## Appendix A: The Modeling of Sector Impacts for Use in Assessing the Overall Market Impacts of Climate Change

This appendix describes the relationships introduced into IGEM to estimate the overall impacts of climate change. These damage functions or response-surface estimates are based on available data from a variety of impact studies. By using their results to estimate and scale impacts, this study adds empirical content to what often has been an exercise in applying expert judgment (e.g., Nordhaus, 1991; Cline, 1992; Fankhauser, 1995; Tol, 1999; Nordhaus and Boyer, 2000). The response functions portray the degree to which economic processes might be affected through the coming century as climate change trends continue or changes begin to appear. Recognizing the inherent uncertainties reflected in the literature, both optimistic and pessimistic estimates are developed for each sector's response to each of three evolving climate change scenarios.

These relationships are sensitive to the climate variables of temperature, precipitation and sea-level rise. Most of the estimates depict changes in the unit costs of production for various sectors within the economy. Others affect levels of productive spending on investment goods and others influence the quantity and quality of life for U.S. residents. The estimated response functions are applied to the trajectory of climate changes implied by a specific climate change scenario.

The sectors of the economy for which a broad range of outcomes on cost changes due to climate change are available are:

**Crop agriculture**
**Livestock**
**Forestry**
**Fisheries**
**Space heating and cooling**
**Coastal protection**
**Storms, floods and hurricanes**
**Water supply**
**Air quality**
**Health**

Omission of a sector is not meant to imply that no effects are expected, but rather that the net effect of these changes on the market economy currently cannot be adequately or broadly assessed from the available literature.

Estimating impact responses to changes in climate variables is difficult in several respects. First, available studies typically estimate impacts for only a very limited set of climate scenarios. This means that there are only a few data points available for the purposes of estimation. Second, the limited span of the data allows the use of only very simple functional forms, e.g., linear versus non-linear forms. Third, these are inherently dynamic processes with possible discontinuous changes (such as threshold effects). With limited data, these relationships often cannot be adequately characterized. As a result, some studies rely on expert judgment to postulate non-linear relationships. For example, Scheraga et al. (1993) and Nordhaus and Boyer (2000) both hypothesize underlying non-linear relationships. While this can also provide important insights, the difficulty with this approach is its non-empirical subjectivity.

For consistency within IGEM, impact estimates for most of the sectors, including agriculture, forestry, and energy, measure the change in the unit cost of production, holding output or production constant. Figure A-1 illustrates the principle that underlies these impact estimates.

***Figure A-1***

**Conceptual Economic Framework**

**for Measuring the Change in Production Costs**

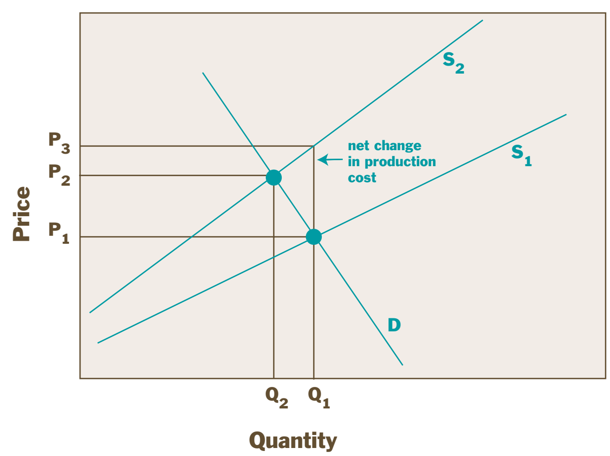


Figure A-1 shows a general supply and demand relationship, with demand given by D and two different supply curves, S1 and S2. S1 represents the supply or the locus of long-run marginal production costs under baseline climate conditions. S2 illustrates the effects of climate change that has served to increase marginal production costs or, equivalently, to decrease productivity implying that the same output now requires more inputs. For the purposes of modeling climate change, interest focuses on the distance corresponding to the change in price from P1 to P3.

The following sections provide details on the development of the impact relationships for each of the sectors.

## A.1. Crop Agriculture

The optimistic estimate is derived from an evaluation of the estimated production changes presented in Table 3.3b of the U.S. National Assessment (USNCCA, 2001). This table gives national average changes in dry land production for all the major crops (assuming adaptation) for both the Canadian Climate (CC) and Hadley Center (HC) models for 2030 and 2090. Several steps were taken to develop estimates using these data so that temperature and precipitation changes could drive the estimated response:

- Changes in annual average temperature and precipitation associated with both the CC and HC models for 2030 and 2090 were developed based on data received from Dr. Benjamin Felzer (NCAR).

- Using crop area data from the 1995 Census of Agriculture (USDA), a weighted average of production changes across crops was developed to estimate an annual average change in total production for the U.S. National Assessment data.

- Then, using the production estimates as a direct proxy for the change in unit production costs, regression coefficients were estimated for temperature and precipitation changes.

- The coefficients then were used to estimate impacts associated with the temperature and precipitation changes under the timelines for each of the three climate change scenarios.

The estimated optimistic relationship between agricultural productivity and climate is:

$$\text{dCost} = [0.016 * \text{dTemperature}] - [0.025 * (\text{dTemperature})^2] + [1.453 * \text{dPrecipitation}] - [0.553 * (\text{dPrecipitation})^2]$$

where dCost, dTemperature, and dPrecipitation are the change in unit production cost, the change in temperature (in °C), and the percentage change in precipitation (in percent), respectively. Note that this is quadratic in changes in both temperature and precipitation and includes the effects of $CO_2$ fertilization in the underlying data upon which it is based.

There is a great deal of uncertainty in identifying a particular temperature-related threshold for the agricultural sector as a whole at a national scale. Agronomic theory, evidence from field experiments, and crop simulation models all suggest the existence of such thresholds for individual crops under region-specific conditions. Heterogeneity across crops, regions, conditions, and water availability makes an accurate determination quite difficult. Techniques such as meta-analysis (which examines multiple studies and models, and controls for variation in crops, regions, and conditions) might offer some additional clarity, but are beyond the current scope. Furthermore, necessary aggregation procedures to produce a specific nation-wide value applicable to agriculture, in general, entails the strong assumption of no adaptation on the part of farmers. That is to say, such a national-scale threshold estimate, were it ever to be identified, would be subject to change and drift as cropping patterns and conditions varied over time and, more importantly, as climate changed and farmers adapted.

For the current purposes of bounding national-scale estimates based on a range of plausible scenario assumptions, it is not necessary that a definitive threshold estimate be identified. It is, however, clearly important that the nature of such a threshold as identified in the existing literature be reflected in the modeling of impacts, so as to best represent and account for important characteristics of the underlying processes.

The objective is to provide IGEM with a specification and set of results for simulating the optimistic scenario for the agricultural sector, while linking this scenario as closely and as consistently as possible to the results and scenarios given by the U.S. National Assessment (2001). The equation above accomplishes this.

The pessimistic scenario is based on the modeling of Adams et al. (1990) in one of the earlier attempts to model the agricultural response to climate change. This study examined agricultural response under two general circulation models (GCMs) for doubled $CO_2$ conditions, the GISS and GFDL models. As before, U.S. average changes in temperature and precipitation from the two GCMs were used to orient the model results to the climate scenarios. Adams et al (1990) present results in the form of price and quantity indices that express the aggregate impacts on the agricultural sector across regions and commodities. These indices can be used to estimate the unit cost changes associated with the two GCMs.

However, given just two data points, there are insufficient statistical degrees of freedom to estimate response coefficients for both temperature and precipitation. To address this limitation, a proxy measure is used to express both the change in temperature and precipitation in a single scalar. With assistance from Dr. David Yates and his 1997 article (Strzepek and Yates, 1997), a water balance model was developed. This model expresses annual run-off as a function of temperature and precipitation. Given the strong relationship observed in data from Adams et al. (1990) between precipitation and agricultural productivity, run-off changes appear a suitable proxy for soil moisture. In turn, this leads to a single-variable model that reasonably associates climate change and agricultural impacts based on the Adams et al. (1990) data.

The water balance relationship given in Strzepek and Yates (1997) appears as:

$$Q_a = P_a \left[ 1 - \frac{L_a}{\sqrt{cL_a^2 + P_a^2}} \right]$$

where $Q_a$ is run-off (mm/yr), $P_a$ is annual precipitation, $L_a = 300 + 25T_a + 0.05T_a^3$, c is a calibration constant (equal to 0.9 for uncalibrated watersheds), and $T_a$ is annual average temperature (°C).

The effects of climate changes on run-off are given by the differentials of the run-off equation with respect to temperature and precipitation changes. A regression model of the change in cost and the change in run-off then is estimated. The estimated pessimistic relationship between agricultural productivity and climate is given as:

$$dCost = -0.013 * dQ_a$$

where dCost is the change in the unit cost of production and $dQ_a$ in millimeters per year is the estimated change in run-off using the water balance relationship given above. As the cost equation indicates, the costs of maintaining agricultural output fall as run-off rises.

## A.2. Livestock

Scheraga et al. (1993) also draw on the earlier efforts of Adams et al. (1993) in constructing models of the impacts of climate change on productivity in livestock production. The optimistic model for livestock production is based on Adams et al. (1993) results for the GISS climate scenario and includes the direct benefits of $CO_2$ fertilization. Formally, the model developed to interpolate and extrapolate the impacts on livestock production is given as:

$$Cost = (100+1.4 * (dTemperature)^{1.5}) * (1-0.16 * L)$$

where Cost is an index of unit cost (relative to a base of 100), dTemperature is the change in the global mean temperature in °C, and L is the logistic function $L=1/(1+exp-(0.022*(CO_2-330)-5))$. The logistic function is designed to capture the beneficial effects of $CO_2$ fertilization in agriculture. Its parameters are set so that its point of inflection occurs at a $CO_2$ concentration of 555 parts per million (ppm). Below 555 ppm, values for L are increasing at an increasing rate while, above 555 ppm, values are increasing at a decreasing rate. The interaction of temperature change and $CO_2$ effects are such that cost benefits for livestock production are sustainable through 2100 and beyond under low warming conditions but erode, beginning in 2080, under high warming conditions. This benefit reversal, like the quadratic expression for crop agriculture, introduces another threshold effect into the set of optimistic driving assumptions.

The pessimistic model for livestock production is based on the Adams et al. (1993) results in the absence of benefits from $CO_2$ fertilization. Here, the index of relative unit cost depends solely on the change in global mean temperature as:

$$Cost = 100+13.49 * (dTemperature)^{1.5}$$

Using this formulation, unit production costs are almost 20 percent higher under low warming conditions and more than double under the higher warming trends. Stated another way, the same inputs generate only 80 percent of the "base" output of livestock under low warming trends and less than 50 percent of the base output under the more severe conditions.

## A.3. Forestry

Forest sector impacts are estimated from the results of Callaway et al. (1995) and Sohngen and Mendelsohn (1999). As with the agriculture estimates, the objective is to estimate the change in the unit cost of production associated with a given change in climate. The best proxy for this is the yield change associated with a change in climate. As in agriculture, yield is the fundamental productivity characteristic that is affected by climate.

The optimistic scenario is derived from data compiled by Dr. Brent Sohngen for the VEMAP project and used to analyze the forest sector in Sohngen and Mendelsohn (1999). The VEMAP project examined the response of ecosystem productivity to changes in climate. Both biogeochemical and biogeographical processes were simulated in the VEMAP project to examine ecosystem productivity changes. The former simulates the fundamental changes in chemical cycling and net primary productivity while the latter simulates the geographic response of vegetation and ecosystem types as they migrate in response to climate change. Of the nine combinations of model types explored in Sohngen and Mendelsohn, this study adopts the combination of the TEM (Melillo et al., 1993) biogeochemical model and the DOLY biogeographical model (Woodward et al., 1995) because this combination is at the higher range of the yield estimates.

Optimistic forestry impact estimates were developed as follows. First, regional productivity changes were averaged, weighted by regional harvests in 1991 (Haynes et al., 1995). Next, annual changes in temperature and precipitation associated with the VEMAP GCMs were constructed based on data provided by Sohngen. Finally, a regression was fit to estimate the coefficients for changes in temperature and precipitation on unit costs (the negative of yield changes). The estimated relationship is given as:

$$dCost = -0.052 * dTemperature + 0.078 * dPrecipitation$$

where the variables are the same as defined earlier. Note here that higher temperatures reduce unit costs while higher precipitation increase unit costs.

The pessimistic scenario is derived from the data used in Callaway et al. (1995). The yield data used in this study were derived from gap model studies that do not explore the results of changes in biogeographical distribution.[1] As a consequence, the estimated effects of climate change are often quite negative.

Callaway et al. give estimated percentage changes in regional softwood and hardwood growing stock (yield) for each of four climate scenarios, 2.5°C with and without $CO_2$ effects, and 4°C with and without $CO_2$ effects. Their study is based on GCM outputs which include precipitation changes consistent with changes in temperature.

Assuming $CO_2$ effects, a weighted average yield change is estimated using regional harvest share data from Haynes et al. (1995). This provides two estimates with two different temperature change

*(1) In addition, gap models do not take $CO_2$ changes into account and, therefore, Callaway et al. (1995) constructed an adjustment factor that is used to mitigate some of the estimated losses.*

assumptions. Regressing on temperature provided the following relationship for estimating pessimistic unit cost changes:

$$dCost = 0.041 * dTemperature$$

## A.4. Fisheries

Rising sea levels due to global warming and measures to protect developed shorelines are expected to result in losses of coastal wetlands. In turn, these will have negative consequences for fish harvests and harvest costs. Titus et al. (1991) estimate the loss of wetlands for 50 centimeter (cm) and 100 cm increases in sea levels. In Scheraga et al. (1993), these results are approximated by:

$$Loss = A * (dSea\text{-}Level)^{0.6}$$

where Loss is the proportion of wetlands lost, dSea-Level is the sea level rise in cm and A is a model parameter. Scheraga et al. estimate that a 50 percent reduction in marsh productivity raises average harvest costs by 12.5 percent. Assuming a linear, one-for-one relationship between the loss in wetlands and the reduction in marsh productivity (Frankhauser, 1993), the effect of sea level rise on harvest costs is given as:

$$Cost = 1+0.25 * Loss = 1+0.25 * (A * (dSea\ Level)^{0.6})$$

where Cost is an index of unit cost for the aggregate commercial fish harvest. In Scheraga et al., the model parameter, A, takes on the value of 0.016 under optimistic conditions and 0.040 for pessimistic outcomes. Under low warming trends, unit costs for commercial fisheries are 2.2 and 5.5 percent higher by 2100 under optimistic and pessimistic conditions, respectively. Under the high warming trends, these percentages rise to 6.3 and 15.7 percent, respectively. On the down side, these results are consistent with more recent estimates by Markowski et al. (1999). However, unlike the smaller optimistic "costs" of Scheraga et al., these authors identify potential cost and production benefits (i.e., lower costs and higher output) in the range of 3.0 to 10.0 percent. While measurable, the impact of fisheries on the overall economy is extremely small as commercial fishing is around 1.1 percent of total agriculture and agriculture is around 3.2 percent of final spending. At a share of 0.03 percent, truly dramatic changes for better or worse will be of little consequence to overall incomes and welfare; they will matter most only to those directly involved in these markets.

## A.5. Space Heating and Cooling

Climate change is expected to change energy use by affecting space heating and cooling requirements (i.e., space conditioning) for both residential and commercial environments. Space conditioning is an important component of energy use, accounting for about 15 percent of total energy expenditures in 1990 (Rosenthal et al., 1995). In the United States, heating expenditures are about 2.3 times those for cooling. Therefore, a moderate general warming is widely expected to generate an average cost savings for space conditioning, particularly in the short run, in which the stock of houses and buildings remains constant. There is also agreement on the existence of a theoretical threshold beyond which cooling cost increases dominate heating cost savings. Additionally, in the long run, adjustments to the stock of houses and buildings may affect the rate at which temperature changes affect energy costs. For example, Morrison and Mendelsohn (1999) suggest that, in a warmer climate, it may be more efficient to reduce investments in capital improvements, such as insulation, which would marginally increase energy use compared to the case where house and building characteristics were held constant.

The goal here is to identify how climate change may affect the energy requirements to produce the level of services currently expected by the control of indoor temperatures. Attempts to measure the impact of warming on energy use have produced a range of results. Rosenthal et al. (1995) estimate energy savings of 6 percent under a 1°C warming and 13 percent under a 2.5°C warming. Nordhaus (1991) and Cline (1992) estimate cost increases of 1 percent and 11 percent, respectively, for a 2.5°C warming. These latter estimates are based largely on changes in electricity use, the primary energy source for space cooling.

Rosenthal et al. (1995) are comprehensive in their examination of energy use. Their model takes into account differences in the use of various energy sources to produce space-conditioning services. The model is regional and considers how warmer temperatures affect the demand for heating and cooling as measured by changes in heating- and cooling-degree days. The model draws on the U.S. Department of Energy's Commercial Buildings Energy Consumption Survey (Energy Information Administration, 1992), and its Residential Energy Consumption Survey (Energy Information Administration, 1993) to estimate the relationships between energy costs and space conditioning demands in the residential and commercial sectors.

Morrison and Mendelsohn (1999) model energy costs and climate change using some of the same dataset as Rosenthal et al. (1995). Their analysis derives from both short- and long-run theoretical models that capture the substitution effects between energy and construction investment. Consistent with the Rosenthal et al. (1995) findings, climate change is likely to reduce unit energy costs in the short-run. However, taking into account long-run changes in house and building characteristics, energy costs could in fact climb by 2 to 4 percent under a 2.5°C warming.[2] While Rosenthal et al. (1995) do not consider changes in building characteristics, there is agreement that, if temperatures rise much beyond 2.5°C, long-run energy costs would rise because cooling cost increases would dominate heating cost savings.

In constructing estimates for IGEM, data were developed from both the Rosenthal et al. (1995) study and from the Morrison and Mendelsohn (1999) study. From Rosenthal et al. (1995), data on space conditioning costs and their estimated change under a 1°C global average warming for both residential and commercial sectors energy and across energy sources (i.e., electricity, natural gas, petroleum, and coal and wood) were used to estimate the cost change associated with a 1°C increase in global average temperature. The percentage changes in costs are weighted by the share of total energy used from each source and by the two sectors, residential and commercial. The result is -5.766 percent per °C change in global average warming. The optimistic estimate appears as follows:

for temperature changes up to 2°C

dCost = -5.766% * dglobal average temperature,

and, for temperature changes beyond 2°C

dCost = 5.766% * (dglobal average temperature - 2°C) + (2°C * -5.766%)

Reversing the weighting scheme in Rosenthal et al. (1995) leads to estimates of cost changes by fuel type. Under optimistic conditions, electricity-based costs increase while space conditioning from coal, wood, oil and gas becomes relatively less expensive and more than compensating.

The overall impact on energy is a two-piece linear relationship, where average costs fall over temperature increases up to 2°C. As temperature changes rise above a 2°C increase, energy costs rise linearly

*(2) Mendelsohn and Morrison argue that changes in the capital stock will most likely result from climate change. For example, insulation requirements will likely fall as a result of climate change and, therefore, consumers can be expected to shift expenditures away from building costs and into higher energy bills, with the understanding that total space conditioning costs, including capital, would be lower.*

at the same rate they were falling. Because Rosenthal et al. (1995) do not identify the point at which the trend reverses, the threshold change identified in Morrison and Mendelsohn (1999) is employed here.

Like agriculture, the threshold assumption and behavior are uncertain. The true threshold may be above or below 2°C and there is no reason that the rates of change in energy costs should be equal above and below this threshold. However, there are no available estimates to suggest something other than a symmetrical relationship and this represents a more plausible assumption than simply continuing the linear fall in energy costs with ever increasing temperatures.

The pessimistic estimates of energy cost changes due to climate change are based on the model and work of Morrison and Mendelsohn (1999). Building on this effort, Mendelsohn and Schlesinger (1999) estimate a reduced-form relationship summarizing the fuller model. The reduced-form equation appears as:

$$\text{Welfare (millions of \$1995)} = -[(251{,}000 + 7380 * \text{Temp} - 368 * \text{Temp}^2) * (\text{GDP}/\text{GDP}_{2060})].$$

From this, the percentage change in the unit cost of energy, dCost, is given as:

$$\text{dCost} = [\text{Welfare (climate change)} / \text{Welfare (baseline)} - 1] / 0.7$$ [3]

Strictly interpreted, IGEM does not represent space heating and cooling among its economic activities. However, within the market demands for coal, wood, refined petroleum products, electricity and natural gas are the uses of these commodities for the purposes of space conditioning. In accounting for the energy effects of climate change, the direct effects are applied to the total outputs of commodities (coal, wood, oil, electricity and gas) in proportion to their use in supplying residential and commercial heating and cooling. Implicit in this scheme is the presumption that the producers in these sectors include those who own and operate the equipment in which these energy inputs are consumed. Also implicit in this scheme is the notion that the outputs of these sectors are not really commodities but, rather, the services these commodities provide (e.g., space conditioning, water and process heating, cooking, motive power, etc.). Viewed in this manner, IGEM can portray the economy-wide adjustments to the energy changes arising from global warming. Success in this portrayal depends on the extent to which a) the relative responsiveness implied for these energy users to price and cost changes is accurate and b) the inability of IGEM to strictly isolate energy products and end

*(3) The scale adjustment dividing the expression by 0.7 is made to reflect the difference between using measures of welfare, which are based on producer and consumer surplus, and changes in the marginal cost of production. The adjustment is exact when demand is relatively inelastic (i.e., -0.35) and when producers are willing to supply all that is demanded at prevailing prices.*

uses (e.g., distillate oil for space heating versus gasoline for automobiles, natural gas for space heating versus natural gas for industrial processes, electricity for air conditioning versus electricity for lighting and appliances, etc.) does not seriously bias the estimated economic outcomes.

## A.6. Water Supplies

Water resources provide a variety of services and have been the subject of many studies related to climate change. Two of the more recent studies that have attempted to estimate the changes in socioeconomic costs include Hurd et al. (1999) and Frederick and Schwarz (1999).

Optimistic estimates are based on market impacts estimated by Hurd et al. (1999). Here, detailed models of four selected watersheds (Colorado, Missouri, Delaware, and Apalachicola-Flint-Chattahoochee) were developed and used to assess the economic impacts of run-off and demand changes under alternative climate scenarios. The welfare changes then were extrapolated to other regions and all then were aggregated to the national level. Mendelsohn and Schlesinger (1999) then estimated a reduced-form equation, similar to the one developed for energy, to relate impacts to changes in precipitation and temperature. This relationship appears as follows:

$$\text{Welfare (millions of \$1995)} = 134{,}000 - (4124 * \text{Temperature}) + (67.4 * \text{Temperature})^2 + (4941 * \text{Average Monthly Precipitation}).$$ [4]

From this, the percentage change in the unit cost of energy, dCost, is given as:

$$\text{dCost} = -[\text{Welfare (climate change)} / \text{Welfare (baseline)} - 1] / 0.7$$

Pessimistic estimates are derived from Frederick and Schwarz (1999). Estimates of the potential impacts of climate change are developed under both the HC and CC GCMs used in the U.S. National Assessment. The authors report total annual additional costs of approximately $105 billion related to water resource services by 2030 under the relatively dry CC scenario and benefits of $4.7 billion under the relatively wet HC scenario. The methodology accounts for forgone opportunity costs associated with water

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*(4) In the United States, the average annual temperature is around 10.7°C. Over the relevant range of temperatures and temperature changes, this function shows welfare declining. The linear term dominates the quadratic term until about 30.6°C, far beyond any projections of temperature rise.*

redirected away from agriculture, for increased conservation efforts, and for ecological services related to streamflow. The costs in Frederick and Schwarz (1999) associated with providing additional supplies are estimated at $45 billion under the CC scenario and $0 under the HC scenario.

To provide a basis of comparison, 1995 water use rates by sector from Solley et al. (1998) combine with the costs by sector of new supplies estimated in Frederick and Schwarz (1999) to yield an average cost across sectors. Per acre foot (af) estimates by sector from Frederick and Schwarz (1999) and the average cost weighted by water use are as follows:

| | |
|---|---|
| 1. public supply | $538/af[5] |
| 2. domestic | $538/af |
| 3. commercial | $538/af |
| 4. irrigation | $50/af |
| 5. livestock | $50/af |
| 6. industrial | $125/af |
| 7. mining | $125/af |
| 8. thermoelectric | $125/af |
| **Average Use Weighted Value** | **$151/af** |

Using $151/af as the average baseline marginal cost of developing additional water supplies, the total baseline cost for current water services is estimated at $77.4 billion per year.[6] The estimated cost increase under the CC scenario is 58 percent (i.e., $45 billion / $77 billion), and under the HC scenario is 0 percent.

The run-off equation developed for agriculture again was applied to estimate the climate response function for these two data points. Run-off changes estimated from temperature and precipitation changes were used to estimate changes in water supply costs yielding the following:

$$dCost = -2.143 * dQ_a/Q_a$$

*(5) The estimated per acre foot costs for the public supply, domestic, and commercial sectors were based on the Frederick and Schwarz's estimated costs for other sectors, which reflect differences in relative regional scarcity, and averaged across all regions.*

*(6) This estimate is derived as the product of total average per capita water use (1,350 gallons per person per day), 365 days per year, 340 million people (projected in 2030), 325,851 gallons/af, and $151/af.*

## A.7. Coastal Protection

Accelerated sea-level rise is expected to impact coastal areas and increase costs to protect developed areas, beaches and other natural habitats. Estimates of the cumulative and annualized costs projected to occur with climate change are available from several sources including Smith and Tirpak (1989), Nordhaus (1991), Frankhauser (1995), and Yohe et al. (1996). As summarized recently in Yohe et al. (1999), these estimates can be used directly along with the estimated rise in sea-level to estimate the direct costs on the economy.

The optimistic estimate is based on the results in Yohe et al. (1996). Here, 50 and 100 centimeter (cm) increases in sea-level yield annualized costs of $0.06 billion and $0.16 billion, respectively. Accordingly, the estimated coefficient for sea-level rise is $1.52 million per centimeter.

The pessimistic estimate is based on Nordhaus (1991), which builds on an earlier EPA effort. In this case, the estimated range of cumulative impacts with a 100 cm rise by 2100 is $73 to $111 billion, which Nordhaus annualizes to approximately $5.0 billion. Therefore, the estimated annualized cost for sea-level rise is $50 million per centimeter.

## A.8. Storms, Floods and Hurricanes

Scheraga et al. (1993) posit an increase in the damages from storms, floods and hurricanes attributable to global climate change. Damages over baseline amounts grow according to the following relation:

$$\text{dCost} = A * (\text{dTemperature}/4)^{1.2} * \text{Cost}$$

where dCost is the additional damage in a given year due to warming, dTemperature is the change in global mean temperature (°C), Cost is the baseline damage estimated for that same year and A is a model parameter. Under optimistic conditions, the value of A is taken as 0.1 and, under pessimistic outcomes, A is 0.5. In Scheraga et al. (1993), baseline damages were presumed to rise over time based on evidence of the increasing frequency, intensity and area of storm, flood and hurricane occurrences (Riebsame et al., 1986). However, in light of more current data (Changnon, 2003, National Climate Data Center, 2003, and Pielke and Landsea, 1998), this analysis assumes no such trend. From these sources, baseline expected damages are estimated at a constant annual average of $7 billion, in year 2000 dollars. Under this formulation and under the low warming trends assumed herein, global climate change increases the expected average annual damages from storms, floods and hurricanes by just over 1 percent, optimistically, and by just over 6 percent, pessimistically. Under the high warming trends of this analysis, these increases rise to 4 and 21 percent, respectively.

## A.9. Health

Changes in temperature are related to fluctuations in the incidence of adverse cardiovascular and respiratory outcomes through thermal stress. Therefore, as temperatures rise, the number of premature cold-related deaths in winter is likely to fall, while the number of heat-related deaths is expected to increase. This section seeks to account for the net effect of these two changes.

Martens (1997) and Kalkstein and Greene (1997) estimate thermal stress mortality rates. Martens presents an optimistic relationship that shows net mortality rates declining in cold temperate regions. Specifically, Martens' (1997) relationship suggests that there will be a reduction of 3 cardiovascular deaths per 100,000 persons under 65 for approximately each 1.2°C warming. This mortality benefit translates into 2.5 net lives saved per 100,000 persons per 1°C warming.

In comparison, Kalkstein and Greene (1997) estimate an overall increase in mortality rates as a consequence of climate change. The Kalkstein and Greene analysis suggests that continued warming has a much greater effect on heat-related mortality in the summer than on cold-related mortality in the winter. Their study examined the effects of climate change on the change in the frequency of "unhealthy" air masses both in winter and summer. Their results for 2050 indicate a mortality cost of 3.8 net lives lost per 100,000 persons per 1°C warming.

## A.10. Air Quality

This section summarizes the analytical efforts of Chestnut and Mills (2000).

Concentration-response functions derived from the epidemiological literature for the effects of changes in ambient ozone concentrations yield a range of health outcomes varying in severity from days where individuals experience minor restrictions in their normal activity, to hospitalizations, and, at the extreme, premature mortality (U.S. EPA, 1999).

Abt Associates (1999) reports estimates of the number of ozone-related hospitalizations, emergency room visits, and symptom days in the 37 Eastern states and the District of Columbia for April through October 1997. One percent of the Abt Associates (1999) values are taken as the starting point estimate of the number of adverse health outcomes that would be attributable to a 1 percent increase in ambient ozone concentrations. These starting values are scaled upward by a factor of 1.28 to account for the population of the remaining Western states not captured in the original Abt Associates (1999) estimates (U.S. Bureau of the Census, 1998). This population adjustment assumes the per capita incidence of these ozone-related outcomes is the same in the East and West.

In this analysis, people and time are the chosen metrics for examining the market consequences of changes in mortality and morbidity. Mortality affects the population as a whole and the discretionary time available to the working-aged population for work and leisure. Morbidity is assumed to affect only the latter.

Table A-1 shows the steps in developing the morbidity effects arising from ozone concentrations. Age distributions of the outcomes in Table A-1 were developed from the 1996 and 1997 National Hospital Discharge Survey, the 1996 and 1997 National Hospital Ambulatory Medical Care Survey and the 1996 National Health Interview Survey. The 1996 and 1997 data from these surveys were averaged to yield the age distributions of occurrences. The shares in column 2 assume that the age distribution of ozone-related outcomes is the same as the age distribution for all outcomes in the same category. For example, the survey data indicate that 33 percent of all cardiovascular hospital admissions in the U.S. are for patients of working age. Therefore, it is assumed that 33 percent of ozone-related cardiovascular hospital admissions also are for patients of working age.

***Table A-1***

### Ozone-Related Labor-Leisure Days Lost From Morbidity Outcomes per 1% Increase in Ozone Concentration

| Health outcome | Estimated ozone-related outcomes for all ages in U.S. (1,000s) | Share of outcomes realized by the working aged population | Labor-leisure days lost per outcome | Fraction of the year relevant to labor-leisure choice (235 days out of 365 days) | Total labor-leisure days lost |
|---|---|---|---|---|---|
| Cardiovascular hospital admissions | 0.20 | 33% | 4.7 | 0.644 | 200 |
| Respiratory hospital admissions | 0.68 | 33% | 5.3 | 0.644 | 766 |
| Respiratory emergency room visits | 2.04 | 51% | 1.0 | 0.644 | 670 |
| Symptom days | 1062.40 | 60% | 0.25 | 0.644 | 102,628 |
| **Total loss in labor-leisure days per 1% increase in ozone concentration** | | | | | **104,264** |

From the National Hospital Discharge Surveys for 1996 and 1997, it is estimated that working-aged individuals had an average length of stay of 4.7 days for a cardiovascular hospitalization and 5.3 days for a respiratory hospitalization. Emergency room visits are assumed to result in the loss of 1 labor-leisure day per occurrence. Ozone-related symptom days are primarily respiratory-related and may include some restriction in activity. Lacking data on how much activity restriction occurs within an average minor restricted activity day, an assumption is made that each occurrence represents the loss of 1/4 of a labor-leisure day.

Finally, it is assumed that ozone-related outcomes occur on both work and non-work days. This results in a 0.644 adjustment assuming 235 out of 365 days are work days. For IGEM, this scalar adjusts the morbidity effects for the assumed fraction of a year over which households make discretionary labor-leisure choices. Table A-1 combines the information on ozone-related outcomes, age-based allocation shares, and labor-leisure days lost per occurrence to produce an annual estimate of the total national ozone-related loss in labor-leisure for a 1 percent change in ozone concentration.

***Table A-2***

**Relationship of Ozone-Related Premature Mortality and Respiratory Hospital Admissions**

| | |
|---|---|
| Premature mortality concentration-response parameter | $5.1 \times 10^{-9}$ |
| Respiratory hospital admissions concentration-response parameter | $16.0 \times 10^{-9}$ |
| Ratio of mortality to respiratory hospital admissions parameters | 0.32 |
| National estimate of ozone-related respiratory hospital admissions | 67,840 |
| Estimated ozone-related premature mortalities | 21,624 |

Ozone-related premature mortalities were calculated using the ratio of the central concentration-response parameter estimate for ozone-related premature mortality and the low concentration-response parameter estimate for ozone-related respiratory hospital admissions provided in BenMod 1.0 Benefits Model for Air Quality Documentation Report (Chestnut et al., 1997). The latter is equivalent to the pooled parameter estimate used in Abt Associates (1999) to calculate respiratory hospital admissions attributable to ozone. This concentration-response parameter ratio was then multiplied by the national estimate of ozone-related hospital admissions (see Table A-1) to estimate ozone-related premature mortalities for 1997. The information used to estimate the number of ozone-related mortalities in 1997 is presented in Table A-2.

From this, Chestnut and Mills (2000) estimate that a 1 percent increase in ozone concentrations is responsible for 216 to 217 premature mortalities.

The ozone-related premature mortality parameter used in this process is a weighted average of the results from a group of nine studies that satisfied a set of study selection criteria such as including controls for particulate matter and using year round data. As a group, these studies found both statistically significant and insignificant effects for ozone on premature mortality. Plausible alternative estimates for the impact of ozone on premature mortality include a lower bound "no effect" estimate, which is supported by the statistically insignificant results in the group and upper bound estimates based on alternative groupings of the statistically significant results. The decision to use the weighted average result from the entire group of studies reflects a desire to incorporate all the data from the studies.

Evidence suggests that some aspects of air quality are strongly affected by climate. Elevated urban and regional oxidant concentrations, in particular ozone, are the result of complex interactions between sunlight, $NO_x$, and other precursors. Given the relationship between oxidant formation and sunlight, ambient ozone concentrations tend to increase with temperature (Penner et al., 1989). This assumes that the increased temperature raises marginal ambient concentrations and does not result in greater efforts to control emissions. Penner et al. (1989) estimate that ambient ozone concentrations could increase between 1 and 2 percent per °C increase in temperature. This analysis assumes the midpoint of this range is 1.5 percent per °C.

For the optimistic scenarios, it is assumed that ozone levels are controlled below standards in the future and that the marginal effect of climate change on ozone formation is negligible. Therefore, there are no labor-leisure days lost or premature mortalities under these conditions.

Assuming that a 1°C increase leads to a 1.5 percent rise in ozone, the pessimistic relationship for morbidity effects is given as:

$$\text{labor-leisure days lost} = 104{,}264 * 1.5\% * dOzone/1°C * dTemperature.$$

The pessimistic relationship for ozone-related mortality effects appears as:

$$\text{premature mortalities} = 216.24 * 1.5\% * dOzone/1°C * dTemperature.$$

Each of these impose costs on the economy as they reduce the household sector's time endowment for labor-leisure choice and/or the nation's population.

## A.11. Modeling Mortality Effects

The mortality effects related to thermal stress (section A.9) and air quality (section A.10) appear as annual changes to the base population and, depending on the person's age, the amount of time available for discretionary work and leisure decisions. These changes are either upward or downward as optimistic or pessimistic circumstances prevail. A premature death avoided is a benefit to the economy until such a time as that person dies anyway, presumably unaffected by climate change. Similarly, a premature death is a cost to the economy until such a time as the person would have died anyway, again, presumably unaffected by climate change. Accordingly, the annual changes in population due to climate change first must be distributed by age group. These, then, are accumulated, also by age group. The annual cumulative benefits or costs are adjusted downward by the cumulative number of persons that just either have (benefit side) or would have (cost side) died anyway. This is a crude overlapping generations calculation in that it does not account for changes in births or actuarial deaths along the way but, nevertheless, avoids large overstatements of the mortality benefits or costs.

***Table A-3***

**Age Distribution of Ozone-Related Premature Mortalities**

| Age group | Estimated premature mortalities in 1997 |
|---|---|
| Less than 1 year | 33 |
| 1–4 | 12 |
| 5–9 | 6 |
| 10–14 | 8 |
| 15–19 | 14 |
| 20–24 | 22 |
| 25–29 | 35 |
| 30–34 | 67 |
| 35–39 | 132 |
| 40–44 | 235 |
| 45–49 | 374 |
| 50–54 | 534 |
| 55–59 | 712 |
| 60–64 | 1,057 |
| Age 65+ | 18,383 |
| **Total** | **21,624** |

The age distribution of mortalities is assumed to be the same as for all respiratory and cardiovascular mortalities reported for 1997 by the Centers for Diseases Control and Prevention (2000). This subset of all deaths is selected because climate-related health outcomes are assumed to be generally associated with respiratory and cardiovascular conditions. Table A-3 shows the age distribution of premature mortalities for ozone-related deaths. The weights implicit in these data are applied to the net lives saved or lost due to thermal stress and to ozone-related deaths to arrive at the age distribution of annual benefits and costs to the population. In turn, these are accumulated to yield the total effects of climate change unadjusted for when these persons should no longer be counted in the stream of benefits or costs.

The departure of individuals from the mortality benefit-cost streams is a lagged reduction in the cumulative deaths avoided or incurred. Table A-4 shows the assumptions used to perform this adjustment. For example, persons aged 20 to 24 are represented by an average 22 year old. This individual is presumed to have 52 years remaining before retirement and 59 years of remaining life. Thus, a 22 year old entering the benefit or cost stream in the year 2020 is no longer counted as a benefit or cost after the year 2072 for labor-leisure decisions, and after the year 2079 for population considerations.

***Table A-4***

**Years Remaining** in the Mortality Benefit-Cost Pool

| Age group | Assumed age | Number of remaining working years | Number of remaining years |
|---|---|---|---|
| Less than 1 year | 1 | 73 | 80 |
| 1–4 | 3 | 71 | 78 |
| 5–9 | 7 | 67 | 74 |
| 10–14 | 12 | 62 | 69 |
| 15–19 | 17 | 57 | 64 |
| 20–24 | 22 | 52 | 59 |
| 25–29 | 27 | 47 | 54 |
| 30–34 | 32 | 42 | 49 |
| 35–39 | 37 | 37 | 44 |
| 40–44 | 42 | 32 | 39 |
| 45–49 | 47 | 27 | 34 |
| 50–54 | 52 | 22 | 29 |
| 55–59 | 57 | 17 | 24 |
| 60–64 | 62 | 12 | 19 |
| Age 65+ | 70 | 4 | 11 |