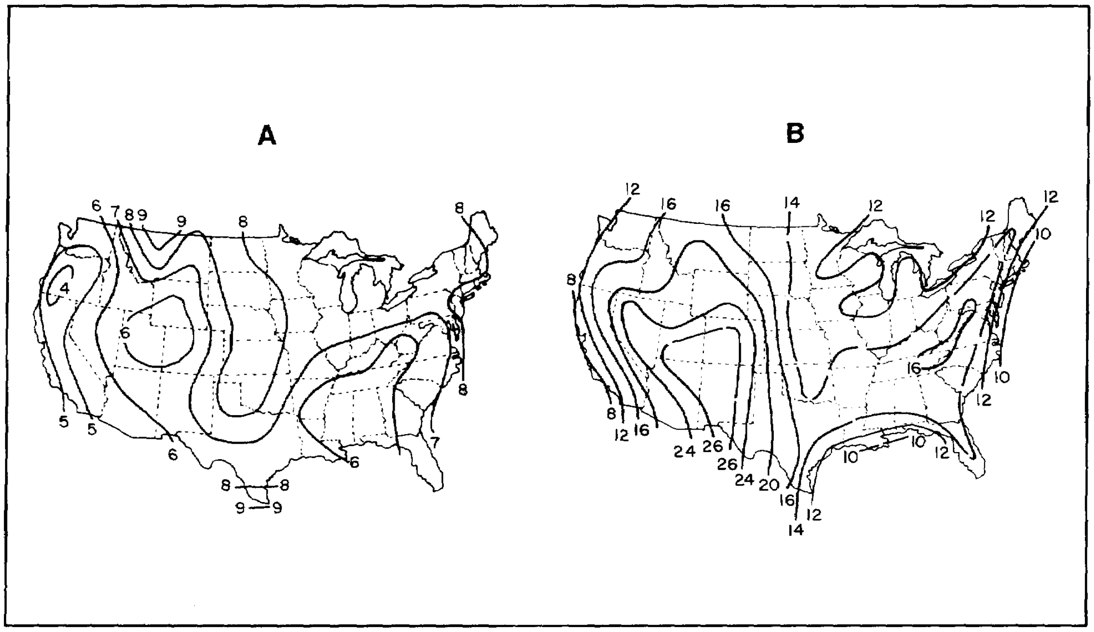

Figure 11-1. (A) Mean annual windspeed averaged through the afternoon mixing layer (speeds are in meters per second); (B) mean annual afternoon mixing height, in hundreds of meters (adapted from Holzworth, 1972).

Precipitation

Atmospheric pollutants in both particulate and gaseous forms are incorporated into clouds and precipitation. These pollutants can then be transported to the ground through rainfall (wet deposition). Cloud-formation processes and the consequent type of precipitation, together with the intensity and duration of precipitation, are important in determining wet deposition of pollutants.

PATTERNS AND TRENDS IN AIR QUALITY

To protect the public health and welfare, the U.S. EPA has promulgated National Ambient Air Quality Standards (NAAQS). In 1986, more people lived in counties with measured air quality levels that violated the primary NAAQS for ozone (O_3) than for other pollutants (Figure 11-2).

Although millions of people continue to breathe air that is in violation of the primary NAAQS, considerable progress is being made in reducing air pollution levels. Nationally, long-term 10-year (1977-86) improvements have been seen for a number of pollutants, including total suspended particulates (TSP), O_3, carbon monoxide (CO), nitrogen dioxide (NO_2) lead, and sulfur dioxide (SO_2). This section does not attempt to predict future trends in emission levels.

Total Suspended Particulates

Annual average TSP levels decreased by 23% between 1977 and 1986, and particulate emissions decreased by 25% for the same period. The more recent TSP data (1982-86) show that concentrations are leveling off, with a 3% decrease in ambient TSP levels and a 4% decrease in estimated emissions during that time.

In the future, air quality may decrease as the benefits of current pollution control measures are affected by increases in population and economic growth.

Sulfur Dioxide

Annual average SO_2 levels decreased 37% from 1977 to 1986. Aneven greater improvement was observed in the estimated number of violations of the 24-hour standard for SO_2 concentration, which decreased by 98%. These decreases correspond to a 21% drop in sulfur dioxide emissions during this 10-year period. However, most of the violations and the improvements occurred at source-oriented sites, particularly a few smelter sites. Additional reductions may be more difficult to obtain. The higher concentrations were found in the heavily populated Midwest and Northeast.

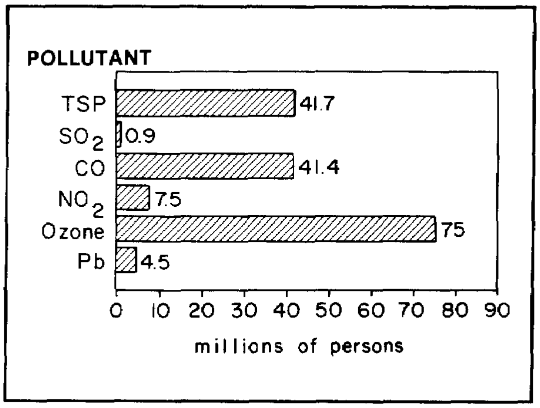

Figure 11-2. Number of persons living in counties with air quality levels above the primary National Ambient Air Quality Standards in 1986 (based on 1980 population data) (U.S. EPA, 1988).

Ozone

A national standard for ambient levels of ozone was established with the original Clean Air Act in 1972, along with standards for five other pollutants. While headway has been made in meeting all these national air quality standards, progress in meeting the ozone standard has been particularly slow and frustrating for concerned lawmakers and environmental officials at all levels of government. At the end of 1987, the date anticipated in the act for final attainment of the ozone standard, more than 60 areas had not met the standard. In recent years, the number of nonattainment areas has fluctuated with meteorology, often overwhelming the progress being made through reduced emissions. Thus "bad" weather (summertime conditions favorable to ozone formation) in 1983 led to an increased number of nonattainment areas, and "good" conditions in 1986 led to a decreased number of areas.

Nationally, between 1979 and 1986, O_3 levels decreased by 13%. Emissions of volatile organic compounds (VOCs), which are ozone precursors, decreased by 20% from 1979 to 1986. The estimated number of violations of the ozone standard decreased by 38% between 1979 and 1986. The highest concentrations were in southern California, but high levels also persisted in the Texas gulf coast, the northeast corridor, and other heavily populated regions.

Acid Deposition

Widespread concern exists concerning the effects of acid deposition on the environment. With the present monitoring network density in eastern North America, it is now possible to quantify regional patterns of concentration and deposition of sulfate, nitrate, and hydrogen ions, primary constituents of acid deposition. In Figures 11-3 through 11-5, isopleth maps show the geographic pattern of acid deposition, as reflected by the concentration and deposition of these three species (Seilkop and Finkelstein, 1987).

For the relatively short period from 1980 and 1984, evidence indicates the total deposition and average concentration of sulfate, nitrate, and hydrogen ions in precipitation falling over eastern North America decreased by 15 to 20%. The observed decreases correspond with reported reductions in the U.S. emissions of sulfur oxides (SO_X) and nitrogen oxides (NO_x), and sulfate and nitrate precursors. However, the emission figures are subject to estimation error and should be used cautiously (Seilkop and Finkelstein, 1987).

STUDIES OF CLIMATE CHANGE AND AIR QUALITY

Some of the climate factors that could affect air quality are listed in Table 11-1. To explain these relationships, two projects were undertaken for this report to identify the potential impacts of climate change on air quality:

- Climate Change and Its Interactions with Air Chemistry Perspectives and Research Needs - Penner, Connell, Wuebbles, and Covey - Lawrence Livermore National Laboratory (Volume F)

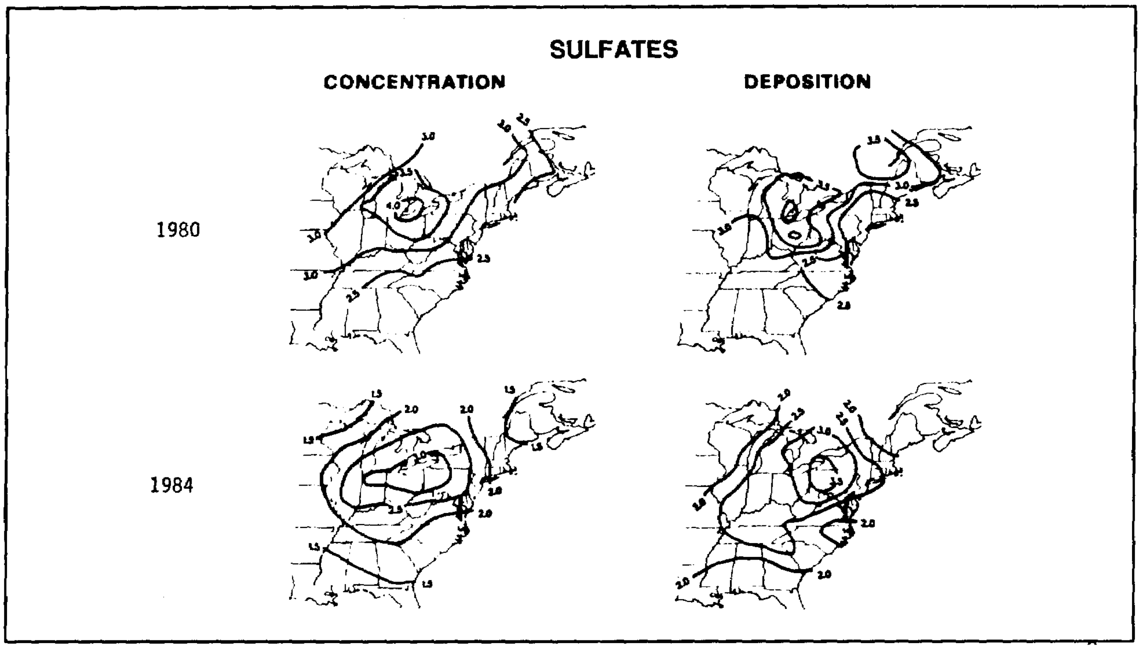

Figure 11-3. Isopleth maps of average annual concentrations (mg/liter) and total annual deposition (g/m) of sulfates in 1980-84 (Seilkop and Finkelstein, 1987).

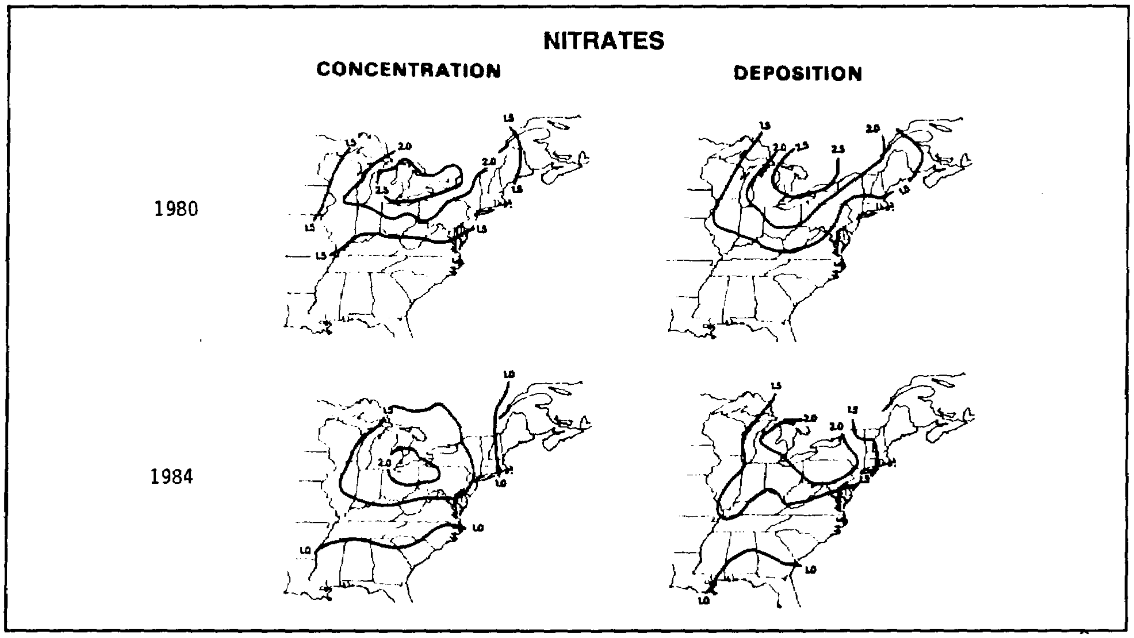

Figure 11-4. Isopleth maps of average annual concentration (mg/liter) and total annual deposition (g/m1) of nitrates in 1980-84 (Seilkop and Finkelstein, 1987).

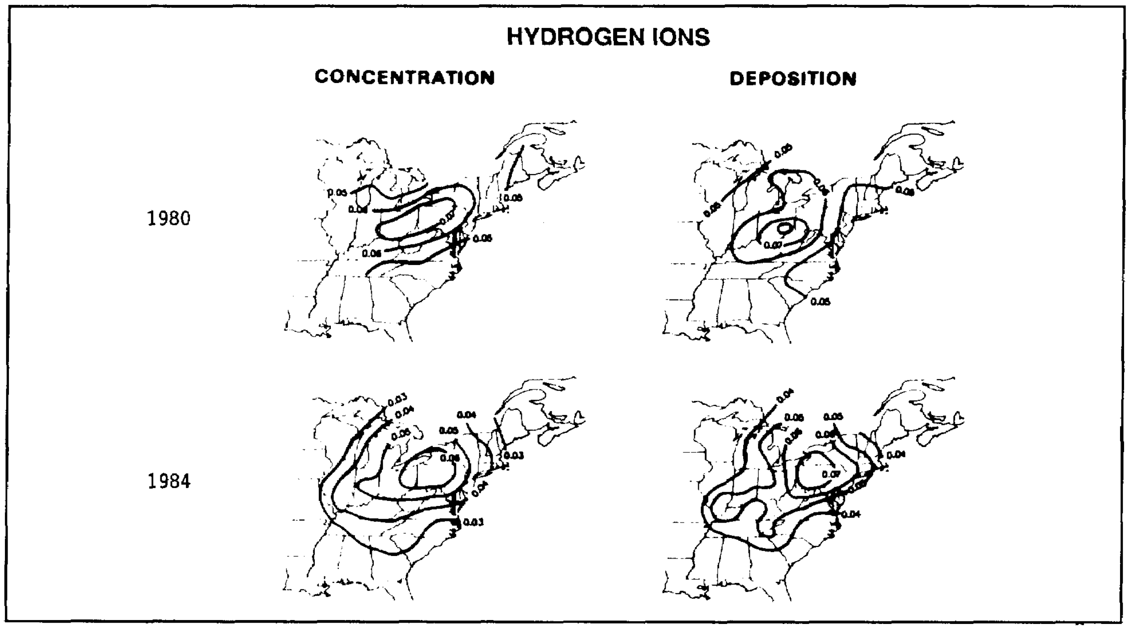

Figure 11-5. Isopleth maps of average annual concentration (mg/liter) and total annual deposition (g/m) of hydrogen ions in 1980-84 (Seilkop and Finkelstein, 1987).

Table 11-1. Climate Change Factors Important for Regional Air Quality

Changes in the following affect air quality:

1. the average maximum or minimum temperature and/or changes in their spatial distribution leading to a change in reaction rates and the solubility in gases in cloud water;
2. stratospheric O_3 leading to a change in reaction rates;
3. the frequency and pattern of cloud cover leading to a change in reaction rates and rates of conversion of SO_2 to acid deposition;
4. the frequency and intensity of stagnation episodes or a change in the mixing layer leading to a more or less mixing of polluted air with background air;
5. background boundary layer concentrations of water vapor hydrocarbons, NO_x, and O_3, leading to more or less dilution of polluted air in the boundary layer and altering the chemical transformation rates;
6. the vegetative and soil emissions of hydrocarbons and NO_x that are sensitive to temperature and light levels, leading to changes in their concentrations;
7. deposition rates of vegetative surfaces whose absorption of pollutants is a function of moisture, temperature, light intensity, and other factors, leading to changes in concentrations;
8. energy usage, leading to a change in energy-related emissions;
9. aerosol formation, leading to changes in reaction rates and the planetary albedo (reflectivity); and
10. circulation and precipitation patterns leading to a change in the abundance of pollutants deposited locally versus those exported off continent.

Source: Adapted from Penner et al. (Volume F).

- Examination of the Sensitivity of a Recional Oxidant Model to Climate Variations -Morris, Gery, Liu, Moore, Daly, and Greenfield - Systems Applications, Inc. (Volume F)

The literature does not contain studies on the effects of climate change on air quality. Thus, these studies should be considered as preliminary analyses of the sensitivity of air quality to climate change.

Climate Change and Its Interactions with Air Chemistry

Penner et al. conducted a literature review of studies on the relationship of climate and air quality. They also organized a workshop on the issue.

Effect of Climate Chance on Ozone Formation

Changes in ventilation, circulation, precipitation, and other aspects of climate affect the concentrations of the ozone precursors (VOCs and NO_x). Climate changes can also increase or decrease the rates at which these precursors react to form ozone. The effects of change in global temperature and in stratospheric ozone concentration on tropospheric ozone precursor concentrations, reaction rates, and tropospheric ozone concentrations are discussed below.

Temperature Change

Studies of the Effects of Temperature on Ozone. Smog chamber and modeling studies have shown that ozone levels increase as temperature increases. Kamens et al. (1982) have shown in an outdoor smog chamber study that the maximum ozone concentration increases as the daily maximum temperature increases (holding light intensity constant). Their data show that there is no critical "cut-off' temperature that eliminates photochemical ozone production. Instead, a general gradient is observed as a function of temperature.

Samson (1988) has recently studied ambient data for Muskegon, Michigan, and found that the number of ozone excursions above the standard (0.12 ppm) is almost linearly related to mean maximum temperature. In 1988, the mean maximum temperature was 77 F and there were 12 ozone excursions. In 1984, with a mean temperature of 73.50 F, there was only one excursion.

Temperature-dependent modeling studies were conducted by Gery et al. (1987). For this modeling effort, Gery et al. used the OZIPM-3 trajectory model, which is city specific. The scenarios for the different cities used actual observed mixing heights, solar radiation and zenith angle, and pollutant concentrations characteristic for the particular city considered for June 24, 1980. This base case was chosen because it was a high-pollution day, and ambient data were available. The increased temperature scenarios applied the increase throughout the day and were added to the base case scenario. The light intensity increase was achieved by increasing the photolyses rates for nitrogen dioxide, formaldehyde, acetaldehyde, hydrogen peroxide, and ozone. Results for New York in June 1980 are shown in Table 11-2. In general, ozone concentration increased with increasing temperature. The concentration of hydrogen peroxide (H_2O_2), a strong oxidant that converts SO_2 to sulfuric acid, was also observed to increase with higher temperatures. This is compatible with the increase in ozone because the entire photochemical reaction process is accelerated when temperature rises. As a result, cities currently violating the ozone NAAQS will be in violation to a greater degree in the future, and cities that are complying with the NAAQS now could be forced out of compliance just by a temperature increase. Figure 11-6 shows the predicted increase in low-level ozone for two temperature increases in Los Angeles, New York, Philadelphia, and Washington.

Modeling studies by Penner et al. have shown that the effect temperature has on ozone formation also depends on the ratio of volatile organic compounds to nitrogen oxides, both of which are ozone precursors. Figure 11-7 shows that ozone levels will generally go up, except in areas where the ratio of VOCs to NO_x is low.

Temperature change has a direct effect on ozone concentrations because it increases the rates of ozone-forming reactions. However, a temperature rise can also affect ozone formation by altering four other aspects of climate or the atmosphere: cloud cover, frequency and intensity of stagnation periods, mixing layer thickness, and reactant concentrations.

Table 11-2. Maximum Hourly Concentrations and Percentage Changes for Ozone, H202, and PAN for the Future Sensitivity Tests Using an EKMA Model for the Simulation of June 24, 1980, New York

Ozone						
	Concentration (ppm)			Percent change (from base)		
Change in Temp (°C)	0	+2	+5	0	+2	+5
Stratospheric Ozone[a]						
Base	0.125	0.130	0.138	--	4	10
-16.6%	0.150	0.157	0.167	20	26	34
-33.3%	0.165	0.170	0.178	32	36	42

Hydrogen Peroxide (H2O2)						
Change in Temp (°C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	0.05	0.06	0.08	--	20	60
-16.6%	0.43	0.58	0.84	760.0	1060	1580
-33.3%	3.08	3.31	3.60	6060.0	6520	7100

Peroxyacetyl Nitrate (PAN)						
Change in Temp (°C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	0.05	0.06	0.08	--	20	60
-16.6%	0.43	0.58	0.84	760.0	1060	1580
-33.3%	3.08	3.31	3.60	6060.0	6520	7100

[a] Base refers to the present stratospheric ozone column. The -16.6 and -33.3% refer to a depletion of the base value. Ultraviolet light will increase with the depletion (Gery et al., 1987).

Effect of Changes in Cloud Cover. The reduction in light intensity caused by increased cloud cover can reduce ozone production. Penner et al. (Volume F) calculate that a reduction in light intensity of 50% throughout the day will reduce the ozone formation. However, the magnitude of ozone reduction depends on the time of day when the cloud cover occurs. If clouds occur in the afternoon or evening, little effect is observed in the ozone production, but if clouds occur during the morning hours, photochemical reactions are slowed, and less ozone is produced. Jeffries et al. (1989) suggest that cloud cover can decrease ultraviolet radiation by 7 to 14% in their outdoor smog chamber located in North Carolina. Although a global temperature change would affect cloud cover, the type and direction of the change are unknown.

The Penner et al. study assumes that cloud cover causes an equal decrease in all wavelengths of solar radiation. However, clouds are not expected to cause an equal decrease at all wavelengths. Solar radiation is needed to form ozone. Since Penner et al.

may have underestimated the intensity of some wavelengths of light, they may have overestimated the decrease in ozone production.

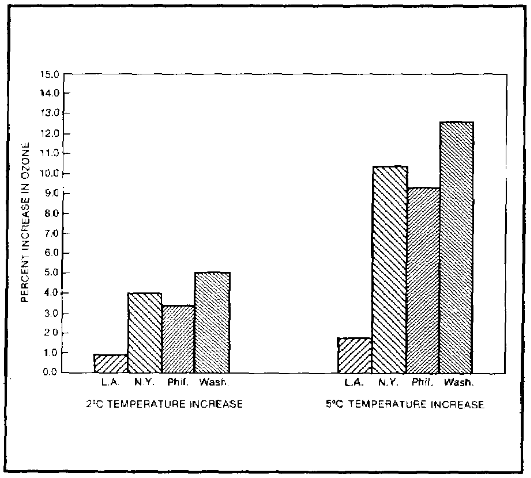

Figure 11-6. Percent increase in predicted O_3 over future base case (0.12 ppm) for two temperature increases in four cities (Gery, 1987).

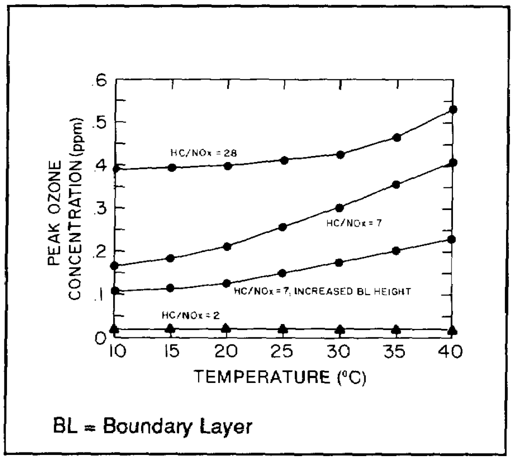

Figure 11-7. The effect of temperature on the peak O_3 concentrations predicted in a box model calculation of urban O_3 formation. Calculations are shown for three hydrocarbon to NO_x ratios. The effect of increasing the boundary layer depth for the case with a hydrocarbon to NO_x ratio of 7 is also shown (Penner et al., Volume F).

Effect of Water Vapor. Water vapor is involved in the formation of free radicals (reactive compounds) and hydrogen peroxide, which are necessary for the formation of ozone. Global increases in temperature are expected to raise tropospheric water vapor levels.

If sources of water vapor are not perturbed by vegetative changes, and if global circulation patterns do not significantly affect precipitation events (an unlikely assumption), then global water vapor levels are expected to increase with increasing temperature. A temperature increase of 2 C could raise the water vapor concentration by 10 to 30% (Penner et al., Volume F). This change should affect both oxidant formation and sulfur dioxide oxidation (acid deposition).

Smog chamber studies have shown that at high pollutant levels, increases in water vapor can significantly accelerate both the reaction rates of VOCs and the rate of oxidant formation (Altshuller and Bufalini, 1971). Walcek (1988) has shown with the use of a regional acid deposition model (RADM) that the ozone, hydrogen peroxide, and sulfate production rates in the boundary layer of the troposphere all increase with increasing water vapor.

Effect of Changes in Frequency and Intensity of Stagnation Periods. As noted previously, highpressure systems significantly enhance ozone formation potential. During a high-pressure episode, pollutants are exposed to high temperatures and prolonged irradiation (Research Triangle Institute, 1975), resulting in high levels of ozone. If the intensity and frequency of high pressure episodes increase with global warming, then ozone levels can be expected to be even higher.

Effect of Changes in Mixing Layer Thickness. As shown in Figure 11-7, increases in the mixing layer height decrease ozone formation, presumably because there are less ozone precursors per volume of atmosphere. An increase of global temperature would probably lead to an increase in average mixing depths as a result of greater convection, which raises the mixing depth and increases mixing.

Effect of Changes in Reactant Concentrations. The concentrations of ozone precursor pollutants (VOCs, NO_x) play a large part in determining the amount of ozone produced. With increasing temperature, natural hydrocarbon emissions are expected to increase. Also, unless preventive measures are taken, manmade emissions would increase (vapor pressure of VOCs increases with increasing temperature). If these ozone precursors increased in concentration, ozone production would increase.

Lamb et al. (1985) have shown that natural hydrocarbon (VOC) emissions from deciduous forests would increase by about a factor of three with a temperature change from 20° to 30°C. However, as discussed in Chapter 5: Forests, the abundance of some deciduous forests could decline because of global warming. However, grasslands or shrubs that replace forests would still emit hydrocarbons. The net effect is probably uncertain. Emissions of NO from powerplants would grow because of a greater demand for electricity during the summer months. Soil microbial activity is also expected to increase with increasing temperature. This will increase natural emissions of NO_x. Evaporative emissions of VOCs from vehicles and refueling would also be expected to rise with warmer temperatures. However, exact predictions of the effects of all these factors on ozone formation are difficult to make because the relationship between precursor emissions and ozone is extremely complex and not fully understood, and because increases in emissions are difficult to quantify.

An example of this complex relationship between ozone and its precursors is shown in Figure 11-8 (Dodge, 1977). At high VOC levels and low NO_x, adding or reducing VOCs has very little effect on ozone formation. Likewise, when NO_x concentrations are high and VOC concentrations are low, increasing NO_x reduces ozone formation while lowering NO_x increases ozone formation. Thus, VOCs and NO_x must be examined together when considering any ozone reduction strategy based on controlling ozone-forming precursors.

Stratospheric Ozone Change

Changes in stratospheric ozone concentration can also affect tropospheric ozone formation because stratospheric ozone regulates the amount of ultraviolet (UV) radiation available for producing ozone in the troposphere. Stratospheric ozone absorbs UV light from the sun and decreases the UV energy striking the Earth's surface. When stratospheric ozone is depleted by the chlorofluorocarbons (CFCs) generated by human activity, more UV radiation reaches the Earth's surface, which increases the photolysis rates[1] of compounds that absorb solar radiation (NO_2, formaldehyde, acetaldehyde, O_3, and H_2O_2)Faster photolysis produces more free radicals (high-energy species) that increase the amount of smog. Thus, less stratospheric ozone will lead to enhanced ozone formation in the troposphere.

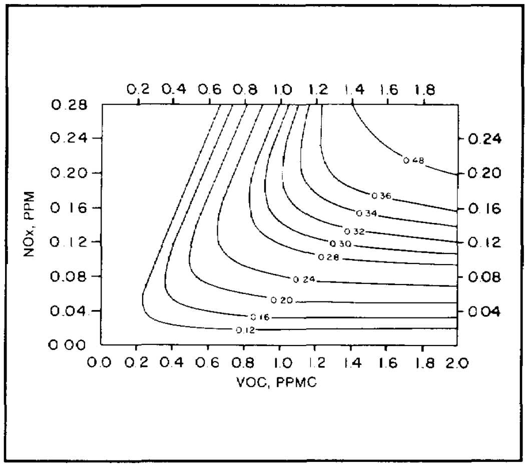

Figure 11-8. Ozone isopleths as a function of NO_x and volatile organic compounds (VOCs) (Dodge, 1977).

Modeling results for New York from Gery et al. (1987) show that tropospheric ozone increased when stratospheric ozone decreased (see Table 11-2). They also show that H_2O_2 and peroxyacetyl nitrate (PAN) yields increase. H_2O_2 is a strong oxidant that converts SO_2 to sulfuric acid, and PAN is an air pollutant that damages plants and irritates eyes. The 16.6 and 33.3% decreases (Table 11-2) in stratospheric ozone far exceed the expected decrease resulting from the buildup of CFC concentrations. This is especially true since the Montreal Protocol agreement will limit CFC production. These high values of stratospheric ozone depletion are used only for illustrative purposes.

Changes in Tropospheric Hydroxyl Radicals

Hydroxyl radicals (reactive compounds) are the most important free radicals found in the atmosphere. These reactive compounds are responsible for removing many atmospheric pollutants (such as CH_4, VOCs, methyl chloroform, CO) from the atmosphere (Penner et al., Volume F). Without these free radicals, pollutants would not be removed from the atmosphere and would build up to higher levels (global heating would be greater). Hydroxyl radicals in the free troposphere are produced primarily by the decomposition of ozone by

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[1] Photolysis is the breakdown of chemicals as a result of the absorption of solar radiation.

sunlight and the subsequent reaction of high-energy oxygen with water. In the urban atmosphere, hydroxyl radicals are produced through a complex series of reactions involving VOCs, nitrogen oxides, and sunlight. The solar photolysis of hydrogen peroxide also gives rise to hydroxyl radicals. This occurs in both urban and rural areas.

The effect of global climate changes on hydroxyl radical abundance is unclear. In urban areas with increases in VOCs and NO_x, a temperature increase will increase hydroxyl radical concentration. Also, if natural hydrocarbons and NO_x increase in rural areas, hydroxyl radicals are expected to increase. However, if methane, CO, and natural hydrocarbons increase without an additional increase in NO_x, then hydroxyl radicals will be depleted. A definitive prediction on the effect of increasing temperature on global concentrations of hydroxyl radicals cannot be made at this time.

Effect of Climate Change on Acid Deposition

Rainwater and surface waters are more acidic than natural background levels because of industrial and mobile emissions of SO_2 and NO_x , which form sulfuric and nitric acids in the atmosphere. In the air, sulfuric acid (H_2SO_4) is produced primarily by the reaction of SO_2 with hydroxyl radicals (high energy species); in clouds, the oxidation of SO_2 to H_2SO_4 is more complex, involving reactions with hydrogen peroxide and other dissolved oxidants. Nitric acid (HNO_3) is produced in air by the reaction of hydroxyl radicals with NO_x.

Organic acids, such as formic and acetic acids, are also formed in the atmosphere. However, their relative importance to the acid deposition ,.problem is unknown at present. Because they are weak acids (compared to H_2SO_4 and HNO_3), their contribution to the problem is expected to be much less than that of the inorganic acids (Galloway et al., 1982; Keene et al., 1983, 1984; Norton, 1985).

The acids produced in the atmosphere can be "dry deposited" to the Earth's surface as gases or aerosols, or they can be "wet deposited" as acid rain. Changes in total acid levels depend on changes both in atmospheric chemistry and changes in precipitation. Wet deposition is affected most by the amount, duration, and location of precipitation. Since the direction of regional precipitation changes is unknown, it is not known whether acid rain will increase or decrease in the future. However, many of the same factors that affect ozone formation will also affect the total deposition of acids.

Temperature Change

Higher temperatures accelerate the oxidation rates of SO_2 and NO_x to sulfuric and nitric acids. Gery et al. 1987) have shown that a temperature rise would also speed the formation of H_2O_2, increasing the conversion of SO_2 to sulfuric acid (see Table 11-2). Hales (1988) studied the sensitivity to a 10°C temperature rise using the storm-cloud model PLUVIUS-2. Considering only the chemistry occurring with a 10°C temperature rise, sulfate production increased 2.5 times. No modeling was performed at more modest temperature increases (e.g., ~4°C); however, it is likely that oxidation would also increase with a smaller increase in temperature. The limiting factor in the oxidation of SO_2 appears to be the availability of H_2O_2. The model also suggested that a temperature increase would cause more sulfuric acid to form near the sources where SO_2 is emitted.

Effect of Global Circulation Pattern Changes. Potential changes in global circulation patterns would greatly affect local acid deposition, because they would alter ventilation and precipitation patterns. Galloway et al. (1984) have calculated that over 30% of the sulfur emissions from the eastern United States are transported to the north and farther east. Changes in circulation patterns would affect this transport, although the direction or magnitude of the effect is unknown.

Effects of Changes in Emissions. If electricity demand rises with rising temperatures (see Chapter 10: Electricity Demand), if more fossil fuels are burned, and if technology is not improved, SO_2 and NO_x emissions will increase. An approximate 10% growth in use of electricity in the summer could increase SO_2 emissions during the summer by approximately 30% if present-day technology is used in the future. This, in turn, would increase acid deposition.

Effects of Reduced Stratospheric Ozone. A decrease in stratospheric ozone due to CFCs may increase acid deposition because more UV radiation would be available to drive the chemical reactions. As discussed above, a modeling study by Gery et al. (1987) showed an increase in the yield of H_2O_2 when stratospheric ozone was reduced by 16 and 33%. Because H20z is a strong oxidant, SO_2 would probably also be oxidized more quickly into sulfate aerosols and acid rain, but this depends on the availability of water vapor (e.g., clouds, rain). Implementation of the Montreal Protocol should help reduce CFC emissions.

Reduced Visibility. The growth in natural organic emissions and increases in sulfates resulting from warmer temperatures should reduce visibility, assuming that the frequency of rain events, wind velocity, and dry deposition rates remain the same. If rain events increase, washout/rainout should increase and visibility would be better than predicted (see Chapter 3: Climate Variability).

MODELING STUDY OF CLIMATE AND AIR QUALITY

Study Design

Morris et al. (Volume F) applied a regional transport model RTM-111 to an area covering central California and a region covering the midwestern and the southeastern United States. The model was run for the present-day conditions and for a future climate. For California, Morris et al. used input data from August 5-10, 1981; for the Midwest and the Southeast, they used input data from July 14-21, 1981. These were periods with high ozone levels and may be most sensitive to changes in climate. The scenario assumed that temperatures would be 4°C warmer than in the base case, but all other climate variables were held constant (relative humidity was held constant). The scenario assumed no change in emission levels, no change in boundary layer, and no change in wind velocity.

The RTM-111 is a three-dimensional model that represents point sources embedded in a grid framework. The model has three prognostic vertical layers and a diagnostic surface layer. This means that the surface layer is represented by actual observations. The other three layers are predicted by using the surface layer data. The photochemical reactions are based on the latest parameterized chemical mechanism.

Limitations

Perhaps the most important limitation is that emission levels were held constant. It is likely that future emission levels will be different, although this study did not estimate how. The results of this study are useful for indicating the sensitivity of ozone formation to temperature, but should not be considered as a prediction of future ozone levels. The model ignored future increases in emissions that would occur with increased temperatures. The estimates for ozone are only coarse approximations. Morris et al. used the National Acid Precipitation Assessment Program (NAPAP) emissions data of 1980. These data appear to underestimate actual ratios of VOCs to NO as measured in urban areas. Ching et al. (1986) state that for most cities, the NAPAP data underestimate VOC emission values by a factor of three or more. The model simplified some reactions of the hydrocarbons (VOCs) because the chemistry is not well known.

This study did not estimate climate-induced alterations in most meteorological variables, except temperature and water vapor, which is an oversimplification. For example, this study assumed that the mixing heights remain unchanged for the temperature increase scenario; in reality, mixing heights could increase with rising temperature. Holding the mixing heights constant probably overemphasized the importance of temperature in oxidant production, because an increased mixing layer depth might have had a dilution effect. Also, as stated earlier, cloud cover will affect ozone production. If cloud cover increases, then ozone is expected to decrease. Frequency and intensity of stagnation periods can also have profound effects on ozone formation. This modeling exercise did not consider these factors.

Results

Central California Study

Table 11-3 summarizes the results from the base case scenario and a climate sensitivity scenario that used a 4°C temperature increase and an attendant increase in water vapor concentration. All of the days studied show a larger area exposed to high levels of ozone. An increase in temperature may lengthen the duration of high ozone levels, although the maximum levels may be the same. Figure 11-9 illustrates the

August 6 base case and climate sensitivity case. The temperature change increased the August 6 maximum ozone concentration from 15 parts per hundred million (pphm) to 18 pphm, a 20% increase in ozone. The area in which the NAAQS was exceeded almost doubled from 3,700 to 6,600 square kilometers.

The temperature increases in the two main cities in the San Joaquin Valley (Fresno and Bakersfield) resulted in an approximate 0.5-pplun increase (approximately 8%) in maximum daily ozone concentration. In regions farther away from the emissions, such as the Sierra Nevada Mountains, little change in ozone levels was observed with the increased temperature.

Midwest and Southeast Study

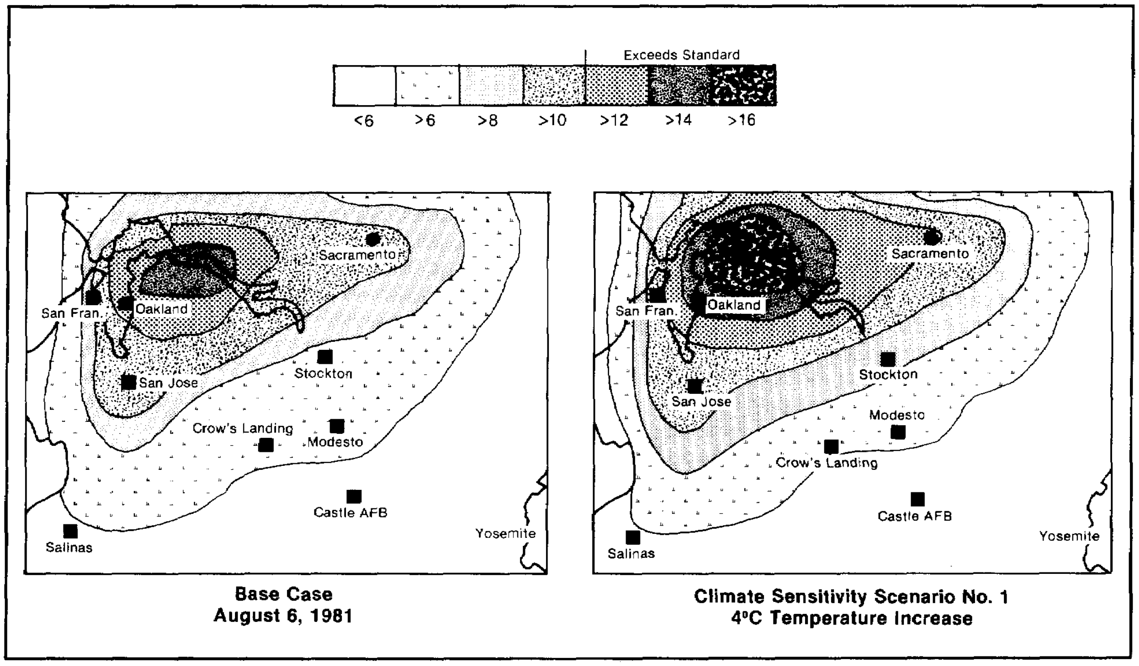
The results from applying RTM-III to the midwestern and southeastern areas are shown in Table 11-4. On one particular day (July 16), raising the temperature caused maximum ozone to increase from 12.5 pphm to 13.0 pphm (Figure 11-10). Although this is only a slight increase (0.5 pphm), the predicted area of exceedance of the ozone NAAQS increased by almost a factor of three, from 9,800 to 27,000 square kilometers. The differences occurred mainly in the upper Midwest. In general, the results range from a reduction of 2.4% to an increase of 8.0% in ozone levels. Although a temperature increase will generally increase ozone formation, it is noted in Table 11-4 that on two days, July 14 and July 21, no ozone increases were observed. This occurs when there are insufficient precursors to sustain ozone formation. Under these conditions, ozone is produced more quickly with increasing temperature but the total amount produced need not be greater and could even be less in some cases.

Both modeling exercises indicate that temperature change alone could increase ozone levels over what they would be without climate change.

Table 11-3. Maximum Daily Ozone Concentrations Predicted by the RTM-111 for Each Day of the Central California Modeling Episodes for the Base Case and the Case of Climate Sensitivity to Increased Temperature of 4 C

	Maximum daily ozone concentrations (ppbm)		
Date of Episode (1981)	Base case	4°C temperature increase	Percent increase
August 5	11.8	12.1	3
August 6	15.0	18.0	20
August 7	11.7	13.1	12
August 8	13.5	13.7	2
August 9	10.5	11.2	7
August 10	9.1	9.18	8

Source: Morris et al. (1988).



Base Case
August 6, 1981

Climate Sensitivity Scenario No. 1
4°C Temperature Increase

Figure 11-9. Comparison of estimated maximum daily ozone concentrations (pphm) for the base case and climate sensitivity scenario No. 1 (temperature and water increase) for August 6, 1981 (Morris et al., 1988).

Table 11-4. Maximum Daily Ozone Concentrations Predicted by the RTM-111 for Each Day of the Midwestern/Southeastern Episode for the Base Case and the Case of Increased Temperature of 4°C

	Maximum daily ozone concentrations (ppbm)		
Date of Episode (1981)	Base case	4°C temperature increase	Percent increase
July 14	11.3	11.3	0.0
July 15	11.5	11.9	3.5
July 16	12.5	13.0	4.0
July 17	11.7	12.0	2.6
July 18	11.2	12.1	8.0
July 19	13.8	14.8	7.2
July 20	11.1	11.2	0.9
July 21	12.6	12.3	-2.4

Source: Morris et al. (1988).

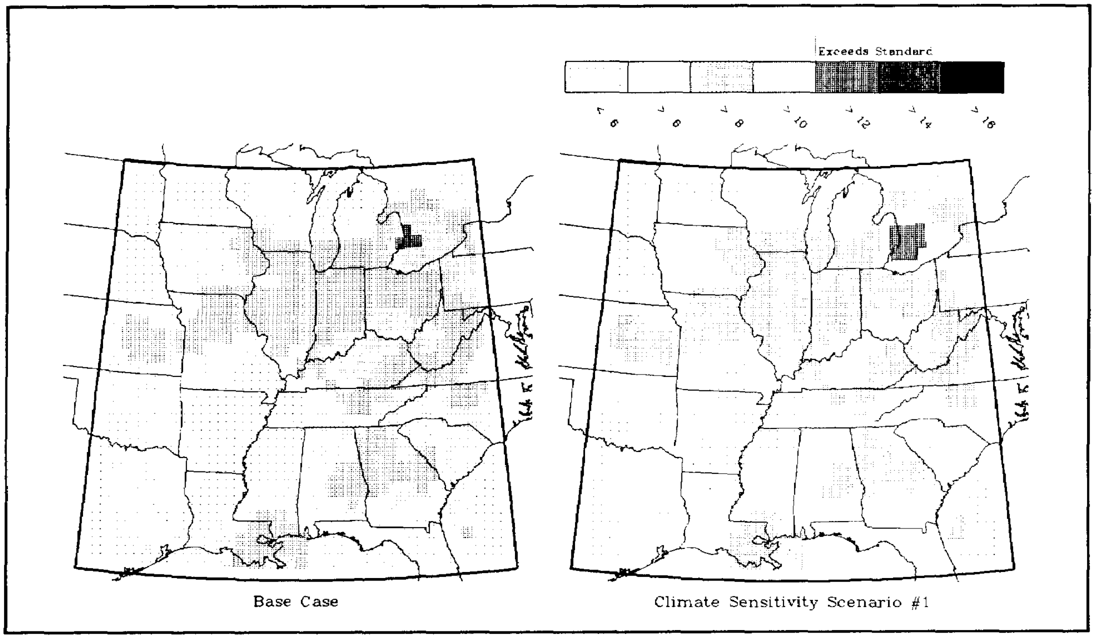


Figure 11-10. Comparison of predicted estimated maximum daily ozone concentrations (pplun) for the base case and climate sensitivity scenario No. 1 (temperature and water increase) for July 16, 1980 (Morris et al., 1988).

Population Exposure

As discussed above, both the California and Midwest/Southeast studies show a significant increase in the area that is potentially exposed to higher levels of ozone when the temperature is increased as compared with base case conditions. Data taken from the 1980 census from central California and the midwestern and southeastern areas were used to determine the number of people exposed to ozone for the base case and a 4°C temperature rise scenario. Table 11-5 presents the number of people-hours of exposure to ozone concentrations exceeding 8, 12, and 16 pphm. These estimates of human exposure were generated by multiplying the number of people in the grid cells by the total number of hours that the estimated hourly ozone concentration in those grid cells exceeded the 8-, 12-, or 16-pphm levels. Actual exposure levels may be less because indoor levels are generally lower than ambient air levels.

ECONOMIC, ECOLOGICAL, AND ENVIRONMENTAL IMPLICATIONS

Ozone

An increase in ozone levels due to climate change is important for several reasons:

- Ozone itself is a radiatively important gas and contributes to climate change. Ozone absorbs infrared energy much like carbon dioxide. It has been calculated that a 15% increase in tropospheric ozone could lead to a 0.1 C rise in global temperature (Ramanathan et al., 1987).
- Ozone levels in many areas are just below the current standard. If emissions are not reduced, any increase in ozone formation may push levels above the standard.

Table 11-5. Number of People-Hours of Exposure to Ozone Concentrations in Excess of 8, 12, and 16 pphm for the Base Case and the Case of Climate Sensitivity to Increased Temperature

Scenario	Exposure to $O_3 \geq$ 8 pphm	Exposure to $O_3 \geq$ 12 pphm	Exposure to $O_3 \geq$ 16 pphm
	Central California Modeling Episode		
Base case	70,509,216	660,876	0
Increased temperature	102,012,064	2,052,143	92,220
	Midwestern/Southeastern Modeling Episode		
Base case	1,722,590,208	29,805,348	0
Increased temperature	1,956,205,568	47,528,944	0

Source: Morris et al. (1988).

- Many inexpensive controls for ozone are already in place in nonattainment areas. Increases in ozone levels would require relatively expensive measures to sufficiently reduce ozone precursors to attain the standard.

- The standard itself is defined in terms of the highest levels of ozone experienced in an area, not average levels. (As a yearly average, no area of the country would exceed the standard of 0.12 ppm.) Thus, a factor such as temperature that may have a modest effect on average levels of ozone formation may have a much more significant effect on peak levels.

A rough estimate of each of these factors can illustrate the potential policy problems created by a rising temperature scenario. The data in Figure 11-9 suggest that 4 C degree rise in temperature may lead to an increase in peak ozone concentrations of around 10%. A 10% increase in peak ozone levels could affect a number of potential ozone violations. In the 1983-85 period for example, 68 areas showed measured exceedances of the ozone air quality standards (for technical and legal reasons, not all these areas were officially designated nonattainment areas). A 10% increase in ozone levels in that period doubled the number of nonattainment areas to 136. This would include 41 new metropolitan statistical areas (MSAs) added to the list and 27 non-MSAs. These new nonattainment areas would add most midsize and some small cities in the Midwest, South, and East to the list of nonattainment areas.

The policy implications of this should be put into context because the full effect of climate change may not be felt until well into the next century. Over the next several decades, various national measures to reduce ozone precursors, such as a reduction in the volatility of gasoline, may go into effect. These would provide a cushion to marginal areas and could offset a temperature effect. However, other factors suggest that rising temperatures could be a problem.

Ozone levels and ozone precursors are closely related to economic expansion and population growth. Consumer solvents (e.g., paints, sprays, and even deodorants) area major source of ozone precursors. These are very difficult to control and are likely to increase in the future in areas currently attaining the standards. Growth in other sources of ozone precursors would bring many areas relatively close to the limits of the ozone standard. Gradual increases in temperature would make remaining in compliance with the standard more difficult. Although any sudden change in the number of nonattainment areas as a result of a secular trend toward increased temperature is unlikely, a number of small to midsize cities eventually may be forced to develop new control programs.

The implications of warmer temperatures for existing nonattainment areas can also be estimated. In these areas, existing and planned control measures may not be adequate to reach the standard, if additional ozone forms. In the past, EPA has attempted to project the emission reductions and costs associated with the attempts of existing nonattainment areas to reach the ozone standard. Using the same modeling approach, the effects of a temperature increase were analyzed to estimate the additional tons and costs associated with a projected temperature rise. Extrapolations of existing inventories to the year 2000 suggest that higher temperatures could require an additional reduction of 700,000 tons of VOC from an inventory of about 6 million tons. Given that most current nonattainment areas already will have implemented the most inexpensive measures, these additional reductions may cost as much as $5,000 per ton per year. Their aggregate cost could be as much as $3.5 billion each year.

These conclusions should be viewed as preliminary. Nonetheless, they demonstrate that the potential economic consequences could be significant for an already expensive program to combat ozone.

Acid Rain

The global climate change is likely to affect acidic deposition in the near future for several reasons.

First, emissions from fossil fuel powerplants both influence acid rain and contribute to global warming. In the future, global warming may increase energy demand and associated emissions. Because the growth in demand for electricity in northern states (see Chapter 10: Electricity Demand) may be lower than in southern states, regional shifts in emissions may occur in the future.

Second, global climate change would influence atmospheric reaction rates and the deposition and form of acidic material. It is conceivable that regions of high deposition may shift or that more acid rain may be transported off the North American continent. Strategies that seek to control powerplants in regions near sensitive areas may or may not be as effective, as global climate change occurs.

Third, global climate change may alter the impacts of acid rain on ecological and other systems in as yet unpredictable ways. For example:

- Changes in the amount of rainfall may dilute the effect of acid rain on many sensitive lakes.
- Changes in clouds may alter the fertilization of high-elevation forests.
- Changes in humidity and frequency of rain may alter degradation rates for materials.
- Increased midcontinental dryness would alter the amount of calcium and magnesium in dust, neutralizing impacts on soils.
- Increased numbers of days without frost would decrease forest damage associated with frost and overfertilization by atmospheric nitrogen.
- Changes in snowpack and the seasonality of rainfall would change acid levels in streams and alter the timing and magnitude of spring shocks on aquatic species.

Finally, solutions to both problems are inextricably linked. Some solutions, such as SO_2 scrubbers and clean coal technologies, may abate acid rain levels, but they may do little to improve air quality or may increase global warming. Other solutions, including increased energy efficiency and switching fuels to natural gas or to renewable energy sources, may provide positive solutions to both problems.

In summary, an examination of the time horizons of importance to both acid rain and global climate change problems suggests that these two issues should not be viewed in isolation. Emissions, atmospheric reaction rates, pollutant transport, and environmental impacts will likely be altered by climate change. This suggests that a more holistic approach must be taken to air pollution problems and that proposed solutions should be evaluated on the basis of their contributions to solving both problems.

POLICY IMPLICATIONS

The Environmental Protection Agency issues air pollution regulations to improve air quality and to protect public health and welfare. In general, current regulations to reduce oxidant levels will also provide positive benefits toward a goal of limiting the rate of growth in global warming. Other programs aimed at reducing carbon monoxide levels, particularly from mobile sources, or CFCs to protect the stratospheric ozone layer, also positively affect greenhouse gases and the rate of global warming. However, the regulatory activities of the Agency have not been retrospectively reviewed to determine their impacts on global warming. In some cases, there may be important benefits; for example, current emission standards for automobiles do not encourage more efficient use of gasoline. A different form of standard, while potentially disruptive to air pollution efforts, might produce positive greenhouse gas benefits via reduced energy consumption. These issues will have to be analyzed in the future.

Because of the climate change issue, the following are some of the more important policy issues:

- Air pollution control agencies should as EPA should undertake a broad review to determine the impact of global climate change on air pollution policies. In particular, the cost of added controls resulting from climate change should be determined, perhaps as each significant regulation is proposed or reevaluated.
- The impact of EPA regulations, particularly the impact on energy use and greenhouse gases, should be a more important weight in future regulatory decisions. Since EPA regulations often serve as models for other countries, the cost penalty for better energy usage, while sometimes small in the United States, may be important on a global basis.
- Future reports to Congress and major assessments of ecological effects, e.g., the 1990 Acid Deposition Assessment document, should include sensitivity analyses of alternative climates. Risk management decisions of the Agency could then be made with improved knowledge of climate impacts.

RESEARCH NEEDS

Some of the key questions that need to be resolved regarding climate change and air quality include the following: How important will climate change be relative to other factors such as population growth to future air pollution problems? Is the impact of climate change likely to be significant enough to require totally different air pollution strategies? What mix of control strategies could be most cost effective in reducing acid rain, global warming, tropospheric ozone, and other pollution problems? The research elements needed to address these issues include basic research, sensitivity analyses, full-scale atmospheric modeling, and cost-effectiveness studies. Examples are presented below:

Basic Research - There is an important need to understand how manmade and natural emissions of hydrocarbons and other pollutants might change in the future when temperature, CO_2, and UV-B radiation increase and other climate parameters vary.

Sensitivity Analyses - Analyses of ozone concentrations are dependent on boundary layer height, clouds, water vapor, windspeed, UV-B radiation, and other parameters. Sensitivity tests using single models could improve our understanding of the relative importance of these variables and could provide important information for general circulation modelers.

Full-Scale Modeling - Complete understanding of the interactions of climate change and air quality will ultimately require that general circulation models and mesoscale chemistry models be linked in some direct or indirect manner. This will require the development of innovative approaches between the general circulation and air pollution modeling communities.

Cost-Effectiveness Studies - There are currently a number of congressional proposals to improve the Clean Air Act and to reduce global climate change. To assume that both air quality and global climate change goals are achieved, analyses of the cost-effectiveness of alternating strategies will be necessary.

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CHAPTER 12
HUMAN HEALTH

by Janice A. Longstreth

FINDINGS

Global warming may lead to increases in human illness (morbidity) and mortality during summer. Populations at particular risk are the elderly and very young (age 1 year and below), particularly those who are poor and/or homeless. These effects may be more pronounced in some regions than in others, with northern regions more vulnerable to the effects of higher temperature episodes than southern regions. Milder winters may offset increases in morbidity and mortality, although net mortality may increase. Mortality in southern cities currently shows a lesser effect from heat waves, presumably because populations have acclimatized. If northern populations show this same acclimatization, the impact of global warming on summer mortality rates may be substantially lower than estimated. The full scope of the impacts of climate change on human health remains uncertain and is a subject for future research.

- Although there may be an increase in weather related summer deaths due to respiratory, cardiovascular, and cerebrovascular diseases, there may be a decrease in weather-related winter deaths from the same diseases. In the United States, however, our studies suggest that an increase in weather-related deaths in summer would be greater than the decrease in weather-related deaths in winter. To draw firm conclusions, however, this area needs additional study.

- Sudden changes in temperature are correlated with increases in deaths. So if climate variability increases, morbidity and mortality may also increase. Conversely, a decrease in the frequency or intensity of climate extremes may be associated with a decrease in mortality and morbidity.

- Seasonal variation in perinatal mortality and preterm birth (higher in the summers, lower in the winters) have been observed in several areas in the United States. The longer and hotter summers that may accompany climate change could increase infant mortality rates, although changes in variability may be more important than average changes in temperature.

- Vector-borne diseases, such as those carried by ticks, fleas, and mosquitoes, could increase in certain regions and decrease in others. In addition, climate change may alter habitats. For example, some forests may become grasslands, thereby modifying the incidence of vector-borne diseases.

- While uncertainties remain about the magnitude of other effects, climate change could have the following impacts:

  – If some farmland is abandoned or some forests become grasslands, a result could be an increased amount of weeds growing on cultivated land, and a potential increase in the incidence of hay fever and asthma.

  – If humidity increases, the incidence and severity of skin infections and infestations such as ringworm, candidiasis, and scabies may also rise.

  – Increases in the persistence and level of air pollution episodes associated with climate change may have adverse health effects.

CLIMATE-SENSITIVE ASPECTS OF HUMAN HEALTH

Human illness and mortality are linked in many ways to the environment (Figure 12-1). Mortality rates, particularly for the aged and very ill, are

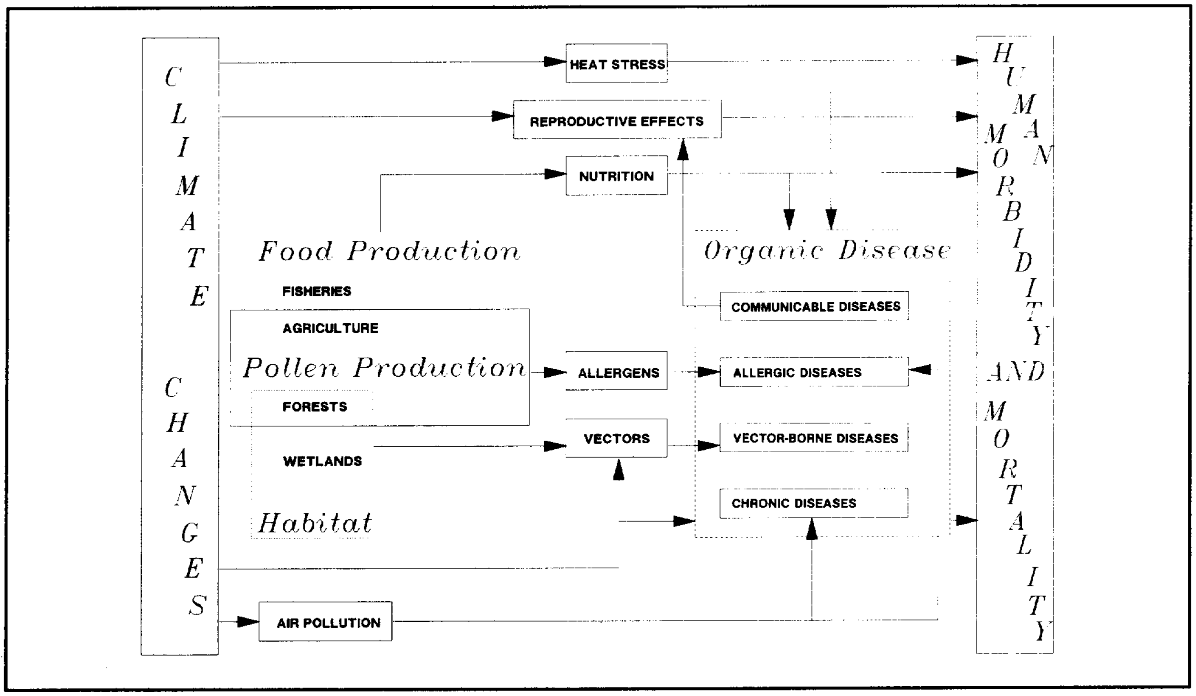

Figure 12-1. Schematic showing how climate change can affect human health.

influenced by the frequency and severity of extreme temperatures. The fife cycles of disease carrying insects, such as mosquitoes and ticks, are affected by changes in temperature and rainfall, as well as by modifications in habitat that result from climate change. Air pollution, frequently associated with climate change, is known to increase the incidence or severity of respiratory diseases such as emphysema and asthma. A variety of human illnesses show sensitivity to the changes in temperature (and/or humidity) that accompany changes in season. Stroke and heart attacks increase with very cold or very warm weather. Allergic diseases such as asthma and hay fever increase in spring and summer when pollens are released. Diseases spread by insects such as St. Louis encephalitis[1]increase in the warmth of summer when the mosquitoes that transmit it are active. In addition, adverse effects on reproduction, such as increased incidence of premature births, show a summertime peak in some cities. Table 121 lists the number of deaths and the number of physician visits (used to estimate the incidence of illness associated with a given effect) associated with major causes of mortality and illness in the United States.

General Mortality and Illness

The relationship between mortality and weather has been studied for over a century (Kutschenreuter, 1959; Kalkstein, Volume G), with the relationship between mortality and temperature receiving the most attention. Kutschenreuter (1959) observed "mortality is higher during cold winters and hot summers and lower during warm winters and cool

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[1] St. Louis encephalitis is an example of a vector-borne disease. Such diseases are spread to humans or animals by arthropods (e.g., mosquitoes or ticks). The disease-causing organism, such as a virus, is carried and transmitted by the vector, also known as the agent. Some vectors, such as ticks, live on other animals, such as deer and birds, which are called intermediate hosts. For example, Lyme disease is caused by a bacteria (the agent), which is carried by a certain type of tick (the vector), which lives on deer and mice (the intermediate hosts).

Table 12-1. Major Causes of Illness and Mortality in the United States (1984)[a]

Causes of illness and mortality	Estimated number of physician contacts	Estimated mortality	
		Number	Rate/100,000
Accidents and adverse effects	70,000,000	93,520	39.6
Cerebrovascular diseases[b]	9,100,000	154,680	65.5
Chronic liver disease and cirrhosis	1,400,000	26,690	11.3
Chronic obstructive pulmonary diseases and allied conditions	20,500,000	70,140	29.7
Congenital abnormalities	4,300,000	12,900	5.5
Diabetes mellitus	35,600,000	35,900	5.2
Heart diseases	72,400,000	763,260	323.2
Malignant neoplasms	20,300,000	453,660	192.1
Pneumonia and influenza	14,500,000	58,800	24.9
Suicides, homicides	---	47,470	20.1
Total for potentially weather-sensitive diseases	152,100,000	1,082,780	448.5
Total for all causes	248,100,000	1,717,020	717.1

[a] Causes are presented in alphabetical order and therefore are not ranked by severity.
[b] Conditions that can be influenced by changes in weather and climate are indicated in **bold type**.
Source: CDC (1986).

summers." The people most sensitive to temperature extremes are the elderly (White and Hertz-Picciotto, 1985). One explanation is the increased susceptibility of the elderly is that for individuals already stressed by the circulatory problems associated with vascular and heart disease, heat waves (temperatures above 100°F for 5 consecutive days) "overload" the thermoregulatory system, which is struggling to maintain the appropriate body temperature. This results in heat stress, heatstroke, and often mortality as well (White and Hertz-Picciotto, 1985).

In addition to the elderly, people working in hot environments, such as steel mills and construction sites, are at special risk from heat waves (Dukes-Dobos, 1981). These workers face even greater risk if they have underlying medical problems such as impaired circulation; higher than normal body temperature due to disease; chronic diseases such as alcoholism, diabetes, and obesity; or other problems.

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Although much of the earlier information characterized the relationship between weather and total mortality from all causes, a growing body of literature evaluates the relationship of weather to specific causes of death. For example, changes in weather have been associated with impacts on the cardiovascular, cerebrovascular, and respiratory systems. As previously shown in Table 12-1, diseases of these three systems cause the majority of deaths observed on a yearly basis in the United States, as well as significant illness. Incidences of these diseases rise as climate extremes increase.

The relationships of weather variables to diseases of these systems are diverse and complicated. Weather is not the main causative factor in these diseases but, rather, changes in weather have an impact because they add stress to systems that have already been compromised for some other reason(s). For example, although it has been observed that deaths in individuals with diseases of the cardiovascular system go up with heat waves, the precise reason for this relationship is not known.

To understand the relationship between weather and these diseases, one must examine the specific diseases that come under broad categories such as "cardiovascular disease." For instance, heart attack, coronary heart disease, and possibly coronary arteriosclerosis and rheumatic heart disease are apparently sensitive to changes in temperature (particularly cold and heat waves), whereas ischemic heart disease is not (Vuori, 1987).

That these different relationships exist is not unexpected given that different parts of the system are compromised (e.g., the arteries in arteriosclerosis and the heart muscle in rheumatic heart disease), and that different causes are also likely (e.g., an infection-related process in rheumatic heart disease and diet and heredity in arteriosclerosis). What this information does indicate, however, is that these relationships are very complex and that unraveling them to predict the effects of global warming will require considerable analysis (Lopez and Salvaggio, 1983).

The relationship between temperature changes and illness (morbidity) from diseases such as heart attack and stroke is not as well defined as the relationship reported for mortality. Mortality has national reporting procedures, whereas morbidity must be estimated from such data as hospital admission figures. A few studies have evaluated the relationship of weather to hospital admissions from cardiovascular or cerebrovascular disease. These have shown a relationship to weather changes, e.g., an increase in admissions for cardiovascular effects with heat waves, similar to that observed for mortality (Sotaniemi et al., 1970; Gill et al., 1988).

Morbidity from respiratory diseases is somewhat easier to estimate, principally because two such diseases, asthma and hay fever, affect as much as 3 and 6% of the U.S. population, respectively, causing significant losses of work time. The most common seasonal pattern for the allergic type of asthma and for hay fever is an increased springtime occurrence in response to grass pollens. A nonseasonal form of allergic asthma may also occur in response to allergens such as molds, which are affected by changes in precipitation and temperature.

Vector-Borne Diseases

Two tick-borne diseases currently posing a public health problem in the United States, Rocky Mountain spotted fever and Lyme disease, induce similar initial symptoms: high fever, chills, headache, backache, and profound fatigue. Rocky Mountain spotted fever can eventually result in hemorrhagic areas that ulcerate, and Lyme disease may cause permanent neurologic, cardiac, and rheumatologic abnormalities (APRA, 1985). The ticks that spread these diseases, and therefore the geographic distribution of the diseases themselves, are affected both directly and indirectly by climate variables. Such environmental factors as temperature, humidity, and vegetation directly affect tick populations and the hosts of the tick populations, e.g., deer, mice, and birds.

Mosquito-borne diseases, such as malaria and certain types of encephalitis (inflammation of the brain), are not a major health problem in the United States today because occurrences are relatively rare. However, mosquitoes are also weather-sensitive insects favoring a warm, humid climate. The spread of mosquito populations and the diseases they carry depends in part upon such climate factors as temperature and humidity, and upon vegetation, which is also influenced by the climate.

Human Reproduction

Preterm delivery and perinatal mortality (i.e., death just before, during, or just after birth) are two adverse reproductive outcomes that are associated with particular seasons and, thus, might be affected by climate change. Statistically significant increases in preterm births and in perinatal mortality in the summer months have been documented (Keller and Nugent, 1983; Copperstock and Wolfe, 1986) (see Figure 12-2). The data on total perinatal deaths correspond closely with those on perinatal deaths associated with infection in the mother or infant, suggesting that the observed seasonality in perinatal death is linked to a seasonality of reproductive infections (Keller and Nugent, 1983).

POTENTIAL HUMAN HEALTH EFFECTS OF CLIMATE CHANGE

To assess the effects of climate change on human health, EPA sponsored three studies for this report (Table 12-2). Longstreth and Wiseman (Volume G) reviewed the literature on the incidence of, and mortality due to, vector-borne diseases. In November 1987, they also conducted a workshop of scientists to evaluate the potential impacts of global climate change on vector-borne infectious diseases in the United States. Following the workshop, Haile (Volume G) conducted modeling studies of the potential impact of climate change on (1) the distribution of the American dog tick, the vector of Rocky Mountain spotted fever; and (2) the potential for malaria transmission in the United States. The third study, by Kalkstein (Volume G), as an extension of an earlier modeling study that assessed the potential effects of global climate change on the elderly and on total mortality in New York (Kalkstein et al., 1986). Kalkstein (Volume G) expanded the New York analysis to include 14 other cities. A detailed review of these three studies, supplemented with other information from the literature, is presented in this section.

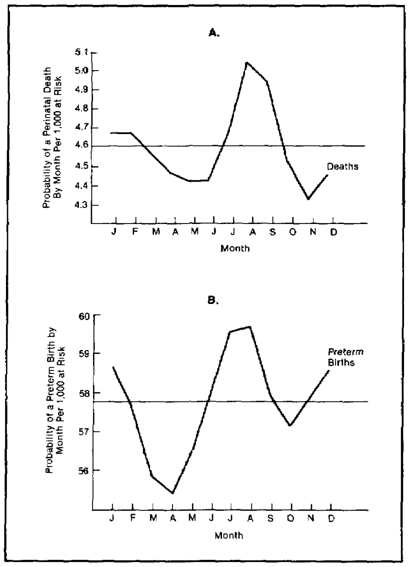

Figure 12-2. Probabilities of (A) perinatal death or (B) preterm delivery (Kelley and Nugent, 1983).

Table 12-2. Studies Conducted for This Report

- <u>The Impact of CO_2 and Trace Gas-Induced Climate Change Upon Human Mortality</u> - Kalkstein, University of Delaware (Volume G)
- <u>Computer Simulation of the Effects of Changes in Weather Pattern on Vector-Borne Disease Transmission</u> - Haile, U.S. Department of Agriculture (Volume G)
- <u>The Potential Impact of Climate Change on Patterns of Infectious Disease in the United States</u> - Longstreth and Wiseman, ICF/ Clement Associates, Inc. (Volume G)

General Mortality

Preliminary analyses suggest that unless the U.S. population becomes fully acclimatized[2] to higher temperatures, climate change will be associated with a sharply rising number of summer deaths. With full acclimatization to the warmer summers, heat-related mortality might increase less dramatically or not at all. In winter, the number of weather-related deaths will probably decline regardless of acclimatization. It is not clear what the net effect of these two offsetting trends may be.

Only a few studies have evaluated the effects of global climate change on human mortality. Kalkstein et al. (1986) developed a regression equation involving nine weather elements, such as temperature, windspeed, and humidity, to give the best algorithm for describing the current impact of weather on mortality. The algorithm used mortality data from New York City for 1964-66, 1972-78, and 1980.

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[2] Estimations of the impact of warming on future mortality must address the question of whether humans will acclimatize (socially, psychologically, or physiologically adapt) to changing weather. How quickly humans may become acclimatized is a topic of considerable controversy, so it is difficult to predict whether the climate changes due to global warming will occur slowly enough to permit acclimatization.

The analysis revealed the existence of a summertime "threshold temperature" -- the maximum temperature above which mortality increases -- for New York City of 92 F for total deaths. This information was then used to assess the potential impact of climate change under the assumption that the population would not acclimatize, as well as under the assumption that it would acclimatize. Unacclimatized impacts were estimated by combining the climate scenarios and the historical weather algorithm described above, and acclimatized impacts were estimated by analyzing analog cities that have values of weather variables today that look like those New York is estimated to have under climate change.

Assuming full acclimatization and a scenario predicting that New York will be 3 to 4°C (5 to 7°F) warmer than it is today, no additional deaths were predicted. However, assuming no acclimatization, the number of summertime deaths attributable to temperatures above the threshold (hereafter called suprathreshold summer deaths) increased seven- to tenfold. Changes in winter weather, i.e., more subthreshold temperatures, were not estimated to affect mortality.

For this report, Kalkstein (Volume G) extended the New York analysis to cover 14 additional metropolitan areas and to evaluate the impact of two climate scenarios: the GISS doubled CO scenario, and the GISS transient A scenario, e4uated at 1994 to 2010 and at 2024 to 2040. Threshold temperatures were calculated for each city for summer and winter. Historical relationships between mortality and temperature were derived independently for each of these 15 cities for both summer and winter. Table 12-3 summarizes the results for total mortality, by city and by season (summer or winter), for the doubled CO_2 scenario with and without acclimatization. The cities with the highest estimated number of suprathreshold summer deaths historically were New York City, Chicago, and Philadelphia; each averaged over 100. All of the cities with the highest average number of summer deaths are in the Midwest or Northeast, and those with the lowest number are in the South.

Table 12-3. Estimated Future Mortality Under Doubled CO_2 Climate Conditions without and with Acclimatization Human Health

City	Number of deaths per season					
	Summer			Winter		
	Current	Without	With	Current	Without	With
Atlanta	18	159	0	2	2	0
Chicago	173	412	835	46	2	96
Cincinnati	42	226	116	14	6	0
Dallas	19	309	179	16	1	0
Detroit	118	592	0	16	2	37
Kansas City	31	60	138	21	5	0
Los Angeles	84	1,654	0	0	0	0
Memphis	20	177	0	0	0	0
Minneapolis	46	142	235	5	1	0
New Orleans	0	0	0	0	0	0
New York	320	1,743	23	56	18	25
Oklahoma City	0	0	47	0	0	0
Philadelphia	145	938	466	10	1	1
St. Louis	113	744	0	47	7	0
San Francisco	27	246	159	10	7	0
Total	1,156	7,402	2,198	243	52	159

Source: Kalkstein (Volume G).

As would be expected, generally more deaths were predicted for populations that do not acclimatize. However, for certain cities, e.g., Chicago, Kansas City, and Minneapolis, more deaths were predicted with acclimatization than without. Exactly why this occurred is uncertain. The results appear to be very sensitive to the choice of the analog city. For example, Chicago appears to have more deaths if its population becomes acclimatized than if it does not. It may be that the analog city chosen to represent a particular acclimatized city, Chicago for instance, is more sensitive to weather effects on mortality than Chicago currently is. More research is planned to investigate this apparent anomaly to refine the estimates of what global warming will mean in terms of mortality. Thus, Kalkstein's results should not be used as predictions of individual city behavior, but as illustrations of sensitivities.

In the absence of any acclimatization, suprathreshold summer mortality in the United Stated under conditions of doubled CO_2 is estimated to rise from an estimated current total of 1,156 deaths to 7,402 deaths, with deaths in the elderly (aged 65 or over) subset contributing about 60% of each figure (727 and 4,605, respectively). Currently, the percentage of elderly in the U.S. population is increasing. Thus, the mortality estimated to result from climate change may be larger than that found by Kalkstein because his analysis is predicated on today's age distribution. Even with full acclimatization, the number of weather-associated summer deaths almost doubles to 2,198, possibly because hot weather increases physiological stress. Kalkstein's analysis also estimates a drop in the number of subthreshold winter deaths. Historically, however, the number of these deaths during the winter in the United States is much smaller (243) than that observed for the summer, and subthreshold winter deaths were estimated to fall to 52 without acclimatization and to 159 with acclimatization. The net result for the United States is an increase in yearly mortality associated with doubled CO_2.

This study is exploratory research in the field of the potential impacts of climate change on human health. Some aspects of the analyses that led to these estimates need further investigation; thus, the estimates should be accepted with caution. The direction of predicted change, i.e., an increase, is probably much more solid than the magnitude of change. In addition, this research has concentrated on mortality occurring above a particular threshold temperature for summer or below a particular threshold temperature for winter. Consideration of a broader range of temperatures could conceivably result in different conclusions being drawn.

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Overall global warming and climate change may exacerbate the effects of cardiovascular, cerebrovascular, and respiratory diseases. Data from these studies show an inverse relationship between mortality and temperature (i.e., deaths go down as temperature goes up) for the range between -5 C and about +25 C, with sharp increases at temperatures above and below this range, particularly for the elderly and for hot weather (White and Hertz-Picciotto, 1985); the exact range appears to depend on the city. Illustrations of this relationship for coronary heart disease and stroke are shown in Figures 12-3 and 12-4, respectively (Rogot and Padgett, 1976). This complex relationship precludes simple prediction of the net effect of climate change. For example, it is possible that hot weather-associated mortality from these diseases may increase in some localities, but this trend may be offset, at least in part, by a decrease in cold weather-associated mortality.

Just as higher summer temperatures are associated with increases in mortality from cardiovascular, cerebrovascular, and respiratory diseases, they are also likely to be associated with increases in morbidity from these diseases through increases in the number or duration of hospital admissions. Particular stress may be put on the respiratory system because climate change can potentially increase pollen, urban smog (discussed below), and heat stress, all of which have an adverse effect on the respiratory system.

For example, if, as has been suggested in the chapter on forests, climate change encourages a transition from forest to grassland in some areas, grass pollens could increase. This, in turn, may increase cases of pollen-induced hay fever and allergic asthma. (However, the switch from forest to grassland would reduce the amount of tree pollens that also cause allergic responses in some individuals.) Rises in humidity also may affect the incidence of mold-induced asthma and hay fever.

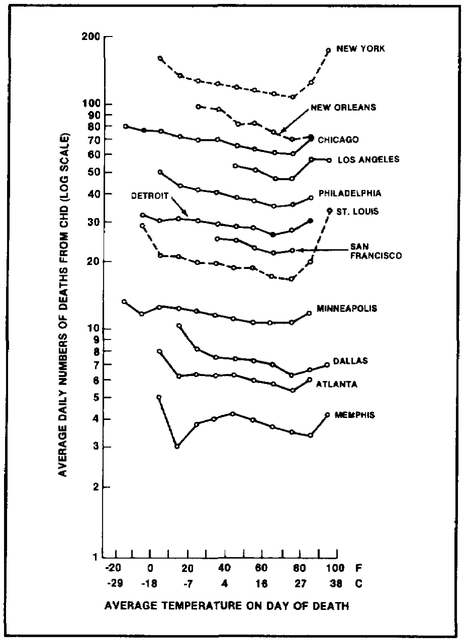


Figure 12-3. Relationship of temperature to heart disease mortality (adapted from Rogot and Padgett, 1976).

As indicated in Chapter 11: Air Quality, global warming may modify global and regional air pollution because it may increase concentrations of ozone and may also have impacts on acid deposition and general oxidant formation. The increasing occurrence of numerous respiratory diseases, such as lung cancer, emphysema, bronchitis, and asthma, has been attributed to the pollutants in urban smog (Lopez and Salvaggio, 1983). Many of the trace gases implicated in global warming contribute to these problems; other pollutants are created from the interaction of ultraviolet light with these and other chemicals present in the atmosphere.

The component that causes the greatest concern in urban smog is ozone (Grant, 1988). If global warming causes an increase in tropospheric ozone, adverse consequences could result for adult asthmatics and people who suffer from acute or chronic bronchitis.

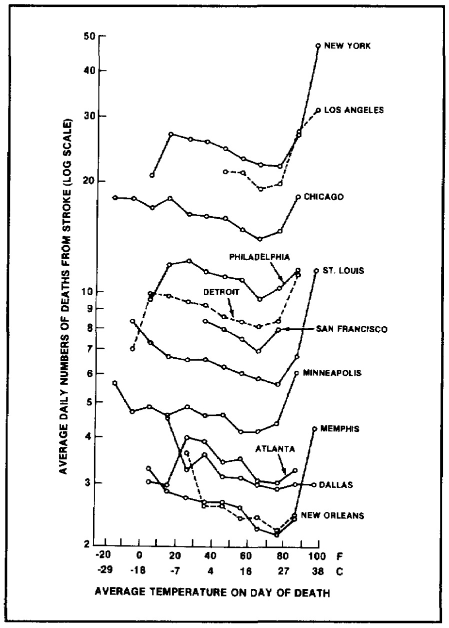


Figure 12-4. Relationship of temperature to mortality from stroke (adapted from Rogot and Padgett, 1976).

Vector-Borne Diseases

Potential changes in humidity and temperature could alter the geographic ranges and life cycles of plants, animals, insects, bacteria, and viruses. (For further discussion of forestry and agriculture, see Chapters 5 and 6, respectively.) For example, the range of many plant pests may move northward by several hundred miles. Such changes could occur for insects that spread diseases to both humans and animals. Vector-borne diseases that affect humans are relatively rare in the United States. The incidence of most of those found, however, is increasing. The incidence of some, such as Lyme disease, is increasing dramatically (CDC, 1986).

Tick-Borne Diseases

Both Rocky Mountain spotted fever and Lyme disease are considered to be public health problems in the United States. Although these two diseases are spread by different species of ticks, some overlap exists in their geographic distribution (Figure 12-5). Because tick populations appear to be limited by the size of their intermediate host populations (such as white-tailed deer), the spread of tick-borne diseases may be particularly sensitive to any change that may affect the geographic range of these hosts and, consequently, the range of the vector, or carrier.

In addition to the presence of the host, tick populations also depend upon the seasonality of environmental factors such as temperature, humidity, and vegetation. Optimally, climate must be warm enough to promote progression through the life cycles, humid enough to prevent the drying out of eggs, and cold enough in winter to initiate the resting stage.

As for many tick-borne diseases, the opportunity for a tick to acquire the infective agent from an infected animal is limited to the short period when the level of the agent in the blood of the host is high enough for the tick to receive an infective dose. Higher temperatures may increase the amount of the agent (the organism that is transmitted by the carrier, such as a virus) and the time it remains lodged on the host animal. Both these mechanisms would increase the rate of infection of the carrier. However, although higher temperatures may favor the presence of the agent, there is some indication that they could disrupt the life cycle of some tick species. In these cases, warmer temperatures would reduce both tick survival and the spread of diseases they carry.

Tick populations also vary with the natural vegetation of an area. The incidence of Rocky Mountain spotted fever, in particular, has been linked to natural vegetation and changes in climate.

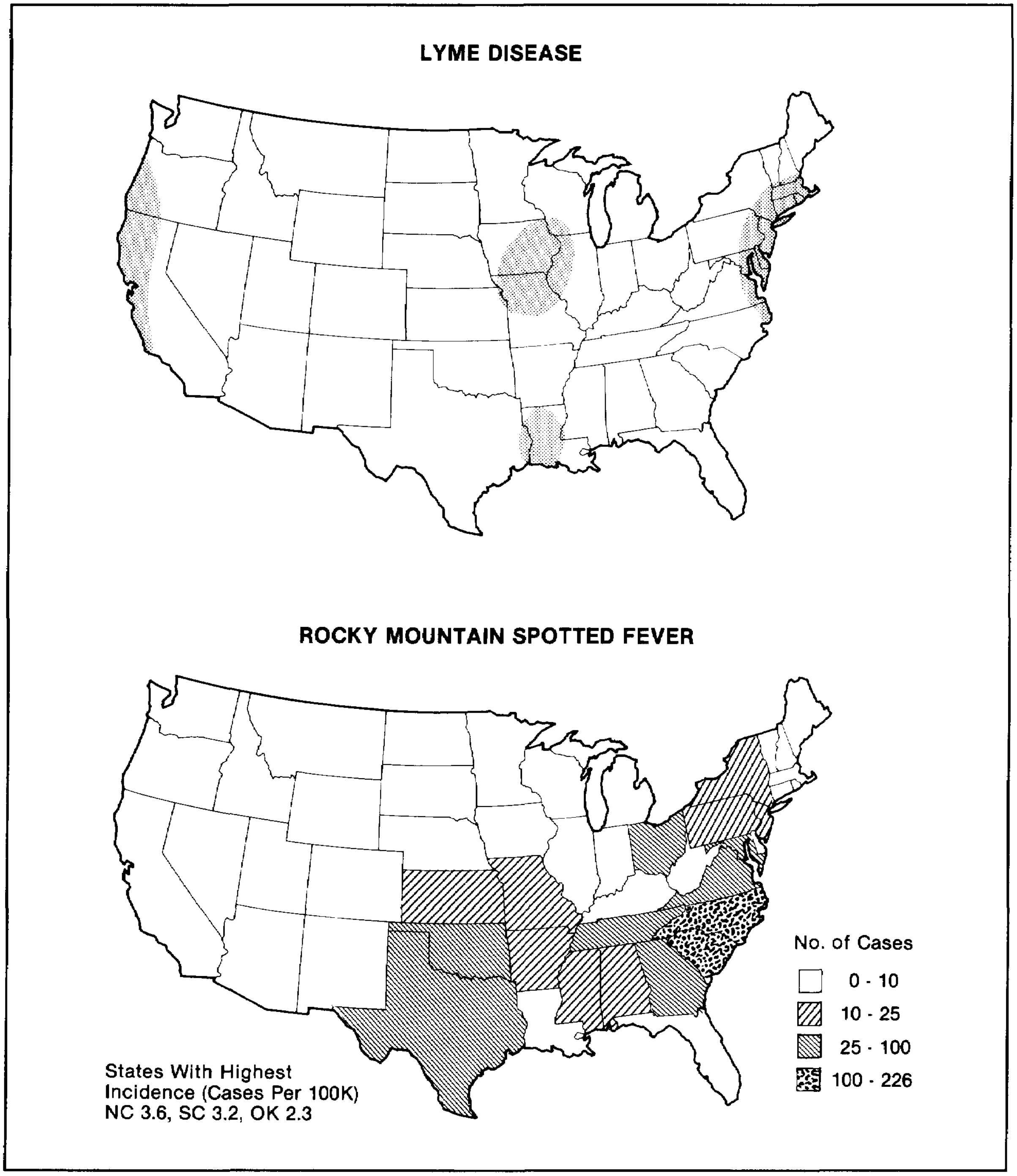
In examining the potential impact of climate change in the United States on Rocky Mountain spotted fever, Haile (Volume G) used a weatherbased model, ATSIM, to evaluate the impact of the scenario climate changes on the distribution of the American dog tick, the primary carrier of this disease (Haile, Volume G; Mount and Haile, 1988). The model uses data inputs from the three doubled CO_2 scenarios (GISS, GFDL, and OSU) to estimate population dynamics, growth rate, and generation time. Haile assumed that habitats and host density did not change in response to global warming. Sample results for six cities representing the most southern, the most northern, and the two middle latitudes are presented in Figure 12-6. The results indicate that under all scenarios, tick populations would shift from south to north and would be virtually eliminated from the most southern locations (Jacksonville and San Antonio). However, in the middle latitude cities, the results are mixed and depend on the scenario evaluated. The model does not estimate changes in incidence of the disease.

In this analysis, the only model inputs that were changed to simulate climate change were the weather inputs. Other important parameters in the model are the distribution of habitat between forests and meadows and the presence of suitable hosts. Both parameters are likely to be changed relative to current conditions under climate change. As indicated in Chapter 5: Forests, a change from forests to meadows may occur in certain areas of the country; this would depress the tick population. However, the distribution of small mammals also may change. If small mammal populations increased, tick populations would grow. In addition, this study did not consider changes in climate variability, which may have a major effect on the outbreak of diseases.

In a sensitivity analysis of their model, Mount and Haile (1988) found that the model predictions could vary sixteenfold, depending on the inputs used for host density, whereas the variability conferred by changes in the weather inputs is about fourfold. Based on the sensitivity analysis, host densities are extremely important to these predictions. Keeping them constant, as was done in this analysis, could have underestimated or overestimated the impact of climate change on the density of the American dog tick.

Mosquito-Borne Diseases

A second category of vector-borne diseases that can be affected by climate change consists of diseases carried by mosquitoes. Climate changes resulting in more days between 16 and 35 C (61 to 95 F), with humidity between 25 and 60%, are likely to favor the growth of mosquitoes (White and Hertz-Picciotto, 1985). Mosquito populations are also sensitive to the presence of standing water. It is not clear whether standing water will generally increase or decrease (see Chapter 9: Water Resources). Worldwide, mosquito-borne diseases are associated with significant illness and mortality. In the United States, however, vector control programs and improved hygiene have virtually eliminated endogenously transmitted cases of these diseases, with the exception of sporadic outbreaks of arbovirus-encephalitis. (Imported cases are seen occasionally.) Numerous mosquito species are present



LYME DISEASE

ROCKY MOUNTAIN SPOTTED FEVER

States With Highest Incidence (Cases Per 100K)
NC 3.6, SC 3.2, OK 2.3

Figure 12-5. Geographic distribution of Lyme disease and Rocky Mountain spotted fever (Longstreth and Wiseman, Volume G).

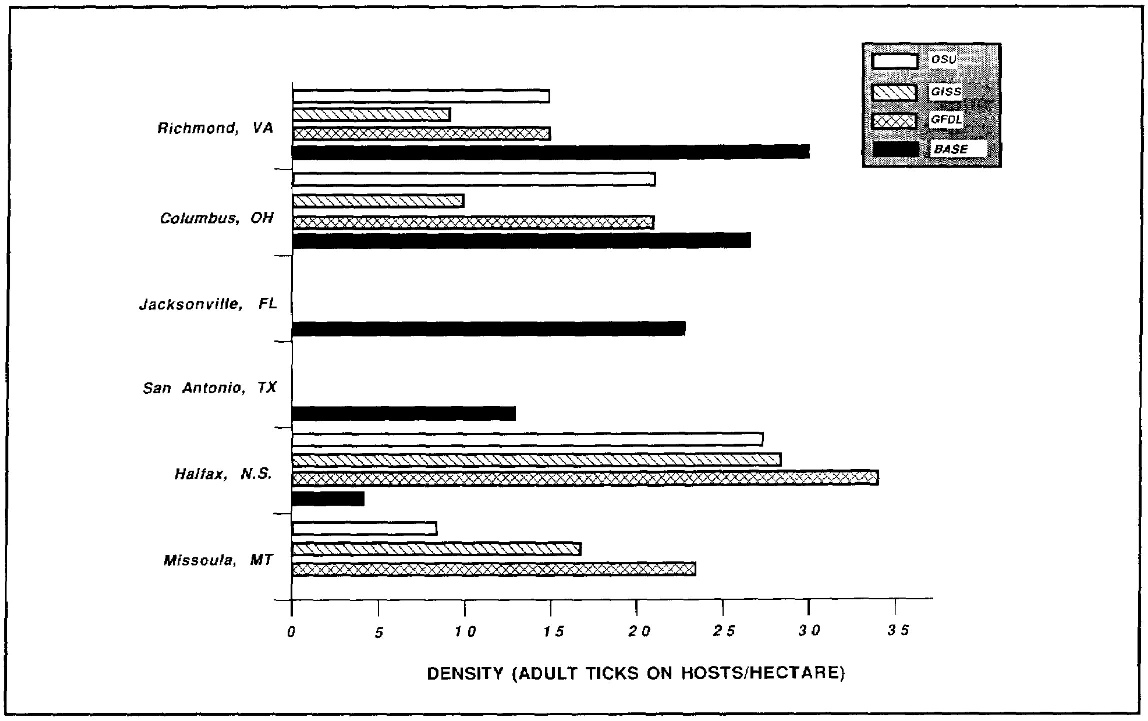


Figure 12-6. Simulated tick densities for selected cities under various scenarios of climate change (Haile, Volume G).

in the United States, however. Recent restrictions on pesticide use, coupled with the influx of visitors and immigrants who can serve as sources of infectious agents, as well as the lack of available vaccines for many of the potential diseases, suggest the potential for reintroduction and establishment of these diseases in the United States -- particularly if global warming provides a more suitable climate for their growth and development (Longstreth and Wiseman, Volume G).

At a recent workshop, five of the numerous mosquito-borne diseases were considered to pose a potential risk to U.S. populations if the status quo is disturbed by climate change (Longstreth and Wiseman, Volume G). Malaria, dengue fever, and arbovirus-induced encephalitides were considered to be significant risks, and yellow fever and Rift Valley fever were considered to be possible risks.

Malaria

Malaria is an infectious disease transmitted by mosquitoes and induced by parasites (Plasmodia). The symptoms are highly variable, depending on the species of the agent. They include chills, sweats, and headache, and in severe cases, may progress to liver damage and even liver and renal failure.

As a result of effective vector control and treatment programs, malaria is no longer indigenous to the United States. However, imported cases occur regularly, and occasionally indigenous transmission has been documented (Longstreth and Wiseman, Volume G). Current U.S. demographic trends, including a large number of legal and illegal immigrants from locations where malaria is endemic, could present a pool of infected individuals that, in conjunction with climate changes, may create sufficient conditions for increased disease incidence.

Haile used the weather-dependent model MALSIM to evaluate the potential impact of climate change on malaria in an infected population living in an area where a competent carrier is present. The model was originally developed to help predict malaria outbreaks in tropical countries such as Kenya. This is

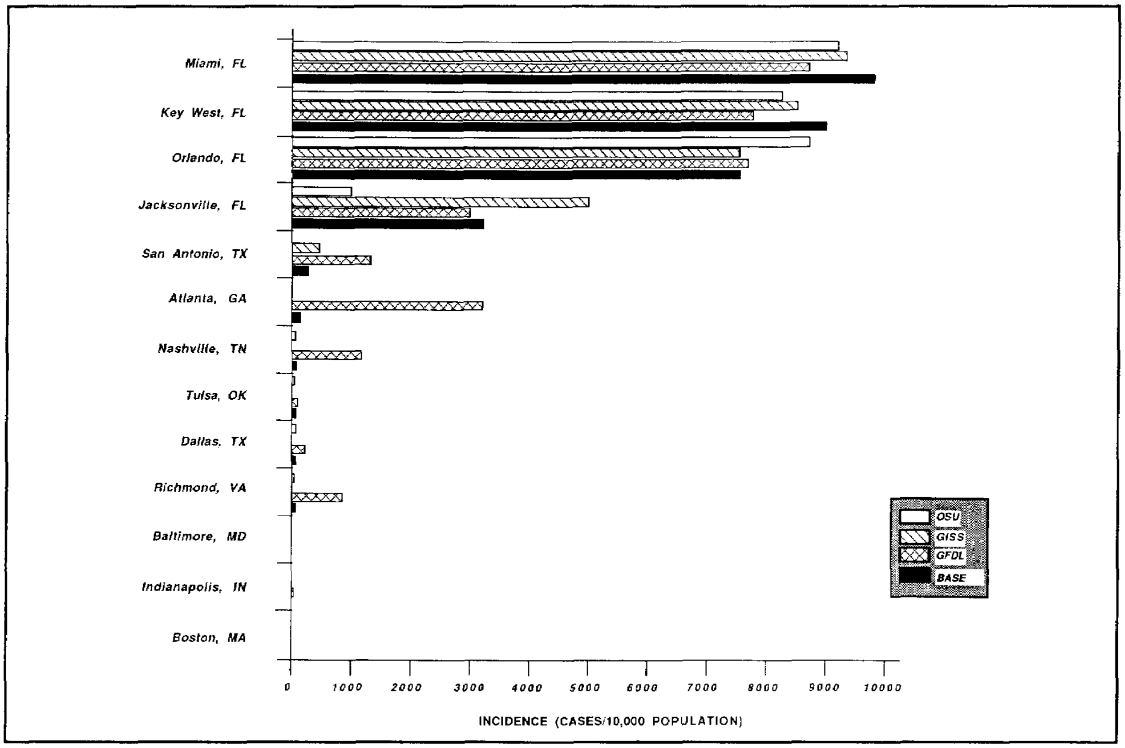


Figure 12-7. Simulated incidence of malaria for selected cities under various scenarios of climate change (Haile, Volume G).

the first application of the model to the United States. This analysis did not consider changes in climate variability, which may be important for the spread of malaria. The MALSIM model showed that several cities in the South (e.g., Miami, Key West, and Orlando), under current climate conditions, are very favorable for malaria transmission.[3] Using the climate change scenarios in MALSIM did little to affect the estimated transmission potential of malaria in the United States (Figure 12-7). In a few cities, e.g., Richmond, Nashville, and Atlanta, the model estimated large increases in one scenario relative to those that would occur normally. However, the results varied with different climate scenarios, did not occur at all locations, and should be considered to be inconclusive.

Dengue Fever

Dengue fever is an arbovirus-induced[4] illness characterized by fever, rash, and severe pain in the joints. The dengue virus has four different types (DEN 1 through DEN 4). Sequential infection by different types is possible and has been suggested to lead to an increased risk of developing a more severe, hemorrhagic form of the disease that can be fatal in the very young and the elderly. Like malaria, it is not

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[3] The MALSIM estimates of malaria incidence by city under current conditions were based on two assumptions: that there were 100,000 female mosquitoes in the vicinity of each city and that 100 infected people were added to the cities' populations. Under those assumptions, infection of virtually the entire population of Miami was predicted to be possible unless protective measures were taken.

[4] An arbovirus is a virus transmitted by an arthropod. Arthropods are a group of animals that includes insects and arachnids. Examples of arthropods that transmit disease include mosquitoes and ticks.

currently endemic in the United States, although potential carriers are present and the disease is imported here regularly by people who have traveled abroad.

The ability of the vector to transmit the agent appears to depend on temperature, and current conditions do not appear to be favorable for this process. Climate changes that raise temperatures, however, may reduce the required incubation period and increase the infectivity of the carrier, increasing the potential transmission of the disease.

Arbovirus-Related Encephalilides

Arbovirus-related encephalitides are a group of acute inflammatory diseases that involve parts of the brain, spinal cord, and meninges. In mild cases, these infections result in feverish headaches or aseptic meningitis; in more severe cases, those symptoms can be accompanied by stupor, coma, convulsions (in infants), and occasionally spastic paralysis (APRA, 1985).

At least seven types of viruses causing encephalitis are present in the United States. These include the three forms that also infect horses (the western, eastern, and Venezuelan equine encephalitis viruses) as well as four that are named after the location of their discovery (the La Cross, St. Louis, Powassan, and California encephalitis viruses). Cases range in severity depending on the type of virus, with yearly fatality rates between 0.3 and 60%. These infections are rare. In 1984, 129 cases were reported to the Centers for Disease Control, which maintains an active surveillance program for them (CDC, 1986).

Outbreaks of encephalitis attributable to these viruses are normally limited to specific geographic locations and seasons for several reasons. First, warm temperatures are normally required for the viruses to multiply and to be transmitted to a new host. Higher temperatures may quicken the transmission process and promote epidemic disease. However, the extent of this effect depends largely on the particular virus. Some viruses require cooler weather and higher moisture conditions. Thus, higher temperatures may reduce their prevalence. Second, environmental conditions that favor the presence of carriers and hosts must prevail. For example, relative humidity may affect plant life necessary for the feeding of hosts.

Other Diseases

The incidence of a variety of other U.S. diseases appears to be sensitive to changes in weather. If humidity is higher, an increased incidence and severity of fungal skin diseases (such as ringworm and athlete's foot) and yeast infections (such as candidiasis) may be observed. Studies on soldiers stationed in Vietnam during the war indicated that outpatient visits for skin diseases (the largest single cause of outpatient visits) were directly correlated to increases in humidity but showed a 4-month lag with relationship to temperature increases (Figure 12-8). In addition, excessively high temperatures can lead to such skin diseases as prickly heat and heat rash, which impair the ability of the skin to breathe and thus place additional stress on people already suffering from overexposure to heat from other causes.

Several diseases appear to be associated with the acquisition of winter infections. If a reduction in winter severity is also accompanied by a decrease in wintertime infections, these diseases could be reduced under global warming.

For example, birth in cold winter months has been associated with a higher risk of schizophrenia in individuals whose schizophrenia is without an apparent genetic component (Kovelman and Scheibel, 1983). In addition, juvenile-onset diabetes, which has been reported to be increasing over the past several decades, has been shown to be associated with a seasonal variation in that the month of first admission peaks in the winter (Glatthaar et al., 1988; Patterson et al., 1988). It is a common clinical experience that a minor viral illness precedes the onset of symptoms.

SOCIAL AND ECONOMIC IMPLICATIONS

Demographic and technological trends (the aging of the population, an influx of immigrants, advances in treatment techniques) make it difficult to analyze the potential impacts of climate change on human health. Although this chapter attempts to identify those human health effects at risk from climate change, the analyses were not designed to consider adaptive responses and should not be treated as predictions of what will happen with climate change but as illustrations of sensitivities. Rather, the analyses

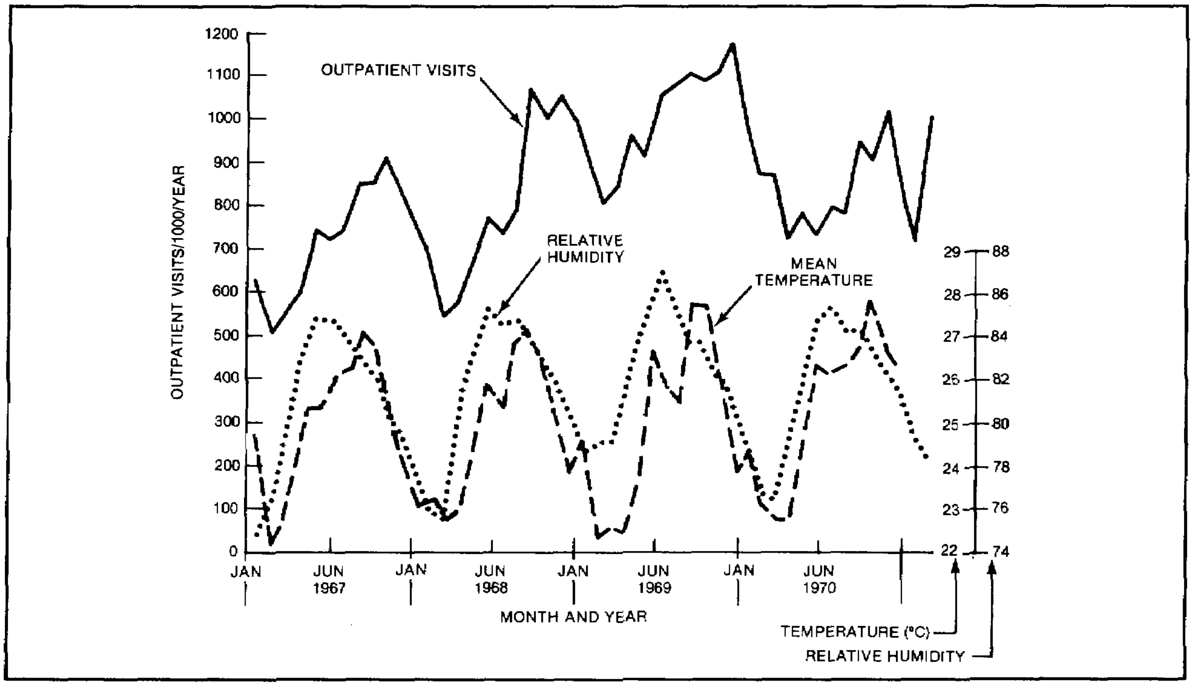

Figure 12-8. Relationship of skin infections to humidity and temperature (Longstreth and Wiseman, Volume G).

presented here represent possible scenarios, in the absence of consideration of demographic trends or adaptive responses, that may either exacerbate or ameliorate the impact of climate change on human health. Societies possess considerable ability to adapt to change. The potential for climate to affect human health may be considerably modified by adaptive responses, such as immunizations, modification of the environmental temperature (e.g., use of air conditioners), and control of disease carriers.

Climate change may affect regional and national health care. For instance, the treatment requirements for asthma may increase or decrease as locations experience changes in the distribution and intensity of pollen concentrations. Increased resources may be needed to treat premature infants if the number of preterm births increases. If heart attacks, stroke, and respiratory problems increase, hospitalization costs and costs due to days lost from work may also increase. Higher health care costs might be particularly obvious in Medicaid and Medicare because those below the poverty line would be less able to take adaptive measures (e.g., air-conditioning), and the elderly are more susceptible to the ill effects of extreme weather conditions.

The United States is already experiencing an infant mortality higher than that of any other industrialized nation (World Bank, 1987). Some studies have found that perinatal mortality is higher in the summer; consequently, the increased temperatures expected with global warming may well exacerbate infant mortality (or at least neonatal mortality).

The need for irrigation may increase in many regions of the United States (see Chapter 6: Agriculture). Irrigation may result in greater amounts of standing water and can therefore increase mosquito populations. Arbovirus encephalitis may become a greater problem than at present, and other mosquito-borne diseases, such as dengue or yellow fever, could be more easily spread if introduced.

One health impact of climate change not assessed in this report is the morbidity and mortality associated with certain kinds of extreme events, e.g., tornadoes and hurricanes. These currently cause some mortality in the United States; however, it is difficult to say whether there will be a change in the mortality induced by these events with global warming. As indicated in Chapter 3: Variability, changes in the frequency of such extreme events cannot be predicted on the basis of an analysis of the general circulation model (GCM) output, although an increase in severity of some kinds of storms, e.g., hurricanes, is not inconsistent with current theories and more detailed models of storm behavior.

The impact of global change on human health will most likely be greater in the lesser-developed countries (LDCs) that do not have the resources to take the adaptive or preventative measures available to the United States. Impacts on agriculture and water resources in the LDCs could result in poor nutrition and water shortages that may make populations more susceptible to disease. Changes in insect (arthropod) habitats may allow diseases to flourish where they never have before. Changes in extreme events such as monsoons or floods could significantly affect mortality in the developing world. Such external impacts on health might have an impact on the United States not only via the potential for introduction of diseases already discussed but also via our participation in international aid and relief programs.

POLICY IMPLICATIONS

The full impacts of climate change on human health will require more research. Agencies such as the Department of Health and Human Services should consider conducting studies on potential impact.

In the future, a cadre of trained professionals may be needed to respond to outbreaks of diseases. A shift in the distribution of carriers of human disease may necessitate regional shifts in surveillance and eradication programs. States that do not have these programs may need to develop them.

RESEARCH NEEDS

Although information evaluating the relationship of weather and season to various health effects is plentiful, research into the significance of these relationships in the context of global warming is scarce. A number of areas requiring further research are described below.

A number of studies have identified relationships between temperature changes and mortality from diseases of the heart, respiratory system, and cerebrovascular system. These studies show slightly different relationships depending on the city that provided the data, although some common elements exist. A statistical analysis of this information might be warranted to determine if one general relationship (across the United States, or perhaps related to latitude) could be developed for each of these categories. Such a relationship could then be used to estimate the impact of global warming by specific disease category.

A companion study to that proposed above should identify the top 10 causes of deaths associated with changes in weather in the Kalkstein study. The results could then be compared with the information derived above to determine other causes of mortality that show great sensitivity to the weather.

The Kalkstein analysis did not look at deaths occurring in the very young (aged 1 year and below). Given the seasonality of perinatal mortality and preterm death observed in several studies, an investigation of the relationship between temperature and mortality in the very young probably would be worthwhile. More baseline information is needed for the latter study. Related studies on perinatal mortality could examine the following:

- Whether the South has a higher per capita incidence of perinatal mortality.
- Whether infections, which have been suggested as a potential cause of the perinatal mortality observed, show a seasonality in parallel to perinatal mortality, and whether more such infections occur in the South.
- The principal causes (e.g., bacteria, viruses) for perinatal infections, and whether they are the same as those for skin infections, and whether they are the same as those for skin infections that increase with increases in humidity.
- Whether the incidence of preterm birth or perinatal mortality is related to weather parameters such as temperature, humidity, or high-pressure systems.

The following additional research areas are suggested:

- Synergism between stratospheric ozone depletion (due to increases in UV-B radiation) and global warming. Increased UV-B radiation and global warming might be expected to exacerbate infectious diseases. UV-B radiation may have an impact on the ability of an individual to respond to a disease, and global warming may change the incidence of certain infectious diseases. For example, leishmaniasis is an important disease in many African countries. In animal models, UV-B irradiation adversely affects the development of immunity to Leishmania. If climate change creates more favorable habitats for the sand-fly vector of this disease, then a double insult to the system could occur: a higher incidence, and a worse prognosis.

- The impacts on LDCs. The Agency for International Development is supporting the development of a Famine Early Warning System (FEWS) that will use a variety of inputs (many of them weather related) to help predict when conditions leading to famine may be occurring. Appropriate GCM outputs could be input into this system to evaluate how the changes associated with global warming may affect famine development. Similarly, the Department of Defense is using a number of models comparable to those used by Haile to attempt to predict where infectious diseases are likely to pose problems for U.S. troops. It might be interesting to evaluate how the climate variables from the GCM-generated scenarios would affect these predictions, particularly in the LDCs where these diseases present a very real problem to the health care systems.

- Introduction of infectious diseases into the United States via immigrants. Anecdotal information indicates that many immigrants are not served by the health care system; consequently, they could become a population where diseases might develop into full-blown epidemics before initiation of treatment. Determining whether or not global warming will affect this process, either directly via the provision of a more hospitable environment for the disease or indirectly via an increased number of immigrants and refugees, will require a better characterization of the current situation.

- Intermediate hosts and their habitats. In the models used by Haile, two important input parameters that were held constant were the size of the intermediate host population and the distribution of habitat between forest and meadow. It is likely that both of these parameters will themselves be affected by climate change. A better grasp of how climate change will affect these parameters needs to be developed and integrated into the infectious disease models.

- Irrigation and incidence of vector-borne disease. An increase in irrigation is possible, which could have a significant impact on mosquito development and therefore on mosquito-borne diseases. The importance of such water is timedependent, however (i.e., it must occur at the right moment in the insect's lifecycle). Thus an analysis of how the growing season overlaps transmission of diseases such as La Cross encephalitis might provide an indication of whether changes in irrigation practices should be a concern in terms of public health.

- Mortality from extreme events. Another issue that might warrant investigation is how climate change may affect the mortality associated with extreme events, such as hurricanes and floods.

- Air pollution and respiratory disease. Air pollution is already a major contributing factor in the incidence and severity of respiratory disease in the United States. An analysis of the extent that global warming will exacerbate air pollution is critical to an assessment of the potential health effects of climate change.

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CHAPTER 13
URBAN INFRASTRUCTURE

by Ted R. Miller

FINDINGS

Global climate change could require U.S. cities to make major changes in capital investments and operating budgets. Areas most likely to be affected include water supplies, roads, and bridges; storm sewers and flood control levees; and energy demand in municipal buildings and schools.

- Most urban infrastructure in the United States will turn over in the next 35 to 50 years. If potential changes in climate are considered, this turnover will allow cities to prepare for climate change at lower costs. In some cases, the risk of climate change should be incorporated into decisions beginning today, such as coastal drainage systems that are likely to last for 50 to 100 years.

Northern and Southern Cities

- Northern cities, such as Cleveland, may incur a change in the mix of their expenditures. In such locations, increased electricity costs for air-conditioning could be offset by reductions in expenditures for heating fuel, snow and ice control, and road maintenance. Southern cities could see increases in operating budgets due to the demand for additional air conditioning.

Coastal Cities

- Coastal cities, including 12 of the 20 largest metropolitan areas, may face somewhat larger impacts, such as the following:
    - – Sea level rise or more frequent droughts would increase the salinity of shallow coastal aquifers and tidal surface waters. Cities that rely on water from these sources should examine water supply options. Such areas as Dade County, Florida, or New York City would probably be vulnerable.
    - – As sea level rises, some coastal cities would require levees to hold back the sea or fill to raise the land surface area. In the case of Miami, the cost of these activities might exceed $500 million over the next 50 to 75 years, necessitating an average increase of 1 to 2% in annual capital spending in Greater Miami.

Water Supply and Demand

- Climate change will influence the supply and demand for water in many cities. A lengthened summer season and higher temperatures would increase the use of water for air conditioners, lawns, and gardens. Changes in rainfall patterns, runoff, and flood control measures may alter water supplies. In the Hudson River Basin, summer water demand could increase by 5% over the demand for water without climate change, while supplies might fall. Such a change would require new institutional and management approaches for both the Delaware and Hudson Rivers.

Policy Implications

- Climate change has implications for many national programs and policies, including the following:
    - – The National Flood Insurance Program may react to climate change by redrawing floodplain maps and adjusting insurance rates to account for sea level rise and changes in riverflows. This program might consider discouraging development that would be vulnerable to sea level

rise.

– Because of the key role federal programs play in the development of cities, the Department of Housing and Urban Development should examine the implications of climate change on long-term policies. A minimum response might be to provide guidance on the certainties and uncertainties of climate change to groups such as the National League of Cities, the U.S. Conference of Mayors, and the American Planning Association.

– Because water supply infrastructure may last several centuries improved planning is important. The U.S. Geological Survey should study the probable impacts of global climate change and sea level rise on the water supplies of major cities. The U.S. Army Corps of Engineers should factor climate change into the design of major projects.

– Given the assumption that modest changes in the design and location of many transportation systems may facilitate an accommodation to climate change, the Department of Transportation should factor climate change into the design of roads, bridges, and mass transit facilities.

– Voluntary standards organizations, such as the American Society of Civil Engineers, the Building Officials and the Code Administrators International, and the American Society of Heating and Refrigerating and Air Conditioning Engineers should examine the need for changes in existing energy and safety factors to account for the possibility of climate change.

RELATIONSHIP BETWEEN URBAN INFRASTRUCTURE AND CLIMATE

Three-quarters of the U.S. population is concentrated in urban areas (Statistical Abstract, 1988). The majority of the nation's investment in water supply, wastewater transport and treatment facilities, drainage, roadways, airports, mass transit, electric power, solid waste disposal sites, and public buildings serves these urban areas. The current value of selected infrastructure nationwide, displayed in Table 13-1, provides insight into the aggregate investment at stake if climate changes. Most of these items could be considered part of urban infrastructure; their locations and designs have been based on historic meteorologic information. Annually, governments add an average of $4S billion to the capital stock (National Council on Public Works Improvement, 1988).

Of the 20 most populated U.S. urban areas, 18 have access to oceans, major lakes, or rivers and have invested in infrastructure for port facilities and flood control.[1] The expenditure required to construct coastal defense structures – which prevent inundation by the sea, slow oceanfront erosion, control storm surges, slow saltwater advance up rivers, and reduce saltwater intrusion into aquifers – is now minimal.

Although actual practice varies, the nominal replacement cycle for most infrastructure is 35 to 50 years (National Council on Public Works Improvement, 1988). Some water supply investments have 100-year cycles between planned replacement; however, sea level rise, temperature change, and changes in precipitation patterns could alter the balance between water supply and demand. The nature and pattern of precipitation could affect drainage requirements as well as highway design and maintenance.

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[1] Of the 20 most populated urban areas in the United States, 12 are tidal waterfront cities (Baltimore, Boston, Houston, Los Angeles, Miami, New York, Philadelphia/Wilmington, San Francisco/Oakland, San Diego, Seattle, Tampa/St. Petersburg, and Washington, DC), 3 are located on the Great Lakes (Chicago, Cleveland, and Detroit), 3 are on navigable rivers (Minneapolis, Pittsburgh, and St. Louis) and 2 are not on a navigable waterway (Atlanta and Dallas).

Table 13-1. Value of the Nation's Stock of Selected Infrastructure (billions of 1984 dollars)

Component	Value[a]
Water supply	$108
Wastewater	136
Urban drainage	60
Streets	470
Public airports	31
Mass transit	34
Electric power (private only)[b]	266
Public buildings	unknown
Total	$1,105+

[a] Based on a useful life of 35 to 50 years for most assets, and 10 to 20 years for transit vehicles.

[b] About 77% of electric power is privately produced.

Source: Statistical Abstract (1988); National Council of Public Works Improvement (1988).

The heat wave of 1988 illustrated some of the potential impacts. Hundred-degree weather distorted railroad tracks, forcing Amtrak to cut speeds from 200 to 128 kilometers per hour between Washington and Philadelphia (Bruske, 1988) and possibly contributing to a train wreck that injured 160 people on a Chicago-Seattle run (The Washington Post, 1988). A U.S. Army Corps of Engineers contractor worked around the clock for 2 weeks to build a 170-meter-wide, 9-meter-high silt wall across the bottom 40% of the Mississippi River channel, 48 kilometers below New Orleans (Sossaman, 1988a,b). This $2 million wall, designed to wash away when spring snowmelt demands the full capacity of the channel, slowed an advancing wedge of saltwater that threatened the water supply in New Orleans and nearby parishes. In Manhattan, heat exacerbated the effects of longstanding leaks in 256 kilometers of steam pipes, causing the asphalt to soften. As vehicles kneaded the soft asphalt, thousands of bumps formed on city streets, requiring extensive repairs (Hirsch, 1988). In the suburbs of Washington, DC, steel expansion joints bubbled along a 21-kilometer stretch of Interstate 66 (Lewis, 1988).

The following sections of this chapter will examine such issues as the portions of the infrastructure that will be significantly affected, and anticipated costs and who will bear them.

PREVIOUS CLIMATE CHANGE STUDIES ON URBAN INFRASTRUCTURE

Available literature on the potential effects of global climate change on urban infrastructure is sparse. Rhoads et al. (1987) examined the potential impacts of sea level rise on water supply and flood protection in Dade and Broward Counties, Florida, and concluded that the effects might be substantial. Linder et al. (1987) estimated that CO_2 doubling might require raising electric capacity by 21% in a southeastern utility and by 10 to 19% in New York State. Hull and Titus (1986) analyzed the potential impact of sea level rise on water supply in the Philadelphia-Wilmington-Trenton area and found that a rise of 0.3 meters could require adding 140 million cubic meters of reservoir capacity, about a 12% increase, to prevent saltwater from advancing past water intakes on the Delaware River. Additional investment would be required to prevent or respond to saltwater infiltration into underground aquifers. Cohen (1987) estimated that large municipalities along the Great Lakes might increase water withdrawals by 5.2 to 5.6% during May to September because of increased lawn watering.

Two recent studies illustrate the importance of considering sea level rise in urban coastal infrastructure planning and the uncertain nature of the decisions involved. Wilcoxen (1986) examined the impact of sea level rise on a portion of San Francisco's sewage transport system buried near the shoreline. The study estimated that if sea level rose 0.6 meters by the year 2100, an expenditure of roughly $70 million on beach nourishment might be required to prevent damage to a structure that cost $100 million to build in the late 1970s. The author suggested that consideration (at no additional cost) of sea level rise in siting the structure could have prevented these expenses. Titus et al. (1987) examined the impact of sea level rise on a proposed coastal drainage system in Charleston, South Carolina, and estimated that a 0.3-meter sea level rise by 2025 would require almost $2.5 million in additional investments to maintain the target level of flood protection. The present value of these investments is

$730,000. In contrast, only about $260,000, one-third of the cost of responding in 2025, would be required to add this level of protection at initial construction. Thus, the investment would be worthwhile if the probability of sea level rising this rapidly exceeds 35%.

URBAN INFRASTRUCTURE STUDY IN THIS REPORT

Several studies undertaken for this report examined some of the implications of climate change in relationship to urban infrastructure. One study comprehensively examined the impacts on infrastructure in several cities:

- Impact of Global Climate Change on Urban Infrastructure - Walker, Miller, Kingsley, and Hyman, The Urban Institute (Volume H)

The following studies, referenced in this chapter, covered issues relating to urban infrastructure:

- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates - Linder and Inglis, ICF Inc. (Volume H)
- Impacts of Extremes in Lake Michigan Levels Along the Illinois Shoreline: Low Levels - Changnon, Leffler, and Shealy, University of Illinois (Volume H)
- Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the Water Supply Systems of the State of California and Atlanta, Georgia -Sheer and Randall, Water Resources Management Inc. (Volume A)
- National Assessment of Beach Nourishment Requirements Associated with Sea Level Rise - Leatherman, University of Maryland (Volume B)
- The Costs of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two-Meter Rise in Mean Sea Level - Weggel, Brown, Escajadillo, Breen, and Doheny, Drexel University (Volume B)
- Effect of Climate Change on Slipping Within Lake Superior and Lake Erie -Keith, DeAvila, and Willis, Engineering Computer Optecnomics (Volume H)

RESULTS OF THE INFRASTRUCTURE STUDY

Impacts on Miami, Cleveland, and New York City

Walker et al. examined three cities distinctly affected by climate change to determine a range of impacts on urban infrastructure.

Study Design

The study was based on a critical review of existing infrastructure studies in the three cities, discussions of likely impacts with local infrastructure experts, analyses undertaken by these experts, and preliminary calculations of probable impacts. Experts were presented with GCM scenarios for CO_2 doubling, and scenarios were used to calculate effects on energy demand, roadways, and other systems. The study also derived conclusions based on experiences in other cities where current temperatures are analogous to temperatures projected for the cities under study, using the analogs identified by Kalkstein (Volume G).

Limitations

The principal limitation of the overall study is the limited use of hydrologic and other modeling. In addition, experts were asked to derive conclusions regarding conditions beyond their experience. Since only three cities are included, the full range of effects on urban infrastructure was not covered. The authors did not perform engineering analyses of cost-effective responses, and they did not assess the potential for reducing impacts through technological change. Thus, these results should be considered as approximations of the costs of impacts and as illustrative of the sensitivity of urban infrastructure to climate change.

Results and Implications

Miami's Infrastructure

Greater Miami is bounded by water on all sides during the rainy season. An extensive network of canals and levees has been built to control ocean and freshwater flooding and to recharge the aquifer beneath the area. Miami has one of the world's most porous aquifers, which lies less than 1.5 meters below the surface in one-third of the developed area. Federal law requires that roughly 15% of Miami's freshwater be released into the Everglades National Park.

The Miami case study examined the probable impacts of climate change and sea level rise on Dade County's water supply, water control and drainage systems, building foundations, roads, bridges, airports, solid waste disposal sites, and sewage transport and treatment systems, assuming that a gradual sea level rise would be managed through strategies such as raising the land in low-lying areas, upgrading levees and dikes with pumped outflows, retreating selectively from some areas, and increasing the freshwater head roughly in proportion to sea level rise to prevent saltwater infiltration into the aquifer.

As Table 13-2 shows, global climate change could require more than $500 million in capital investment in Greater Miami over the next century. Because needed investments in many systems could not be estimated and because a complete engineering analysis was not performed, these results should be considered only as rough estimates. They imply an increase of 1% to 2% in Greater Miami's capital spending for the next 100 years, no more than $20 per household per year at 1985 population levels (Metropolitan Dade County Planning Department, 1988).

Because the south Florida aquifer extends under the ocean, the typical urban response to a rising sea -- diking the water at the surface and pumping out the seepage from ditches behind the dikes -- appears to be unworkable. Unless the dike extended downward more than 45 meters, rising seawater pressure would cause the sea to rush into the aquifer below the surface and push freshwater upward, almost to the surface.

The one-time capital costs for upgrading existing canals and levees in response to a 1-meter sea level rise could be about $60 million. However, almost $50 million in new control structures, including extensive pumping capacity, might be required for the canals used to maintain the freshwater head. Large-scale pumping along canals also could involve substantial operating costs, but these have not been estimated. Storm sewers and drainage would need upgrading, requiring investment of several hundred million dollars above normal replacement costs.

Table 13-2. Probable Infrastructure Needs and Investment in Miami in Response to a Doubling of CO_2 (millions of 1987 dollars)

Infrastructure Need	Cost
Raising canals/levees	60a
Canal control structures	50.00
Pumping	not estimated
Raising streets	250 added to reconstruction cost
Raising yards and houses	not estimated
Pumped sewer connections	note estimated
Raising lots at reconstruction	not estimated
Drainage	200-300
Airport	30.00
Raising bridges	not estimated
Sewer pipe corrosion	not estimated
Water supply	uncertain
Electric generation	20-30% capacity increase

Building foundations generally should remain stable if the freshwater head rises 1 meter because houses are built on concrete slabs, most buildings in newer areas already are built on raised lots to meet Dade County's flood control ordinance, and the foundations of many larger buildings are designed to extend into the water table. Conversely, the water table could infiltrate the base of about a third of Dade County streets, which would have to be raised or risk collapse. If sea level rose gradually, thereby permitting raising of streets and related sewer mains during scheduled reconstruction, the added public cost might be approximately $250 million. Building owners would incur substantial costs to improve drainage, raise yards, raise lots at reconstruction, and pump sewage to mains.

Miami's airport also would need better drainage, requiring an approximately $30 million investment.

A 1-meter rise in sea level would require raising most bridges to ensure adequate clearances and reduce vulnerability to storm surges during hurricanes.

It is unclear what effect climate change will have on hurricanes. Without increased hurricane activity, climate change probably would exacerbate water shortages that are expected to result from population growth in Greater Miami. Thus, climate change could accelerate Miami's long-range plan for large-scale production of desalinated water at three times current water prices. If hurricanes increase, Miami's added expense for water supply might be roughly $100 million to move some wells farther inland. Conversely, increased hurricane frequency and intensity could cause billions of dollars in property damage.

Analysis of Miami's coastal defense and water supply options provides insight into the impacts of sea level rise on cities built on coral reefs, but not into the response of most mainland cities on the U.S. coastline. Dade County is unusual because readily extracted fill is extensively available on public lands having easy access to a canal system that can be navigated by flat-bottomed barges. Nevertheless, this case study suggests that global climate change could cause large coastal cities to invest billions of dollars over the next 50 to 75 years to add and upgrade infrastructure.

Cleveland's Infrastructure

The Cleveland case study examined impacts of climate change on snow and ice control costs, road construction and maintenance, heating and cooling costs and equipment needs, water supply, and storm and wastewater transport. The study also included a preliminary analysis of the effects of a drop in the level of Lake Erie as estimated by Croley (see Chapter 15: Great Lakes). The impact on the snow and ice control budget was estimated by analogy to the budget in Nashville, Tennessee.

Results are displayed in Table 13-3, which shows that the net impact of climate change on Cleveland's annual infrastructure costs could be negligible, although expenditures probably would shift between categories. In addition to the costs shown in Table 13-3, a one-time capital expenditure of $68 to $80 million could be required to add air conditioners in public buildings. Also, many private residences probably would install air conditioners.

Walker et al. estimated that global climate change could cause annual snowfall in Cleveland to drop from 1.25 to roughly 0.2 meters (4.1 to 0.7 feet), reducing annual snow and ice control costs by about $4.5 million. Decreased frost damage to roads and bridges could yield further savings estimated at $700,000 per year. A drop of $2.3 million per year in heating costs for public buildings also was estimated. Conversely, annual public air-conditioning costs seemed likely to rise by $6.6 to $9.3 million. The impacts on the transit operating budget seemed likely to mirror the impacts on the general budget, with reduced mishaps and traffic delays in ice and snow offsetting increased fuel costs for vehicle cooling.

Table 13-3. Estimated Impacts of a CO_2 Doubling on Cleveland's Annual Infrastructure Costs (millions of 1987 dollars)

Infrastructure category	Annual operating costs
Heating	-2.3
Air-conditioning	+6.6-9.3
Snow and ice control	-4.5
Frost damage to roads	-0.7
Road maintenance	-0.5
Road reconstruction	-0.2
Mass transit	summer increase offsets winter savings
River dredging	less than 0.5
Water supply	negligible
Storm water system	negligible
Total	-1.6 to +$1.1

Source: Walker et al. (Volume H); Keith et al. (Volume H).

The study suggested Cleveland might spend about \$65 to \$80 million to add air-conditioning to older schools and to large nonoffice spaces such as gyms and repair garages. Much of this expenditure would occur as buildings were replaced or refurbished and might have occurred even without climate change.

The rise in winter temperatures associated with a doubling of CO_2 might allow Cleveland to use thinner pavement, resulting in possible savings of about 3% in road resurfacing costs and 1% in reconstruction costs. The net savings could average about \$200,000 per year or 1.3% of the city's current capital budget. Engineering standards (AASHTO, 1987) suggested that the rate of pavement deterioration probably also should decline as winter temperatures rise, saving roughly \$500,000 per year.

A climate-induced drop in the level of Lake Erie probably would not adversely affect Cleveland, although some dredging might be required in the Cuyahoga River and port area (Keith et al., Volume H). Upgrading of the city's combined storm and wastewater collection system appeared to be unnecessary, although this would depend upon rainfall variability.

If temperature rises several degrees, most northern cities probably could anticipate savings in snow and ice control, heating, and roadway construction and maintenance costs similar to those described for Cleveland. These savings might approximately offset the increase in air-conditioning costs. More southern cities could experience modest budget increases.

Cleveland could become a more attractive location for water-intensive industry if water supplies in other areas become less reliable. Resulting in-migration could bring further growthrelated infrastructure costs. Lower Great Lakes levels could require dredging, modification to ports, and relocation of some water intakes. (For a further discussion of these issues, see Chapter 15: Great Lakes.)

New York City's Water Supply

New York City's infrastructure may be affected in many ways by global climate change. Temperature change could affect the same capital expense categories in both New York City and Cleveland. In addition, the city may have to gradually raise its dikes and better protect underground infrastructure from seawater infiltration. Interpolating from Weggel et al. (Volume B), approximately \$120 million might be invested to protect shorelines from a sea level rise of 1 meter. The most pressing, and perhaps largest, problem facing the city may be the effects of global climate change on the adequacy of the city's water supply. The New York City study focused on that issue. Table 13-4 provides estimates drawn from a number of studies about possible infrastructure impacts on New York City.

The New York metropolitan area draws water from the adjoining Hudson and Delaware River Basins and from underground aquifers serving coastal New Jersey and Long Island. Figure 13-1 shows the region and its water supply sources.

Table 13-4. Probable Impacts of a CO_2 Doubling on Selected Infrastructure m the New York Metropolitan Area (millions of 1987 dollars)

Infrastructure category	Costs
Upgrading levees	120
Drainage	increased flooding in low-lying area, minimal sewer system changes
Sewer outflows	more frequent inspection
Water supply	3,000
Snow and ice control	reduced substantially
Road maintenance and construction	winter savings, offset by melting asphalt in Manhattan
Mass transit	summer increase offsets winter savings
Electricity production	65-150
Heating	reduced

Note: Impacts on underground infrastructure, airports, and ports have not been probed, but a discussion of these impacts among Port Authority representatives and other experts at the Second North American Conference on Preparing for Climate Change, Washington, DC, December 7, 1988, suggested they would be small.

Source: Walker et al. (Volume H): Weggel et al. (Volume B); Linder et al. (1987); Schwarz and Dillard (1989).

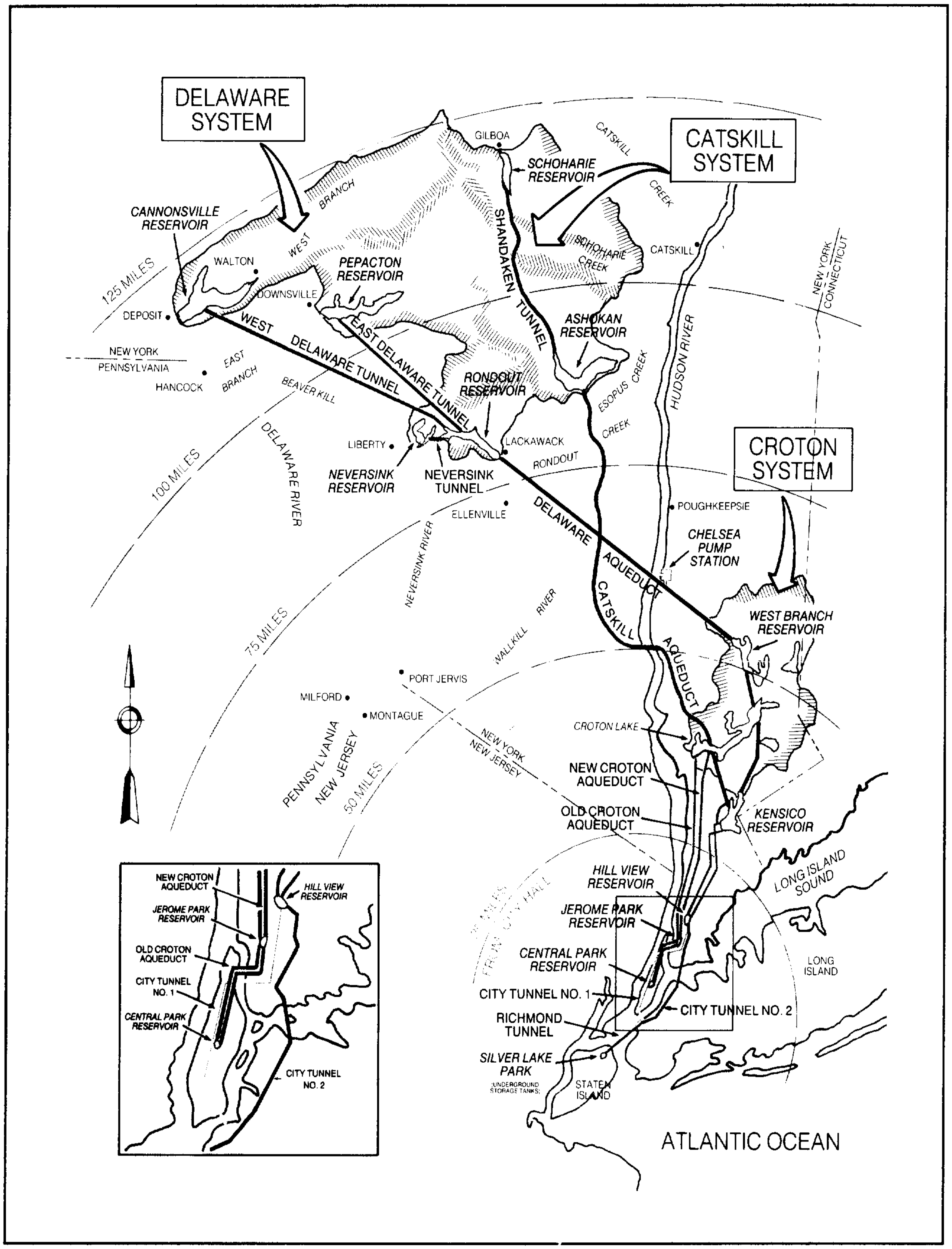

Figure 13-1. The sources of New York City's water supply (New York City Municipal Water Finance Authority, 1986).

The water supply network is in deficit. The Mayor's Task Force (1987) has recommended remedying New York City's portion of the deficit through better management of water demand and detailed study of the possibility of reactivation of a water intake at Chelsea, a $223 to $391 million investment that would yield 375 to 750 million liters of water daily.

Walker et al. estimated changes in water demand using design standards for commercial cooling-tower demand, changes in electricity demand estimated by Linder et al. (1987), and historic residential summer water use. The impact of sea level rise on water supply was estimated by analogy using Hull and Titus (1986), which analyzes possible saltwater advance up the Delaware River. The impact on reservoir supply also was estimated by analogy, using a Great Lakes water balance model (Linder et al., 1987). Walker et al. assumed that baseline demand would not increase above projected demand in 2030, potentially underestimating the increased demand for water.

Walker et al. estimated that a rise in temperatures consistent with the GISS and GFDL scenarios would mean about a 20% increase in cooling degree days. In response, average daily demand for water used in cooling large buildings could increase by 190 million liters during the summer, and increased lawn watering could raise demand by 110 million liters per day, thereby generating a 5% rise in annual demand.

Higher temperatures could increase evaporation and evapotranspiration, decreasing the ability to store water efficiently in surface impoundments. The water balance model indicated the supply loss could range from 10 to 24%.

Saltwater infiltration due to rising sea level would further reduce supply. The study suggested that a 1-meter sea level rise could place the proposed $300 million Chelsea intake below the salt line during the peak summer demand period in mild drought years, reducing supply another 13%. Larger sea level rise or greater droughts might prevent use of the existing Poughkeepsie intake during severe droughts, further reducing supply. In addition, subsurface infiltration could reduce the supply available from the Long Island aquifer.

In summary, a doubled CO_2 atmosphere could produce a shortfall equal to 28 to 42% of planned supply in the Hudson River Basin.

Implications Arising from Other EPA Studies in This Report

Linder and Inglis (Volume H; Chapter 10: Electricity Demand) suggest that increased air conditioning use could raise peak electricity demand by 10 to 30% in the southern half of the United States. Nationally, utilities supplying the northernmost cities could experience decreased demand, while those supplying cities in the remainder of the country could experience electricity needs higher than they have anticipated. Sheer's study of California (see Chapter 14) water supply suggests that new surface water impoundments may be needed to meet urban water needs and other demands. The coastal defense strategies suggested in Chapter 7: Sea Level Rise would apply to most urban coastal areas, especially those along the Atlantic and Gulf coasts.

Changnon et al. (Volume H) conclude that a falling lake level might prompt investment of $200 to $400 million to adapt recreational and commercial harbors and beach facilities, and an investment of $20 million to adjust water supply intakes and sewer outfalls along the Illinois shoreline of Lake Michigan, with similar costs likely on the other Great Lakes. The Keith study (see Chapter 15: Great Lakes) suggests that each commercial harbor on Great Lakes Erie and Superior could spend $5 to $30 million on dredging to maintain harbor access.

RESULTS OF RELATED STUDIES

Metropolitan Water Supply

Schwarz and Dillard (1989) conducted telephone interviews with local infrastructure managers to identify the probable impacts of global climate change on water supply and drainage in several metropolitan areas. Results from some cities are discussed here.

Washington, DC

Longer hot spells could warm the Potomac River and cause trihalomethane formed during chlorination to rise above allowable limits. Remedying this could require a capital investment of roughly $50 to $70 million and could increase treatment costs. Also, lawn watering probably would increase during long spells of hot, dry weather. Although a substantial decrease in runoff could reduce supply in parts of the system, the availability of additional storage capacity would make a shortage unlikely.

New Orleans

Sea level rise could necessitate moving the water intakes considerably farther up the Mississippi and replacing cast iron water mains that would corrode if exposed to saltwater. Reduced riverflow also could increase settling and treatment requirements. Rising sea level could increase saltwater infiltration into the water system and could require increased pumping capacity.

New York City

This study raised many of the same concerns regarding water supply and demand as the study by Walker et al. (Volume H) and indicated that even a 0.25-meter sea level rise would mean the proposed Chelsea intake was too far downstream. The sanitary and storm sewage system capacity and design probably would not need revision. Nevertheless, in a few low-lying areas, higher sea level could increase sewer backups, ponding, and basement flooding when high tides coincided with high runoffs.

Tucson

Tucson is depleting its aquifer despite substantial conservation efforts and lawn watering with treated wastewater. Higher temperatures would increase demand and tighten supply, possibly jeopardizing the city's ability to draw on water from the Central Arizona Project on the already strained Colorado River. While modest savings might be achieved through stricter conservation measures and more wastewater use, purchase of water in the regional market most likely would be the only practical response to climate-related shortfalls.

IMPLICATIONS FOR URBAN INFRASTRUCTURE

The implications of climate change for urban America vary spatially. Some localities, especially those along the Great Lakes, might experience roughly offsetting gains and losses. Others especially those along the coastlines and in watershort areas, could bear increased infrastructure costs. The costs would be especially high if changes came through abrupt "sawtooth" shifts or increases in extreme events, making it difficult to adapt infrastructure primarily during normal repair and replacement. The likely impacts of an effective doubling of atmospheric CO_2 could affect a wide range of infrastructure. Additional climate change effects beyond doubled CO_2 or sea level rise above 1 meter could result in even greater costs.

Water

Hotter temperatures could cause faster evaporation of groundwater and raise the demand for water to support commercial air- conditioning systems and lawn watering. Earlier snowmelt in the West could force a lowering of dam levels to ensure availability of enough capacity to control flood waters. At the same time, sea level rise could cause saltwater to advance up rivers and to infiltrate into coastal aquifers. In droughts, many existing water intakes might deliver brackish water.

The solution to these problems could involve strong conservation measures, such as miles of aqueducts from new water intakes at higher river elevations, new reservoirs, sewage effluent recycling systems to support commercial cooling or lawn watering, and perhaps desalinization efforts along the coasts. The solution for the New YorkPhiladelphia corridor alone is likely to cost $3 to $7 billion. Communities in the Delaware River Basin, northern New Jersey, the lower Hudson, and Long Island might well form a multistate water supply and management district of unprecedented size and complexity to handle financing and capital construction.

Drainage and Wastewater Systems

Increased storm size and intensity could tax many storm sewer systems. Sea level rise also could reduce coastal flood protection levels in low-lying areas. The resulting increases in flooding and releases of untreated waste into watercourses from combined storm and wastewater systems probably would motivate new sewer investments. In Dade County alone, costs to maintain flood protection at existing levels could be $200 to $300 million if sea level rose 1 meter.

Temperature rise could increase hydrogen sulfide formation in sewer pipes, leading to internal corrosion and eventual failure. In coastal areas with increased ocean flooding, storm sewers would carry corrosive saltwater with increased frequency. Sea level rise also could cause more pipes in coastal areas to face the external risk of corrosive seawater. More frequent inspection and earlier replacement of much existing pipe, as well as a gradual shift to more corrosion-resistant pipe with plastic lining, might be required.

Coastal Defenses

Protection from a rising sea could require periodic investment in many major coastal communities. In urban areas, a common approach might be the New Orleans solution, where extensively developed coastal areas are protected by dikes, and covered drainage ditches behind the dikes are pumped to keep out the saltwater.

Roads

Rising temperatures could reduce the costs of road construction and maintenance. Snow and ice control costs might drop dramatically. A decrease in deep freezes and freeze-thaw cycles also would mean fewer potholes. Warmer temperatures and the improved drainage resulting from higher evaporation rates could permit use of thinner pavements in many areas, but could require enhanced expansion capabilities.

Bridges

Sea level rise and increased storm intensity could require upgrading of many bridges either through costly retrofit or as part of normal reconstruction. The range of temperature accommodated by expansion joints also might need to be increased. The costs might be modest if bridge planners upgraded in anticipation of climate change.

Mass Transit

In the North, buses and railcars could experience fewer snow-related delays. Conversely, slight increases in fuel costs could result from increased use of air conditioners.

Electricity and Air-Conditioning

Hotter temperatures could increase air-conditioning use. Consequently, peak load capacity to generate electric power might have to increase in response to global climate change. Fortunately, airconditioning equipment is replaced frequently, so increased loads on existing equipment could be accommodated incrementally. Some houses and public buildings in northern climates might need to add air-conditioning, but such retrofitting has been performed since the first window air conditioners were introduced.

POLICY IMPLICATIONS

The possibility of global climate change increases the risks of infrastructure investment. Application of design standards and extrapolation from historical data still may not provide reasonable assurance that water and power supply, dam strength and capacity, bridge clearances, or storm sewerage capacity will be adequate for the 35-, 50-, and 100-year design cycles of these facilities. For example, the National Flood Insurance Program's maps identifying the historical 100-year floodplain and 500-year floodway may no longer provide a reliable basis for local building and zoning ordinances designed to minimize flood losses to life and property.

Investment Analysis Methods

Especially in coastal areas, the possibility of global climate change may soon require careful decisions regarding how and when to adapt the infrastructure. A strong emphasis on lifecycle costing and upgrading during reconstruction in anticipation of future changes could yield large, long-term cost savings. To accomplish this goal, such institutions as the Department of Housing and Urban Development might work with the American Public Works Association, the National League of Cities, the U.S. Conference of Mayors, the American Planning Association, and similar groups to educate their constituencies regarding the uncertainties and ways to incorporate them into the decisionmaking process.

Water Supply

Water supply is of particular concern because decades are required to plan and complete projects, which then might last 100 years. Dams, reservoirs, and water intakes currently being planned and built could become obsolete or inadequate as a result of global climate change. Elsewhere, communities might be allowing development of land needed for reservoirs to meet the water shortages that would result from climate change.

Such federal agencies as the U.S. Geological Survey, U.S. Army Corps of Engineers, and EPA may wish to work with states and municipalities to study the possible impacts of climate change on the water supply of major metropolitan areas.

Water supply investments frequently affect multistate areas, creating a need for federal coordination. The Supreme Court has been forced to settle previous water rights disputes concerning many major rivers, and global climate change might well generate new disputes. Cost-effective response to climate change also might require new multistate water projects. For example, a major project on the Hudson River that allowed New York City to reduce its use of Delaware River water might be the least costly way to increase water supply in Philadelphia. The upcoming state debates over water supply financing should be informed by the lesson of past infrastructure crises: water piping and pumping costs resulting from global climate change should be fully recovered from the water users to avoid stimulating artificial demand for bargain water.

Infrastructure Standards

Voluntary standards organizations, such as the American Society of Civil Engineers, the Building Officials and Code Administrators International, and the American Association of State Highway and Transportation Officials, may wish to educate their committees on global climate change. Growing uncertainty concerning future temperature, precipitation, and sea levels might dictate a reassessment of existing standards and safety factors for ventilation, drainage, flood protection, facility siting, thermal tolerances, resistance to corrosion, and so forth. Conversely, prompt detection of lasting changes could allow adjustment of geographically based standards -- for example, on roadbed depth and home insulation levels -- and provide significant savings. Thus, the standardmaking organizations might beneficially establish policies concerning how and when their committees should account for global climate change or educate their committees about the prospects.

RESEARCH NEEDS

The following are recommended for further research:

1. More case studies of urban impacts, with priority on a west coast city and an inland city. Issues of particular interest include the effects on subsidence problems in cities similar to Phoenix, the implications for sewage treatment capacity in areas where more frequent and intense periods of low riverflow could reduce acceptable effluent discharge rates, the impact on bridge replacement costs, and the potential for and probable consequences of saltwater infiltration into pipes in older coastal communities.

2. The probable impacts of global climate change on domestic and international migration flows and the infrastructure demands these flows produce. Heat and high water prices might drive jobs and people away from some regions, while others might flourish. Infrastructure investment in new water supply, for example, might be unnecessary in areas that would lose population, but extra capacity might be needed in areas where population would grow. Similarly, as climate change shifts the best growing areas for specific crops, new farm-to-market transportation networks might need to be developed. Rights-of-way for these systems might best be set aside now, before land prices rise in response to climate change.

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