APPENDICES

APPENDIX A
GLOSSARY OF CLIMATE AND AIR QUALITY TERMS

***Aerosols* --** Solid or liquid particles suspended within the atmosphere. Examples are sulfate particles, which reflect light, and black carbon particles, which absorb light.

Anthropogenic Emissions -- Gaseous and particulate pollutants (or precursors to pollutants) that are released into the atmosphere as a consequence of human activities.

Anthropogenic Secondary Organic Aerosols -- Secondary organic aerosols that are formed from anthropogenic precursors.

Atmospheric Processes -- Processes affecting the formation, removal, and distribution of energy, momentum, gases, aerosols, and clouds within the earth's atmosphere as a function of time and space. Examples include gas-phase chemistry, heterogeneous chemistry, aqueous-phase chemistry, gas-to-particle conversion, radiative transfer, nucleation of particles, evaporation of particles, wet and dry deposition, formation of clouds, emissions, and horizontal and vertical transport processes.

Attainment Area -- A geographic area in which levels of a given criteria air pollutant fall below the health-based primary national ambient air quality standard (NAAQS) for the pollutant. An area may have on acceptable level for one criteria air pollutant and unacceptable levels for others. Thus, an area could be both attainment and non-attainment at the same time. Attainment areas are defined using federal pollutant limits set by EPA.

Biogenic Emissions -- Emissions of gaseous and particulate pollutants and precursors to pollutants from natural sources, such as plants and trees.

Clean Air Act -- The original Clean Air Act was passed in 1963, but the national air pollution control program is actually based on the 1970 version of the law. The 1990 Clean Air Act Amendments are the most far-reaching revisions of the 1970 law. In this summary, the 1990 amendments are referred to as the 1990 Clean Air Act.

***Climate* --** The long-term average weather of a region, including typical weather patterns, the frequency and intensity of storms, cold spells, and heat waves. Climate is not the same as weather; it is the average pattern of weather for a particular region. Climatic elements include precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost, and hail storms, and other measures of the weather.

Climate Forcing -- The earth's climate changes when the amount of energy stored by the climate system is varied. The most significant changes occur when the global energy balance between incoming energy from the sun and outgoing heat from the earth is upset. There are a number of natural mechanisms that can upset this balance, for example fluctuations in the earth's orbit, variations in ocean circulation, and changes in the composition of the atmosphere. Changes in the composition of the atmosphere can occur due to man-made pollution, through emissions of greenhouse gases. By altering the global energy balance, such mechanisms "force" the climate to change. Consequently, scientists call them "climate forcing" mechanisms.

Climate Change -- Changes in long-term trends in the climate, such as changes in average temperatures. In Intergovernmental Panel on Climate Change (IPCC) usage, climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. In United Nations Framework Convention on Climate Change usage, climate change refers to a change in climate that is attributable directly or indirectly to human activity that alters atmospheric composition.

Climate System -- The global climate system is made up of the atmosphere, the oceans, the ice sheets (cryosphere), living organisms (biosphere) and the soils, sediments and rocks (geosphere), which all affect the movement of heat, momentum, and moisture, around the earth's surface.

Climate Variability -- Deviations of climate statistics over a given period of time (such as a specific month, season, or year) from the long-term climate statistics relating to the corresponding period.

Criteria Pollutants -- Under the federal Clean Air Act, EPA has identified six major air pollutants that have adverse effects on public health and the environment called "criteria air pollutants:" ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, particulate matter, and lead. EPA has set National Ambient Air Quality Standards for each of these criteria pollutants to protect public health and the environment.

Downscaling -- Methods to obtain high spatial resolution data from a coarser scale atmospheric or coupled oceanic-atmospheric circulation model run on the global domain. Downscaling can be achieved using fine spatial scale (mesoscale) meteorological models (referred to as "dynamical downscaling") or statistical relationships ("statistical downscaling").

Emissions -- Release of substances (e.g., greenhouse gases) into the atmosphere or the substances themselves.

Energy Security -- The stable supply of energy resources to the main consumers. Increasingly, energy security is viewed as a much broader concept that extends to the extraction, transport, and sale of energy.

General Circulation Model (GCM) -- A computer model of the basic dynamics, physics of and internal interactions of the global climate system (including the atmosphere and oceans) and their interactions. GCMs used to simulate climate variability and change.

Global Warming Potential (GWP) -- A system of multipliers devised to enable warming effects of different gases to be compared. The cumulative warming effect, over a specified time period, of an emission of a mass unit of CO_2 is assigned the value of 1. Effects of emissions of a mass unit of non-CO_2 greenhouse gases are estimated as multiples. For example, over the next 100 years, a gram of methane in the atmosphere is currently estimated as having 23 times the warming effect as a gram of carbon dioxide; methane's 100-year GWP is thus 23.

Greenhouse Effect -- The insulating effect of atmospheric greenhouse gases (e.g., water vapor, carbon dioxide, methane, etc.) that keeps the earth's temperature about 60°F warmer than it would be otherwise.

Greenhouse Gas (GHG) -- Any gas that contributes to the "greenhouse effect."

Indirect Effects --As opposed to direct effects of aerosol particles on radiative forcing due to the scattering and absorption of light, indirect effects are due to the ability of some particles to act as cloud condensation nuclei. This changes the number of droplets in clouds and their size distribution, which alters precipitation, cloud extent and lifetime. Because of the reflection of solar radiation by clouds and other interactions between clouds and radiation, there is an indirect forcing of the global system from aerosols via their effects on clouds. Another potential indirect forcing involves the heterogeneous chemistry involving aerosols and greenhouse gases.

Intergovernmental Panel on Climate Change (IPCC) -- The IPCC was established in 1988 by the World Meteorological Organization and the UN Environment Program. The IPCC is responsible for providing the scientific and technical foundation for the United Nations Framework Convention on Climate Change, primarily through the publication of periodic assessment reports.

Mean Climate -- The average of climate variables over a spatial domain or temporal period. For example, the mean sea surface temperature is a measure of climate change. A mean precipitation over a 5-year period may be calculated for a future scenario to average out the year-to-year variability.

Mesoscale -- A spatial dimension ranging from 2 to 2000 km. This is the typical spatial scales of urban air pollution, local winds, thunderstorms, etc.

Meteorology -- The science that deals with the phenomena of the atmosphere, especially weather and weather conditions. Weather is the day-to-day changes in temperature, air pressure, moisture, wind, cloudiness, rainfall, and sunshine.

Negative Feedback -- A process that results in a reduction in the response of a system to an external influence. For example, increased plant productivity in response to global warming would be a negative feedback on warming because the additional growth would act as a sink for CO_2, reducing the atmospheric CO_2 concentration.

Nonattainment Area -- A geographic area in which the level of a criteria air pollutant is higher than the level allowed by the federal standards. A single geographic area may have acceptable levels of one criteria air pollutant but unacceptable levels of one or more other criteria air pollutants; thus, an area can be both attainment and nonattainment at the same time. It has been estimated that 60% of Americans live in nonattainment areas.

Non-Radiative Forcing -- A process or change that leads to energy redistribution within the global climate system, but does not directly affect the energy budget of the atmosphere. Processes that induce non-radiative forcing usually operate over vast time scales (10^7 to 10^9 years) and mainly affect the climate through their influence over the geometry of the earth's surface, such as location and size of mountain ranges and position of the ocean basins.

Positive Feedback -- A process that results in an amplification of the response of a system to an external influence. For example, increased atmospheric water vapor in response to global warming would be a positive feedback on warming, because water vapor is, itself, a GHG. Increases in water vapor in association with increases in greenhouse gases would cause greater warming than would occur if water vapor remained constant.

Radiative Forcing -- Changes in the energy balance of the earth-atmosphere system in response to a change in factors such as greenhouse gases, land-use change, or solar radiation. The climate system inherently attempts to balance incoming (e.g., light) and outgoing (e.g., heat) radiation. Positive radiative forcings increase the temperature of the lower atmosphere, which in turn increases temperatures at the earth's surface. Negative radiative forcings cool the lower atmosphere. Radiative forcing is most commonly measured in units of watts per square meter (W/m^2).

Regional Scale -- A geospatial scale in the global climate-air quality field that is relative rather than absolute. For applications of global circulation models, examples of regions may be North America, Africa, or South Pacific Ocean. For applications within the continental U.S., examples of regions may be Northeastern U.S., the Upper Midwest, or the Pacific Northwest.

Secondary Organic Aerosols (SOA) -- Carbonaceous aerosols that are not emitted but produced in the atmosphere. Typically, precursor gases (such as aromatic hydrocarbons, monoterpenes) undergo chemical reactions, condensation, and other atmospheric processes to form SOA.

Sequestration -- The removal of atmospheric CO_2, either through biological processes (e.g., plants and trees), or geological processes through storage of CO_2 in underground reservoirs.

Sinks -- Any process, activity, or mechanism that results in the net removal of greenhouse gases, aerosols, or precursors of greenhouse gases from the atmosphere.

SRES Scenarios -- A suite of emissions scenarios developed by the Intergovernmental Panel on Climate Change in its Special Report on Emissions Scenarios (SRES). These scenarios were developed to explore a range of potential future greenhouse gas emissions pathways over the 21st century and their subsequent implications for global climate change.

***State Implementation Plan* (SIP)** -- A detailed description of the programs a state will use to carry out its responsibilities under the Clean Air Act. A SIP is a collection of the regulations used by a state to reduce air pollution. The Clean Air Act requires that EPA approve each SIP. Members of the public are given opportunities to participate in review and approval of SIPs.

Stratosphere -- The region of the Earth's atmosphere 10-50 km above the surface of the planet.

Thermohaline Circulation (THC) -- A 3-dimensional pattern of ocean circulation that is driven by wind, heat, and changes in salinity. Thermohaline Circulation is responsible for distributing energy, as heat, and matter, as dissolved solids and gases, throughout the global ocean-atmosphere climate system. In the Atlantic, wind-driven surface currents transport warm tropical surface water northward where it cools and then sinks into the deep ocean. The deep ocean current is driven south, beneath the tropical oceans, eventually warming and rising to the surface in the North Pacific. Global warming is projected to increase sea-surface temperatures, which may slow the THC process by reducing the sinking of cold water in the North Atlantic. In addition, ocean salinity influences water density, and, thus, decreases in sea-surface salinity from the melting of ice caps and glaciers may also slow THC. Other terms for THC include, "the ocean conveyor belt," "the great ocean conveyer," "the global conveyor belt," and "the meridional overturning circulation."

***Troposphere* --** The region of the atmosphere 0 to approximately 10 km above the earth's surface.

Tropospheric Ozone -- Ozone in the lower atmosphere (troposphere) or near ground is considered to be one of the pressing air quality issues. Most ground-level ozone is formed indirectly by the action of sunlight on volatile organic compounds in the presence of nitrogen dioxide and, as such, is a secondary pollutant. There are no direct man-made emissions of ozone to the atmosphere. During photochemical smog episodes, levels can rise to over 100 ppb. Ozone episodes are likely to develop following sustained periods of warmth and calm weather. Once formed, ozone is scavenged by nitric oxide, usually present in urban areas as a result of traffic fumes and less so in the countryside. Consequently, ozone usually occurs in higher concentrations during summer than winter, and in urban rather than rural areas. Background levels of ozone are usually less than 15 ppb but can be as high as 60 ppb.

Tropopause **--** The transitional region between the stratosphere and the troposphere.

Weather -- Weather is the specific condition of the atmosphere at a particular place and time. It is measured in terms of such things as wind, temperature, humidity, atmospheric pressure, cloudiness, and precipitation. In most places, weather can change from hour-to-hour, day-to-day, and season-to-season.

APPENDIX B
U.S. AIR QUALITY: ITS SENSITIVITY TO METEOROLOGY AND EARLY STUDIES OF THE EFFECT OF CLIMATE CHANGE

B.1. INTRODUCTION

This appendix offers information that can serve as a point of reference for evaluating the significance of the projections of meteorological and air quality change discussed in this report. The first section addresses the role of meteorology in determining air quality, followed by a discussion of the observed regional patterns in ozone (O_3) concentrations and meteorological sensitivities. The discussion draws from the open literature and extensive summaries found in the U.S. EPA Air Quality Criteria Documents for O_3 and Particulate Matter (U.S. EPA, 2006, 2004). This appendix concludes with a survey of the climate and air quality literature from earlier modeling efforts and more recent studies conducted independently from the EPA GCRP air quality program.

B.2. THE LINKS BETWEEN METEOROLOGY, BIOGENIC AND EVAPORATIVE EMISSIONS, AND AIR QUALITY

The link between meteorology and extreme ground-level PM and O_3 concentrations is well understood by the air quality management community. The earliest recorded incidences of extreme PM concentrations in London took place in wintertime during periods with low temperature, fog, and low wind speeds (stagnant conditions) (Brimblecombe, 1987). However, the relationship between meteorology and air quality can be complex. Observations of urban O_3 concentrations as a function of ground-level temperature provide an example of this complexity. However, the relationships between O_3 concentrations and any specific predictor are location-specific, e.g., relationships observed in one area may not be readily extrapolated to another.

In addition to temperature, other factors, such as wind speed and direction, humidity, and precipitation frequency, are also known to be important determinants of air quality. Very often, however, individual meteorological variables are closely associated with other air quality-relevant meteorological properties, making simple sensitivity relationships difficult to establish. For example, high surface temperatures are often associated with clear skies and strong inversion layers, making it difficult to establish a causal relationship between any of the given factors and high O_3 concentrations. Nevertheless, strong relationships between pollutant concentrations and simple, easily measured meteorological variables, i.e., temperature and wind speed, have been derived and can inform an analysis of the potential impacts of a warming climate on air quality.

This section discusses the links between specific meteorological variables and air quality. Ozone and PM are often similarly affected by changes in these variables. Therefore, the links between meteorology, O_3, and PM are discussed together. Exceptions, such as the distinctive role of precipitation in determining ambient PM concentrations, are noted.

B.2.1. Surface Temperature

Local O_3 formation depends on atmospheric conditions such as the availability of solar ultraviolet radiation capable of initiating photolysis reactions, air temperatures, and the concentrations of chemical precursors. Daily maximum temperature is one of the strongest predictors for O_3 pollution (Cox and Chu, 1996; U.S. EPA, 2003; Anderson et al., 2001; Vukovich and Sherwell, 2003).

Secondary pollutants, including ozone (O_3) and other photochemical oxidants, particulate sulfate, nitrate, ammonium, and secondary organic aerosols (SOA), are formed in the ambient atmosphere via chemical reactions that take place in the gas phase, on particle surfaces, or in cloud droplets. In many cases, the chemical rate constants for these reactions are temperature sensitive. Furthermore, high surface temperatures are often associated with high levels of solar radiation, e.g., clear skies, leading to increased photochemical smog production. High ambient temperatures can also influence the emissions of anthropogenic and biogenic volatile organic compounds (VOCs) —important precursors of both O_3 and PM.

B.2.2. Temperature Effects on Anthropogenic VOC Emissions

There are direct and indirect effects of climate change on anthropogenic emissions. Direct effects are typically related to the enhanced evaporation of volatile chemicals at higher temperatures. In particular, VOC emissions from fugitive sources and mobile sources (U.S. EPA, 2002) are expected to increase with temperature. Evaporative emissions of the VOCs found in fuel occur during fuel transfer processes and from storage tank and fuel line leakage. This source, accounting for nearly half of all evaporative emissions, contributes significantly to the U.S. ground-level ozone problem.

B.2.3. Temperature Effects on Biogenic Emissions

Biogenic VOCs serve as precursors for both O_3 and secondary organic $PM_{2.5}$. Isoprene has been shown to produce low yields of organic $PM_{2.5}$ (Kroll et al., 2005). However, since isoprene is the most abundant hydrocarbon emitted into the atmosphere after methane, even low yields can produce significant levels of organic $PM_{2.5}$. Isoprene and terpenoid compounds, another source of secondary organic aerosols, are emitted by vegetation. These emissions increase exponentially with temperatures up to a species-dependent limit in the range of 35-40°C (e.g., Geron et al., 1994; Constable et al., 1999; Sanderson et al., 2003; Lathière et al., 2006; Steiner et al., 2006.).

B.2.4. Temperature and Aerosol Thermodynamics

For semi-volatile particulate species (nitrate, ammonium, secondary organic aerosols), climate change could be expected to affect gas/particle partitioning. First, gas/particle equilibrium may shift towards the gas phase at higher temperatures because the saturation vapor pressures of semi-volatile compounds increase with temperature. Thermodynamics dictates that the saturation vapor pressure, which is the capacity of air to hold vapors of a trace gas, increases with increasing temperature. Second, temperature and relative humidity (RH) affect the water content of particles. Aw and Kleeman (2003) modeled the formation of secondary particles in an environment at elevated temperatures and found that even though the production of some condensable gases (e.g., HNO_3) is increased, the partition of condensable material to the particle phase is suppressed when the temperature is increased by 2-5ºC. As a result, both the total mass and size distributions of particles are predicted to decrease.

B.2.5. Atmospheric Stability

Dry deposition is a function of the aerodynamic resistance of the bulk atmosphere, the quasi-laminar sublayer resistance near the surface, and the chemical-specific surface resistance for the gas. The fall velocity of a particle due to gravity and the aerodynamic and laminar sublayer resistance control the overall dry deposition velocity of a particle. Changes in climate can affect the aerodynamic resistance, which depends on the atmospheric stability. Changing temperature and RH can affect the size of particles due to gas-particle partitioning, hence altering their fall velocities.

B.2.6. Mixing Height

Mixing conditions are governed by both synoptic scale pressure systems and local diurnal temperature and humidity changes. The development of the mixing layer is an important controlling factor for air pollution episodes. Stable conditions that typically occur at night, over water or during winter, significantly limit the amount of vertical mixing of pollutants, whereas unstable conditions typical of warm daytime conditions enhance vertical mixing.

The city of Los Angeles is a well-studied example of the air quality consequences of a strong inversion layer. The confluence of a strong temperature inversion with high summertime temperatures effectively creates a closed, heated reaction vessel that amplifies the photochemical production of secondary pollutants, like O_3. (Jacobson, 2002) Other western cities within the

U.S. are subject to strong inversions, especially those located adjacent to mountains, such as Salt Lake City and Denver.

B.2.7. Humidity

Water vapor participates in the suppression of O_3 formation by reacting with the O(1D) radical, the most important precursor to tropospheric O_3 formation. Relative humidity is also a predictor of PM in the southwestern U.S. (Wise and Comrie, 2005). High humidity conditions lead to the partitioning of water into particles. Additional particle water facilitates further partitioning of gas-phase water-soluble compounds into the particle phase (e.g., Liao et al., 2006). When aqueous-phase oxidants, such as peroxides and hydroxyl radical, are present, aqueous-phase oxidation reactions can lead to acidic compounds that alter the particle pH, further enhancing the partitioning of water-soluble compounds.

B.2.8. Wind Speed and Direction

High winds are typically associated with ventilated conditions and disperse air pollution near source areas. However, strong winds can also enhance transport of polluted air to downwind locations. Lower winds are typically associated with stagnant conditions, and stagnant conditions have been found to be associated with high PM and O_3 concentrations (e.g., Pun and Seigneur, 1999; Ellis et al., 2000; Pun et al., 2000). Therefore, wind speeds play a role in the accumulation of air pollutants (e.g., Gebhart et al., 2001, Wise and Comrie, 2005). In addition, changing wind patterns associated with climate change can affect the frequency with which pollution plumes are carried to a specific location (e.g., Mickley et al., 2004).

Land-sea breezes affect the concentration and dispersal of pollutants in coastal zone cities. However, the presence of mountain barriers limits mixing (as in Los Angeles) and results in a higher frequency and duration of days with high O_3 concentrations.

Ozone concentrations in southern urban areas (such as Houston, TX and Atlanta, GA) tend to decrease with increasing wind speed. In northern cities (such as Chicago, IL; New York, NY; Boston, MA; and Portland, ME), the average O_3 concentrations over the metropolitan areas increase with wind speed, indicating that transport of O_3 and its precursors from upwind areas is important (Schichtel and Husar, 2001).

Resuspension of dust and previously deposited particles increases with increasing wind speeds. Emissions of sea salt particles are a strong function of wind speed (Gong et al., 1997).

B.2.9. Cloud Cover and Precipitation

Global climate change may alter the distribution of clouds (Stevenson et al., 2005). Changing cloud distributions will correspondingly alter photochemical oxidation rates in the areas affected.

Wet deposition of PM is a function of the form and amount of precipitation. At locations where climate change alters the precipitation pattern (rain vs. snow), frequency, and intensity, removal of particles and soluble gases by wet deposition may be increased or reduced (e.g., Langer et al., 2005; Sanderson et al., 2006).

B.3. REGIONAL PATTERNS IN THE O_3 CONCENTRATION RESPONSE TO METEOROLOGY

While the time series is too short to provide insight into the long-term role of climate in determining O_3 concentrations, statistical analyses of the U.S. O_3 observational dataset have shown consistent spatial patterns in the relationship between meteorological variables and O_3 production.

These patterns can serve as a useful reference from which to interpret the climate-based projections presented in this report. The variability in annual and seasonal meteorology reduces the predictability of air quality, introducing a noisy "background" on the temporal record of observed air pollution concentrations. This background noise makes detection of the long-term effect of emissions control programs difficult. The air quality science and regulatory community has applied a variety of statistical techniques to the problem of removing meteorological noise from the air quality record, with a high level of success (Cox and Chu, 1993).

In addition to isolating the downward trend in O_3 levels, consistent with declining precursor emissions, from the variable background, the statistical analyses of the air quality record have revealed regionally-oriented air quality sensitivities to specific meteorological variables. The results of these studies suggest a major role for synoptic-scale, as well as local-scale, meteorology in determining air quality. The studies discussed below identified distinctive, regionally specific meteorological sensitivities in regional pollutant concentrations. Useful insights into the impacts of climate change on regional air quality may be found in the comparison of these observed patterns to those synoptic-scale changes projected to occur under different GHG emissions scenarios.

Eder et al. (1994) used a cluster analysis to identify seven meteorological regimes in the Eastern half of the U.S. that affect O_3, each of which can be represented by a multivariate regression model based on temperature, wind speed and direction, pressure, cloud cover, dew point, solar insolation, mixing height, and upper air temperature, dew point, and wind speed and direction. Camalier and Cox (2007), using an alternative approach and observational data taken from the U.S. EPA AQS database, have also identified a series of distinctive regions that are distinguished by the relative sensitivity of O_3 concentration sensitivities to different meteorological variables. Figure B-3 provides a map of these regions and the two most important variables related to O_3 air quality for each region.

Lehman et al. (2004) analyzed the AQS database of daily 8-hr maximum O_3 concentrations collected in the EPA AQS database for 1,090 stations in the eastern half of the U.S. for the 1993 to 2002 period. They applied a rotated principle component analysis to a reasonably complete, spatially representative, non-urban subset of the database in order to identify coherent, regionally oriented patterns in O_3 concentrations. Five spatially homogenous regions were identified: the U.S. Northeast, Great Lakes, Mid-Atlantic, Southwest (including Alabama, Louisiana, Texas, Oklahoma), and Florida. The Mid-Atlantic region displayed the highest mean concentration (52 ppb) of all of the regions analyzed, followed by the Great Lakes, Southwest, and Northeast regions with around 47 ppb. The average concentration derived for Florida was 41 ppb. The authors found strong correlations in measured concentrations among stations within the same region, suggesting that the geospatial patterns of pollutant emissions and meteorological activity may also have a regional orientation. These results suggest that these regions may define natural domains for regional scale modeling studies of the influence of O_3 (as well as PM) on climate.

Camalier et al. (2007) also identified a north-south gradient in the eastern U.S. with respect to the importance of changes in temperature and humidity on O_3 concentrations. Their result suggests that the northeastern U.S. is more susceptible to temperature-induced increases in O_3. It has been suggested that the effect may be attributed to the fact that, currently, the Northeast is subject to a greater range of possible temperature changes during a typical O_3 season—including periods of lower-than-average temperatures—resulting in a regional capacity for additional warm, high O_3 days. The characteristically warmer temperatures and narrower range in temperature variation in temperatures in the Southeast is consistent with the observed lower O_3 sensitivity to temperature. (See Figure B-4)

B.4. CLIMATE CHANGE AND U.S. AIR QUALITY: EARLY AND EXTERNAL STUDIES

Early studies of the potential effect of a warming climate, specifically on U.S. ozone levels, include an evaluation of the consequences of a hypothetical 4°C increase in temperature across horizontal, vertical, and temporal scales (Morris et al., 1989; Morris et al, 1995). The Morris et al. (1989) study modeled specific episodes and projected increased O_3 concentrations ranging from 3-20% in a simulation of Central California and from -2.4-8% for simulations of the

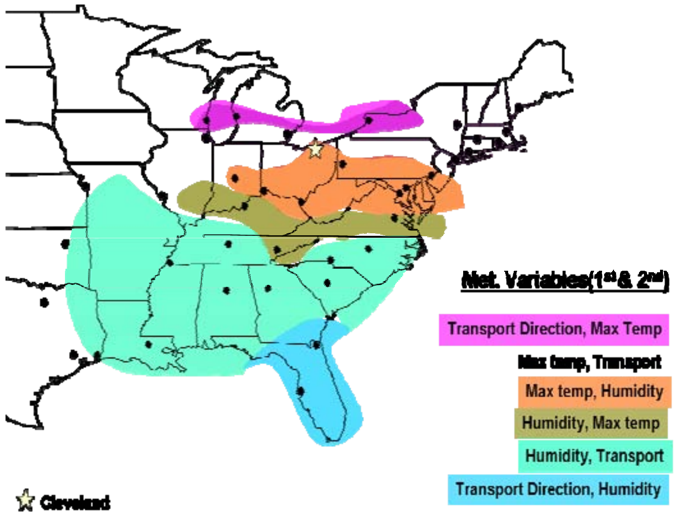

Figure B-3. Patterns of O_3 sensitivity to wind direction, temperature, and humidity, in the eastern portion of the U.S.

Ozone Response to Temperature (Positive response) | Ozone Response to Relative Humidity (Negative response)

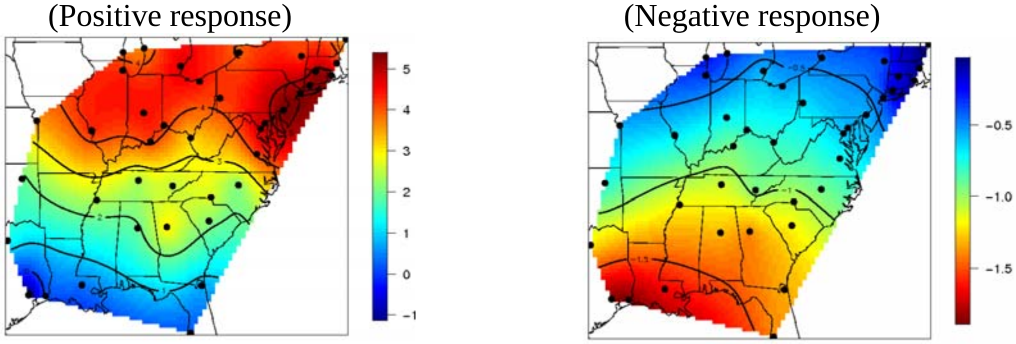

Figure B-4. Trends in ambient O_3 concentration sensitivities with respect to temperature and humidity.

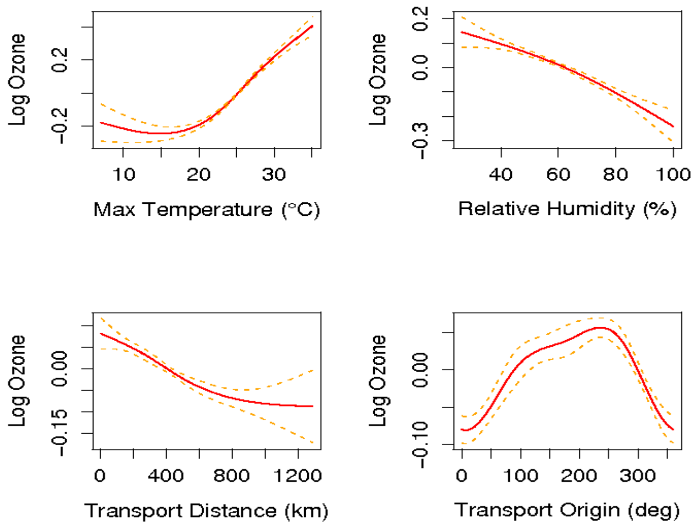

Figure B-5. Ozone response to changes in the four important meteorological parameters affecting ozone for Cleveland, OH. *Panel A:* the O_3 response to temperature is relatively small for temperatures below ~20°C but is strongly positive above 20°C. Panel B: Decreasing O_3 with increasing relative humidity reflects increased cloudiness and atmospheric instability. Panel C: O_3 concentrations are inversely proportional to transport distance, e.g., the distance traveled by the incoming air mass over the previous 24-hours, reflecting the dilution effect of higher wind speed. For Cleveland, the largest increment in ozone occurs when transport winds are from a southwesterly direction (i.e., 200 to 250 deg).

Midwest and Southeast. Morris et al. (1995) included the effect of warmer conditions on mobile source and biogenic emissions in their simulation of a 4-day episode in the Northeast. In that simulation, O_3 concentrations increased 15-25 ppb in much of the modeling domain, above baseline concentrations of 110-120 ppb range and 120-140 ppb range (10-20% increase).

In a recently study, Murazaki and Hess (2006), employing an approach that is similar to one of the approaches used by GCRP-supported STAR researchers, modeled global-scale atmospheric chemistry driven by a climate modeled for an IPCC A1 SRES scenario. They fixed U.S. emissions at 1990 levels and projected U.S. surface O_3 levels for the 2090-2100 timeframe to estimate the effect of a changing climate. The impact of climate change on U.S. surface O_3 levels is investigated. They found that the response of O_3 to climate change in polluted regions is not the same as in remote regions, i.e., a 0–2 ppbv decrease in background O_3 in the future simulation over the U.S. but an increase in O_3 produced internally within the U.S. of up to 6 ppbv. They attributed the decrease in background O_3 to a future decrease in the lifetime of O_3 in low NO_x regions. They also noted that the decrease in background O_3 roughly cancels any increase observed for the Western U.S. and concluded that the Eastern U.S. will be most impacted by climate-induced O_3 increases, i.e., upwards of 5 ppbv. They predicted that in the future over the northeastern U.S., up to 12 additional days each year will exceed the maximum daily 8-hour averaged O_3 limit of 80 ppbv. They attribute the net future increases in O_3 that they detected in their model results to various climatic factors including changes in temperature, water vapor, clouds, transport, and lightning NOx.

Other efforts to relate climate change and air quality have used the sensitivity approach, where important meteorological parameters known to impact air quality are perturbed one at a time. Several groups studied the response of O_3 and PM to increased temperature (e.g., Aw and Kleeman, 2003; Kleinman and Lipfert, 1996; Sillman and Samson, 1995). Aw and Kleeman (2003) found that within the Los Angeles basin, daily O_3 maximum concentrations are not very sensitive to temperature in areas with abundant NO_x emissions but increase by 7 to 16 ppb at downwind locations. Sillman and Samson (1995) studied the response of O_3 to temperature in other urban and polluted rural environments and suggested that the increase in O_3 is due to increased peroxyacetylnitrate (PAN) dissociation at higher temperatures. Thermal degradation of PAN releases NO_x, allowing it to participate in photochemical O_3 production.

Due to the role of NO_x chemistry in urban areas, the response of O_3 to climate change in urban areas may be different from the response of rural or background O_3 where NO_x chemistry is less important. Aw and Kleeman (2003) investigated the formation of secondary particles in an environment with elevated temperatures and found that even though the production of some condensable gases (e.g., HNO_3) is increased, the partition of condensable material to the particle phase is suppressed when the temperature is increased by 2-5ºC. As a result, both mass and size of particles are predicted to decrease.

B.5. REFERENCES

Anderson, HR; Derwent, RG; Stedman, J. (2001) Air pollution and climate change. In: McMichael, AJ; Kovats, RS, eds. Health effects of climate change in the UK. London, UK: Department of Health; pp.193-201. Available online at http://www.dh.gov.uk/assetRoot/04/06/89/15/04068915.pdf (accessed 29 Aug 2006).

Aw, J; Kleeman, MJ. (2003) Evaluating the first-order effect of intraanual temperature variability on urban pollution. J Geophys Res 108(D12):4365, doi: 10.1029/2002JD002688.

Brimblecombe, P. (1987) "The Big Smoke: A History of Air Pollution in London Since Medieval Times," Routledge Kegan & Paul.

Camalier, L; Cox, WM; Dolwick, P. (2007) The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. Atmospheric Environment 41:7127–7137.

Constable, JVH; Guenther, AB; Schimel, DS; et al. (1999) Modelling changes in VOC emissions in response to climate change in the continental United States. Glob Change Biol 5(7):791-806.

Cox, W.M., Chu, S., 1993. Meteorologically adjusted ozone trends in urban areas: a probabilistic approach. Atmospheric Environment 27B: 425–434.

Cox, WM; Chu, SH. (1996) Assessment of interannual ozone variation in urban areas from a climatological perspective. Atmos Environ 30(14):2615-2629.

Eder, BK; Davis, JM; Bloomfield, P. (1994) An automated classification scheme designed to better elucidate the dependence of ozone on meteorology. J Appl Meteorol 33(10):1182-1199.

Ellis, AW; Hildebrandt, ML; Thomas, WM; et al. (2000) Analysis of the climatic mechanisms contributing to the summertime transport of lower atmospheric ozone across metropolitan Phoenix, Arizona, USA. Climate Res 15:13-31. Available online at http://www.int-res.com/articles/cr/15/c015p013.pdf.

Gebhart, KA; Kreidenweis, SM; Malm, WC. (2001) Back trajectory analysis of fine particulate matter measured at Big Bend National Park in the historical database and the 1996 scoping study. Sci Total Environ 276(1-3):185-204.

Geron, CD; Guenther, AB; Pierce, TE. (1994) An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. J Geophys Res 99(D6):12773-12792.

Gong SL; Barrie, LA; Blanchet, J-P. (1997) Modeling sea-salt aerosols in the atmosphere 1. Model development. J Geophys Res 102(D3):3805-3818.

Jacobson, MZ. (2002) Atmospheric pollution: history, science, and regulation. Cambridge, UK: Cambridge University Press.

Kleinman, LI; Lipfert, FW. (1996) Metropolitan New York in the greenhouse: air quality and health effects. Ann NY Acad. Sci 790:91-110.

Kroll JH; Ng NL; Murphy SM; Flagan RC; Seinfeld JH (2005) Secondary organic aerosol formation from isoprene photooxidation under high-NOx conditions. Geophys Res Lett 32 (18): L18808.

Langner, J; Bergstrom, R; Foltescu, V. (2005) Impact of climate change on surface ozone and deposition of sulphur and nitrogen in Europe. Atmos Environ. 39(6):1129-1141.

Lathière, J; Hauglustaine, DA: Friend, AD; et al. (2006) Impact of climate variability and land use changes on global biogenic volatile organic compound emissions. Atmos Chem Phys 6:2129-2146. Available online at http://www.atmos-chem-phys.net/6/2129/2006/acp-6-2129-2006.pdf.

Lehman J, Swinton K, Bortnick S, Hamilton C, Baldridge E, Eder B, Cox B (2004) Spatio-temporal characterization of tropospheric ozone across the eastern United States. Atmos Environ. 38 (26): 4357-4369.

Liao, H; Chen, W-T; Seinfeld, JH. (2006) Role of climate change in global predictions of future tropospheric ozone and aerosols. J Geophys Res. 111:D12304, doi:10.1029/2005JD006852.

Mickley, LJ; Jacob, DJ; Field, BD; et al. (2004) Effects of future climate change on regional air pollution episodes in the United States. Geophys Res Lett 31:L24103, doi:10.1029/2004GL021216.

Morris RE, Gery MS, Liu Mk, Moore GE, Daly C, Greenfield SM. (1989) Sensitivity of a regional oxidant model to variation in climate parameters. In: The Potential Effects of Global Climate Change on the United States (Smith JB, Tirpak DA eds). US Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington DC.

Morris RE; Guthrie PD; Knopes CA. (1995) Photochemical modeling analysis under global warming conditions. In: Proceedings of the 88th Air & Waste Management Association Annual Meeting and Exhibition, Paper No. 95-WP-74B.02. Pittsburgh PA, Air & Waste Management Association.

Murazaki, K; Hess, P. (2006) How does climate change contribute to surface ozone change over the United States? J Geophys Res 111:D05301, doi:10.1029/2005JD005873.

Pun, BK; Louis, J-F; Pai, P; et al. (2000) Ozone formation in the California San Joaquin Valley: a critical assessment of modeling and data needs. J Air Waste Manage Assoc 50(6):961-971.

Pun, BK; Seigneur, C. (1999) Understanding particulate matter formation in the California San Joaquin Valley: conceptual model and data needs – adequacy and validation of meteorological measurements aloft during IMS95. Atmos Environ 33(29):4865-4875.

Sanderson, MG; Jones, CD; Collins, WJ; et al. (2003) Effect of climate change on isoprene emissions and surface ozone levels. Geophys Res Lett 30(18):1936, doi:10.1029/2003GL017642.

Sanderson, MG; Collins, WJ; Johnson, CE; et al. (2006) Present and future acid deposition to ecosystems: The effect of climate chang. Atmos Environ 40(7):1275–1283.

Schichtel, BA; Husar, RB (2001) Eastern North American transport climatology during high- and low-ozone days Atmos Environ 35(6): 1029-1038.

Sillman, SP; Samson, J. (1995) Impact of temperature on oxidant photochemistry in urban, polluted rural, and remote environments. J Geophys Res 100(D6):11479-11508.

Steiner, AL; Tonse, S; Cohen, RC; et al. (2006) Influence of future climate and emissions on regional air quality in California. J Geophys Res 111:D18303, doi:10.1029/2005JD006935.

Stevenson, DS; Doherty, RM; Sanderson, MG; et al. (2005) Impacts of climate change and variability on tropospheric ozone and its precursors. Faraday Discuss 130:41-57.

U.S. EPA (Environmental Protection Agency). (2002) Sensitivity analysis of MOBILE6.0. Office of Transportation and Air Quality, Washington DC; EPA/420-R/02/035. Available online at http://www.epa.gov/oms/models/mobile6/r02035.pdf.

U.S. EPA (Environmental Protection Agency. (2003) Guidelines for developing an air quality (Ozone and $PM_{2.5}$) forecasting program. AIRNow Program, Research Triangle Park, NC; EPA/456/R-03/002.

U.S. EPA (Environmental Protection Agency). (2004) Air quality criteria for particulate matter. National Center for Environmental Assessment, Research Triangle Park, NC; EPA/600/P-99/002aF-bF. Available online at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=87903.

U.S. EPA (Environmental Protection Agency) (2006). Air quality criteria for ozone and related photochemical oxidants. National Center for Environmental Assessment, Research Triangle Park, NC; EPA/600/R-05/004aF-cF. Available online at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923.

Vukovich, FM: Sherwell, J. (2003) An examination of the relationship between certain meteorological parameters and surface ozone variations in the Baltimore-Washington corridor. Atmos Environ 37(7):971-981.

Wise, EK; Comrie, AC. (2005) Meteorologically adjusted urban air quality trends in the Southwestern United States. Atmos Environ 39:2969–2980.

APPENDIX C
THE 2001 EPA GCRP AIR QUALITY EXPERT WORKSHOP

C.1. INTRODUCTION

A meaningful assessment of the impacts of global change requires a reasonably well-resolved understanding of the relevant processes and physical and chemical links between global, regional, and local scales. The atmospheric sciences community has begun to recognize that climate and air quality are linked through atmospheric chemical, radiative, and dynamic processes at multiple scales. The results of a limited number of studies of the relationship between weather and ozone concentrations, the effects of temperature on atmospheric chemistry, and the sensitivity of emissions to weather and land-use suggest that global change could adversely affect air quality. However, the community's understanding of the many climate/air quality links is still very limited. A better definition of these links is required for

- Estimates of future changes in climate and air quality;
- Assessment of impacts; and
- Identification of effective policies and technologies for reducing adverse effects.

In 2001, the National Research Council concluded "Improving our understanding of the interactions between climate and air quality will depend primarily on developing more sophisticated modeling tools; in particular, it will require the ability to couple local- and regional-scale air quality models (which cover spatial scales of a few hundred meters to hundreds of kilometers) with global-scale climate and chemistry models" (NRC, 2001). In addition, tools for simulating other pertinent aspects of global change occurring within the U.S., such as changes in population migration and land-use, or energy and transportation technologies, are needed to prepare future modeling scenarios that would be relevant to U.S. air quality. Furthermore, given the importance of natural and anthropogenic change in determining the frequency of wildfires and the substantial role that wildfires can play in regional air quality, a means of modeling the effect of global change on U.S. wildfire frequency is also needed for the projection of future air quality.

The first step towards accomplishing the goal of assessing global change impacts on regional air quality was the development of an assessment framework. The assessment framework guides activities undertaken by the EPA Global Change Research Program to establish the capability to analyze the relationship between global change and air quality. Initially the Program used existing tools and models, supplemented by additional analyses as needed to define missing components, to implement the assessment framework. However, it was also recognized that research was needed to fill knowledge gaps and enhance our ability to conduct such assessments.

To evaluate the feasibility of assessing climate impacts on air quality and identify key research gaps, the Program hosted a workshop in Research Triangle Park, North Carolina, in December 2001. The workshop drew on the technical expertise of staff from the Office of Research and Development (ORD) and the Office of Air and Radiation (OAR), and an array of invited international experts. Working groups were formulated to address a set of questions prepared by EPA concerning the current science and the capabilities of available modeling tools for regional climate, biogenic and fire emissions, anthropogenic emissions and their drivers, and air quality. Each group identified research and development needs and then prepared and presented recommendations to EPA on how to proceed in designing an assessment-oriented scientific research and modeling effort.

C.2. SUMMARY OF WORKSHOP RECOMMENDATIONS

Recommendations for research that were developed by the four workshop groups and that are required to meet the EPA/ORD objectives on assessing the impact of global climate change on regional air quality follow.

C.2.1. Recommendations from the Regional Climate Modeling Group

(1) Define climate model output variables needed/desired for air quality modeling analysis.

Most studies to date using a regional climate model (RCM) have been designed to address data needs for agricultural or hydrologic impact assessments. Hence, output data have been typically saved for variables directly related to temperature, precipitation, evapotranspiration, soil moisture, and surface runoff. The group felt that most current datasets would probably not be adequate to meet the needs of air quality modelers.

(2) Survey air quality models to identify important variables or statistical aspects (frequencies, persistence, and amplitude) that need to be reproduced by RCMs).

Past studies with regional climate simulations typically evaluated simulation aspects that are important for hydrologic or agricultural assessment (e.g., temperature and precipitation). It is less clear what aspects of the regional simulation are important for air quality assessment. RCM outputs to date have typically been saved at spatial grid resolutions of about 50 km and at time intervals of a few hours to a day. Most analyses of model output emphasize the surface variables or lowest atmospheric layer in the model. Air quality models typically require higher time resolution (hourly or even shorter time intervals) and 3-dimensional data from the surface to the top of the atmospheric mixed layer, if not higher.

(3) Identify appropriate time and space scales for coordinating regional climate and air quality simulations.

Current RCMs typically operate on a spatial grid resolution of 50 km while current air quality models may operate on a range of spatial grid resolutions, from 100 km to as fine as 2 km, depending upon the specific application. Thus, linking RCM outputs to the input needs of air quality models will require careful consideration of both space and time scales in order to provide simulations that are long enough to be climatologically representative yet at time and space resolutions that are computationally (and financially) feasible.

(4) Determine the RCM configurations that are important to air quality assessment (e.g., vertical/horizontal resolution, boundary conditions, model domain).

Once the appropriate scales of inter-model linkage have been identified, a set of specifications will be developed for configuring the RCM and for conducting multiple simulations ("ensembles") with one or more RCM to appropriately characterize climate variance in air quality model input considerations.

(5) Conduct diagnostic studies on variables identified in recommendation #2 to determine the degree of fidelity in RCM simulations.

The breakout group noted examples in previous RCM studies of discrepancies between model outputs and observations that were often related to inadequate parameterizations of physical processes in the model, to insufficient resolution, to insufficient data, to uncertainties in scientific understanding, etc. There could also be instances of RCMs "getting the right answer for the wrong reason," thereby creating uncertainties when applying the model to assess effects of future climate changes.

(6) Conduct model inter-comparisons for variables important to air quality to identify and quantify model biases and uncertainties (e.g., forcing, nesting, performance, and inter-model uncertainties)

It was noted that some RCM inter-comparison studies that have been conducted in the Project to Inter-compare Regional Climate Simulations project (led by Iowa State University and involving more than a dozen modeling groups from around the world). Another study performed by the Electric Power Research Institute (EPRI) described some extensions of the approach that have compared RCMs directly with statistical downscaling methods. But all of these studies have concentrated on model performance in simulating basic meteorological variables (especially temperature and precipitation), which interests the agricultural or hydrologic community and not necessarily the air quality community.

(7) Develop approaches for selecting "meaningful episodes" (days to weeks for specifically selected U.S. regions) out of long (10 years plus) regional climate model simulations.

Air quality standards are typically expressed as short-term (hourly or daily) averages that are not to be exceeded more than a specified number of times per year. Air quality model simulations are typically run over time periods of a few days to a few weeks to identify air quality episodes. It was shown that ensemble climate change simulations of current and future conditions suggest large interannual and decadal variability in future climate and among ensemble members. Multiple, long-term simulations are therefore needed to represent meaningful future climate scenarios. This poses a serious challenge to air quality assessment since physically based air quality models are extremely computationally intensive (as compared to global or regional climate modeling). An alternative approach to long-term simulation is to develop future climate scenarios based on extracting episodes from regional simulations that capture major changes in synoptic events that are significant to air quality. Such episodes may represent changes in intensity or frequency of stagnation, atmospheric inversion, or El Niño-Southern Oscillation (ENSO) cycles, etc.

(8) Identify the appropriate RCM ensembles needed to characterize climate variance for air quality modeling purposes (both multiple simulations and multiple models).

To appropriately characterize the climate variance simulated among models, a new round of RCM simulations will be required, involving multiple RCMs (research recommendation #8). The research recommendations so far have focused on linking RCMs to air quality simulations of specific episodes over relatively short time duration. However, linking air quality assessments to multiple climate change scenarios, and for the many ensembles of simulations necessary to quantify probabilities of climatic and air quality risks, could far exceed the computing resources available to RCM modelers. The hydrological impacts community has addressed a need for long-term assessments through the successful application of statistical downscaling-based climate models to projecting precipitation and river runoff extremes.

(9) Investigate the usefulness of applying statistically downscaled climate models coupled to statistical air quality models for long-term assessments.

Statistical downscaling models for climate parameter inputs are presently used in operational forecasting models for seasonal and interannual basin hydrology on a site-specific basis due to their very efficient computation and successful calibration. Process-based air quality models, however, require extensive descriptions of the 3-dimensional structure of the atmosphere and there are insufficient observational data for developing statistical downscaling for most meteorological variables important for air quality assessment. However, it may be worth exploring whether statistical downscaling may, in some way, be useful for providing climate inputs for empirical air quality models.

(10) Investigate the importance of incorporating "full chemistry" into an RCM for defining background inputs and determining the importance of feedbacks of chemistry into climate.

The members of the breakout group viewed the development of the "Ultimate" model—an RCM incorporating full chemistry—as a vision for the future. While the CMAQ advertises its "Plug and Play" capabilities to test quickly (and easily?) alternative chemical schemes, two-way coupling of CMAQ-type models with climate models is more complicated. Early work on incorporating chemical modules into global climate models has met with rather mixed success and often with a very high "cost" penalty in terms of dramatically increased computing times. Under these circumstances, the breakout group recommended a "go slow" approach toward adding full chemistry to RCMs by determining inputs needs and the potential significance of chemical feedbacks on climate.

C.2.2. Recommendations from the Biogenic and Fire Emissions Group

(1) There is a need to develop algorithms that describe chemical emissions of major vegetative species' response to climate change for use in current and biogenic emission forecasting.

Changes in vegetative growth, yield, and water use have been the foci of research efforts to understand climate change impacts on natural and domestic woody and herbaceous vegetation. Basic research is needed to better understand the physiological impacts of climate change on vegetation chemical emissions. An improved knowledge of species-level response to climate change is needed before complete terrestrial emission budget cycle is possible.

(2) Research is required to integrate land-use/land-cover projection changes with forest physiological models to project current and future changes in VOC emissions.

Both an understanding of climate change impacts on plant physiology and on land-use/land-cover are needed to generate VOC budgets and balances in terrestrial ecosystems. While plant physiological studies provide a measure of VOC contribution per vegetation type, land-use/land-cover data are needed to scale the predictions individual emissions to the regional or continental scale.

(3) There is a need to develop methods to define fire emissions as a function of fire intensity, extent, and frequency.

A good program for monitoring major fire intensity, extent, and frequency currently exists within the federal government. However, research to link monitored data with emission by vegetation type is lacking. Additional development of the relationships between the emission by-products of vegetation combustion and fire monitoring program data are needed before an accurate estimate of fire impacts to atmospheric emissions can be completed.

(4) There is a need to develop methods to relate fire intensity, extent, and frequency to current land-use, land management, fuel loading, and climate.

The current federal fire-monitoring program is designed to track fire intensity, extent, and frequency. However, scientists have only a coarse understanding of how monitored data relates to land-use, land management, fuel loading, and climate. An improved understanding of the drivers of fire intensity, extent, and frequency are needed for use in fire emission projection scenarios.

(5) There is a need to develop methods to relate and apply fire intensity, extent, and frequency to the future socio-economic/climatic scenarios.

Future land-use change, economic conditions, and climate will likely be primary drivers of fire emission through 2050. Therefore, socio-economic and climate change models need to be developed and applied to national scale fire emission models before a complete biogenic emission budget is possible.

(6) Research must be performed concerning current and future emissions from animal husbandry and fertilizer application.

Animal husbandry and agricultural fertilizer applications are major sources of emissions. Some data exist regarding the current type and extent of animal husbandry and fertilizer application type and rates across the continent. However, there is a lack of understanding in relating climate, soil, vegetation, and animal conditions with emission patterns. Additionally, current animal husbandry and fertilizer application practices may change in the future. Both an improved understanding of environmental interaction and projections of future practices are needed to estimate emission inputs of future animal husbandry and fertilizer application before a complete terrestrial emission budget can be completed.

(7) Research must be performed to understand drivers of current and of future rates of ammonia and VOC deposition (e.g., soil moisture, ammonia gas to particulate).

The concentrations of atmospheric gases are dependent on the current atmospheric concentration, inputs, and outputs from the system. The majority of research focuses on changes in atmospheric gases inputs. However, understandings of deposition of gases from the atmosphere are equally needed for the development of an atmospheric emission balance. Deposition of ammonia and VOC are two important gases that have both atmospheric and terrestrial impacts. A better understanding of ammonia and VOC deposition would be useful in predicting future emissions and for use in examining terrestrial impacts.

C.2.3. Recommendations from the Emission Drivers and Anthropogenic Emissions Group

(1) There is a need to perform research on feedbacks of regional climate change on population migration and economic activity.

Regional climate change could have significant impacts on climate sensitive economic sectors such as agriculture and forestry. Current national/regional economic models are not likely to address these impacts. Furthermore, the ability to adapt to regional climate change may vary by regions and economic sectors. Regional climate change may also change the relative attractiveness of certain regions within the U.S. and influence the migration of population. Present research addressing these issues is limited and further research is required.

(2) There is a need to perform research on feedbacks on energy use and emissions from energy use due to regional climate change.

Regional climate change will likely impact energy use especially for heating and cooling. These changes will impact emissions at the commercial, industrial, and domestic levels due to direct use of energy but also impact emissions from electricity generation plants. These changes could increase the frequency and magnitude of episodes with high emissions and poor air quality. Furthermore, changes in water supply and land-use can impact strategies for utilization of biomass to meet energy needs. Present research addressing these issues is limited and further research is required.

(3) There is a need to perform research on feedbacks from climate change on biogenic emissions.

The impact of changes in regional climate of biogenic emissions needs to be quantified. Regional climate change can lead to migration of species, which can change emissions. New approaches to scale national/regional economic, demographic, and energy model results to more detailed geographic resolution are required. Current approaches are relatively simple and may not reflect key trends.

(4) Additional research is required on land-use models.

Land-use change represents one of the most important factors influencing future air quality. Population growth combined with increased wealth; changes in transportation, energy, and communication technology; regional migration; use of personal verse public transport; and lifestyles can lead to significant changes in local drivers for emissions sources along with emission factors. The current modeling capability to address these types of changes is limited and not focused on the longer-term structural effects that may happen in the future.

(5) New research is required on agent-oriented models.

New research into agent-oriented models may provide opportunities to address land-use change, migration, and other issues listed above. Research into these models and application of these models to this problem is limited and further research is required.

C.2.4. Recommendations from the Air Quality Modeling Group

(1) Group recommends three, complimentary modeling approaches: A comprehensive modeling approach, an intermediate modeling approach, and a sensitivity approach.

The comprehensive approach uses linked, dynamic models to simulate air quality. The meteorological chain links a GCM to an RCM. The downscaled, meteorological output from the RCM is linked to a regional air quality model (RAQ) model. A global chemical transport model (GCTM) would produce chemical boundary condition information for the RAQ model. This approach raises concerns, however, about the length of simulation required to achieve a climate signal above the climate variability. Previous regional climate downscaling suggests that simulations over 10–20 years may be required to rigorously meet statistical requirements. However, the computational resources required for this length of simulation greatly exceed the available resources for the near future. Thus, the group considered serious explorations of methods to avoid 20-year simulations and yet produce meaningful results.

The intermediate approach uses a GCTM or coarse scale RAQ model to simulate the impact on air quality due to long-lived GHGs over the 50 years from the present to 2050. The emphasis in this approach will be to explore the change in high air pollution events as the climate changes. It will be important to incorporate the ocean response to the changing climate in order to perform this simulation properly. One set of simulation will hold air pollutant emissions constant over the simulation (besides corrections for temperature and other climate variables). In another set, plausible scenarios of emissions for 2050 can be simulated to compare the magnitudes of the climate influence on the emissions changes. The results will guide the comprehensive modeling approach and may allow selection of episodes using statistical sampling techniques to avoid 20 years of simulation. The intermediate approach may also provide coarse estimates of the impact of climate change on air quality in Hawaii and Alaska.

The sensitivity approach would focus on the application of detailed, state-of-the-art urban and regional air quality models. Rather than a dynamic linkage, the RAQ simulations would vary key parameters to examine the sensitivity of air quality. The issue of climate variability is removed through varying parameters such as temperature to define the potential responses. The sensitivity approach permits use of more detailed descriptions of important processes (i.e., aerosol processes and chemical speciation of fine particulate matter). It also enables detailed comparison to observational data. Therefore, simulations including EPA Supersite locations might prove extremely valuable.

(2) It is recommended that more than one GCM be used to explore the range of possible future climates.

Future climate on a regional scale is highly uncertain. Any analysis will need to grapple with the uncertainty and climate variability.

(3) Close interaction between the regional climate modeling and synoptic climatology communities is recommended to characterize large-scale meteorological events that effect air quality, which would be used to guide the development of air quality modeling scenarios.

The variability of the climate signal, as well as air pollution episodes, will determine the desired sampling time periods. Computational resource requirements are likely to constrain the length of detailed, fine-scale, air-quality simulations to significantly less than the desired length to find the climate signal in the noise due to climate variability.

(4) It is recommended that plausible scenarios for future emissions be developed.

Plausible scenarios for future emissions are crucial to the policy relevance of the air quality modeling simulations. Exogenous socio-economic changes may have a much larger impact than climate change on air quality 50 years into the future. Techniques to explore the root causes of air quality changes, such as simulations holding emissions constant, will need to be utilized to produce significant results for policy decisions.

(5) It is essential that the air quality modeling results from CMAQ be improved.

These improvements should be targeted towards areas of magnified importance due to the novel aspects of this effort.

(6) Quantify the uncertainty produced by the chain of linked models required to make an air quality prediction due to climate change.

The linkage of a chain of dynamic models of different scale requires care in maintaining consistency especially in consideration of nesting schemes and dynamics. The uncertainty introduced by the chain of linked models should be quantified through observational data whenever feasible.

C.3. REFERENCE

NRC (National Research Council). (2001) Global air quality: an imperative for long-term observational strategies. Committee on Atmospheric Chemistry, Washington, DC: National Academy Press; 41 pp. Available online at http://www-nacip.ucsd.edu/NRCAtmosChemCommRpt.pdf.

APPENDIX D
U.S. EPA STAR GRANT RESEARCH CONTRIBUTING TO THE GCAQ ASSESSMENT

D.1. STAR SOLICITATIONS

The Science To Achieve Results (STAR) program plays a major role in the study of the impacts of climate change on air quality. Through the STAR competitive process, EPA ORD has funded several leading university research groups to investigate the various aspects of the impact of global change on air quality. Additional information about the STAR program can be found at http://www.epa.gov/ncer/, which provides links to more detailed descriptions and progress reports for the projects summarized here. Table D-1 lists the Requests for Applications (RFAs) that address various aspects of climate impacts on air quality. Results from awards that were made in 2000 and 2002 are discussed in greater detail in Section 3 of the main report. Research from awards made in 2003-2006 is ongoing and described briefly in Section 4; a synopsis and summary of these awards follow.

Table D-1. Requests for applications for the global program (STAR)

Year	RFA Title
2000	Assessing the Consequences of Interactions between Human Activities and a Changing Climate
2002	Assessing the Consequences of Global Change for Air Quality: Sensitivity of U.S. Air Quality to Climate Change and Future Global Impacts
2003	Consequences of Global Change for Air Quality: Spatial Patterns in Air Pollution Emissions
2004	Regional Development, Population Trend, and Technology Change Impacts on Future Air Pollution Emissions
2004	Fire, Climate and Air Quality
2006	Consequences of Global Change for Air Quality

D.1.1. Assessing the Consequences of Interactions between Human Activities and a Changing Climate

The purpose of this RFA was to foster the development of models that enable assessors to consider the effects of human activities in tandem with the effects of climate change and climate variability. Two of the four proposals selected for funding explored the impacts of climate change and air quality. These projects confirmed the new direction of the program and provided important early results. (See Table D-2)

Table D-2. 2000 STAR grant recipients: assessing the consequences of interactions between human activities and a changing climate

Institution	Title
Johns Hopkins University	Implications of Climate Change for Regional Air Pollution, Health Effects and Energy Consumption Behavior
Columbia University	Modeling Heat and Air Quality Impacts of Changing Urban Land Uses and Climate

D.1.2. Assessing the Consequences of Global Change for Air Quality: Sensitivity of U.S. Air Quality to Climate Change and Future Global Impacts

The focus of this RFA was on linking global and regional models and/or on increasing understanding of the sensitivities of air quality to climate change. The six projects funded under this solicitation (Table D-3) are described in more detail in Section 3 of the report.

D.1.3. Consequences of Global Change for Air Quality: Spatial Patterns in Air Pollution Emissions

The focus of this RFA was on the development of methods for creating plausible North American emission scenarios for use in assessments of climate change impacts on regional air quality. Of particular interest were changes in the spatial distribution of stationary, mobile, and biogenic emissions over the longer timeframes used in global change assessments (e.g., 50+ years or more). For example, the physical characteristics and patterns of land development in a region can affect air quality by influencing travel mode choices, trips, trip speed, number of miles driven, and, therefore, mobile source emissions. Similarly, emissions from stationary air pollution sources, such as power plants and factories, will also be affected by the characteristics and patterns of land development. In addition, economic growth, changes in the composition of economic output (e.g., the gross domestic product or GDP), and technological change have the potential to affect both the total amount and spatial distribution of stationary source emissions. Finally, changes in land use, vegetation, and climate can influence the natural emission of volatile organic compounds (VOC), carbon monoxide, and oxides of nitrogen. Six proposals were funded under this RFA (Table D-4), four of which focused on biogenic emissions.

Table D-3. 2002 STAR grant recipients: assessing the consequences of global change for air quality: sensitivity of U.S. air quality to climate change and future global impacts

Institution	Title
Harvard University	Application of a Unified Aerosol-Chemistry-Climate GCM to Understand the Effects of Changing Climate and Global Anthropogenic Emissions on U.S. Air Quality
Georgia Institute of Technology	Sensitivity and Uncertainty Assessment of Global Climate Change Impacts on Ozone and Particulate Matter: Examination of Direct and Indirect, Emission-Induced Effects
Carnegie Mellon University	Impacts of Climate Change and Global Emissions on U.S. Air Quality: Development of an Integrated Modeling Framework and Sensitivity Assessment
Washington State University	Impact of Climate Change on U.S. Air Quality Using Multi-scale Modeling with the MM5/SMOKE/CMAQ System
University of Illinois at Urbana	Impacts of Global Climate and Emission Changes on U.S. Air Quality
University of California – Berkeley	Guiding Future Air Quality Management in California: Sensitivity to Changing Climate

Table D-4. 2003 STAR grant recipients: consequences of global change for air quality: spatial patterns in air pollution emissions

Institution	Title
University of Colorado at Boulder	New Biogenic VOC Emission Models
University of North Carolina at Chapel Hill	Reduced Atmospheric Methane Consumption by Temperate Forest Soils Under Elevated Atmospheric CO_2: Causative Factors
University of Texas at Austin	Impacts of Climate Change and Land Cover Change on Biogenic Volatile Organic Compounds (BVOCs) Emissions in Texas
University of Illinois at Urbana	Development and Evaluation of a Methodology for Determining Air Pollution Emissions Relative to Geophysical and Societal Changes
University of New Hampshire	A Coupled Measurement-Modeling Approach to Improve Biogenic Emission Estimates: Application to Future Air Quality Assessments
Resources for the Future	An Integrated Framework for Estimating Long-Term Mobile Source Emissions Linking Land Use, Transportation, and Economic Behavior

D.1.3.1. *University of Colorado at Boulder*

Although many studies have shown that emissions of VOCs from forest ecosystems cause an increase in air pollution, current air pollution models lack fundamental insight into the biochemical mechanisms in plants that produce these compounds. Specifically, it is not possible to accurately predict whether the emission of these compounds and their influence on air quality will change if the climate of the earth or the atmospheric concentration of CO_2 changes in the future. The CU-Boulder group is conducting experiments to elucidate the biochemical processes that cause the emission of these compounds and is describing their response to temperature and CO_2 change. The focus of their studies is on isoprene and acetaldehyde, two of the most commonly-emitted compounds from U.S. forests.

D.1.3.2. *University of North Carolina at Chapel Hill*

The overall aim of the UNC-Chapel Hill research is to determine the duration and underlying cause(s) for the decline in atmospheric methane consumption in a CO_2-enriched forest. The Duke Forest Free Air Carbon Dioxide Enrichment (FACE) site is used to (1) quantify the dynamics of soil-atmosphere exchange of methane, (2) quantify the impact of CO_2 enrichment on the exudation of dissolved organic compounds from roots of the loblolly pine into the rhizosphere, and the effects of these compounds on the rates of methane oxidation in soils, (3) quantify the dissolved organic compounds and ions from throughfall precipitation as a supplement to root exudates and the effects of these compounds on rates of methane oxidation in soils, and (4) evaluate the impact of CO_2 enrichment on soil physical and biogeochemical properties central to atmospheric methane consumption, including effective diffusivity, microbial community structure, the soil locus of methanotrophic activity, and physiological characteristics of the methane-oxidizing community.

D.1.3.3. *University of Texas at Austin*

Climate change can influence the emissions of biogenic VOCs (BVOCs) directly (i.e., changes in solar radiation and air temperature, among other variables, affect the vegetation's capability to release BVOCs) or indirectly (climate change-induced changes in vegetation species and their prevalence, thereby modulating the emission rates of BVOC). In addition, human-driven land use change will also impact BVOC emissions. The UT-Austin group is coupling climate models, biogenic emission models, air quality models, and anthropogenic land-use models to quantify direct and indirect effects of climate change on biogenic emissions and to predict future air quality trends, using Texas as a case study.

D.1.3.4. *University of Illinois at Urbana*

The University of Illinois is developing an Emissions Inventory Modeling System (EIMS) that uses econometric models and emission development tools to formulate future emission inventories for different climate change scenarios in the format used for the National Emissions Inventories (NEI). Changes in population, economy, policies and regulations, technological development, transportation systems, energy systems, landscape and land use, and vegetation and land cover are being considered within the development of the EIMS capability. For the initial development and testing of the modeling system, the focus is on the Chicago area, where the econometric modeling is most highly refined. During the later stages of the research, the methods will be extended to the entire Midwest to demonstrate the wider applicability of the techniques.

D.1.3.5. *University of New Hampshire*

This investigation is focused on the northeastern U.S. with overall objectives to (1) predict changes in regional climate that will influence natural biogenic emissions to the atmosphere and air quality, (2) quantify the impact of regional climate change on plant ecosystem composition, (3) estimate the regional impact of a changing plant ecosystem on biogenic emissions, and (4) estimate the impact of changes in regional climate and plant ecosystem on aerosol loading, O_3, NOx, hydrocarbons, and the oxidative capacity of the atmosphere.

D.1.3.6. *Resources for the Future*

The interactions between transportation, land use, and vehicle ownership decisions are fundamental to understanding future mobile source emissions. Furthermore, the importance of these interactions increases for issues that require a long planning horizon, such as climate change. The aim of the proposed research is to create a flexible modeling framework to estimate long-term mobile source emissions in a metropolitan region; a framework that reflects the importance of geographic specificity, technological change, and especially behavioral adjustments by consumers. The development of the framework will provide insight into the sensitivity of estimates of future mobile source emissions to assumptions about economic growth, demographic change, technological innovation, and behavioral responses.

D.1.4. Regional Development, Population Trend, and Technology Change Impacts on Future Air Pollution Emissions

Recognizing the importance of the location and design of new development for creating accurate long-term (50+ years) emissions projections, this RFA focused on methods to project changes in a wide range of key drivers and policy variables. Examples of such changes include transportation infrastructure investments, regional development patterns (e.g., sprawl, Smart Growth), structural and spatial shifts in the organization of production and delivery of services, transportation modal choices (and other lifestyle factors), air quality and climate policies, and population movements, in addition to technological change. More specifically, the spatial and temporal distribution of transportation activities and emissions are key concerns. Because regional development patterns (e.g., housing, roads, commercial development, mass transit systems) vary across the country, both the amount and spatial distribution of air pollution emissions from mobile sources are likely to be affected. Eight proposals (Table D-5) were funded under this RFA.

D.1.4.1. *University of Wisconsin-Madison*

This study is testing the hypothesis that "smart growth" land use strategies can significantly improve regional air quality throughout the upper midwestern U.S. over the next 25 to 50 years. To investigate this question, a fully integrated land use, vehicle travel, and air quality modeling framework is being developed to (1) estimate vehicle trips and miles of travel (VMT) as a function of changes in population density, employment rates, income, and vehicle ownership, (2) estimate mobile source emissions as a function of changing land use patterns (as reflected in VMT), hybrid vehicle technology dissemination, and regional climate, (3) model regional O_3 and PM concentrations as a function of regional land use, hybrid technology, and energy production scenarios, and (4) account for the effects of continental and global scale pollutant transport on O_3 and PM chemistry for the target years 2005, 2025, and 2050.

D.1.4.2. *Georgia Institute of Technology*

Rather than trying to predict how emissions will change in the future and what impact they will have on future air quality, this project is using an inverse approach to identify the desirable distributions of emissions in 50 years. That is, a desirable air quality state is defined and then the emissions and activity profiles required to achieve this state are derived. The project uses the rapidly growing north Georgia area, including Atlanta, to demonstrate the method. Since the Global Program is focused on longer time scales (i.e., 50+ years), emissions and the activities, processes, and infrastructure associated with them can be considered to be

Table D-5. 2004 STAR grant recipients: regional development, population trend, and technology change impacts on future air pollution emissions

Institution	Title
University of Wisconsin-Madison	Modeling the Effects of Land Use and Technology Change on Future Air Quality in the Upper Midwestern United States
Georgia Institute of Technology	Air Quality, Emissions, Growth, and Change: A Method to Prescribe a Desirable Future
University of California - Davis	Regional Development, Population Trend, and Technology Change Impacts on Future Air Pollution Emissions in the San Joaquin Valley
Johns Hopkins University	Methodology for Assessing the Effects of Technological and Economic Changes on the Location, Timing and Ambient Air Quality Impacts of Power Sector Emissions
State University of New York at Buffalo	A Long Term Integrated Framework Linking Urban Development, Demographic Trends and Technology Changes to Stationary and Mobile Source Emissions
University of North Carolina at Chapel Hill	Advanced Modeling System for Assessing Long-Term Regional Development Patterns, Travel Behavior, Emissions, and Air Quality
University of Washington-Seattle	Integrating Land Use, Transportation, and Air Quality Modeling
University of Texas at Austin	Predicting the Relative Impacts of Urban Development Policies and On-Road Vehicle Technologies on Air Quality in the United States: Modeling and Analysis of a Case Study in Austin, Texas

pliant (i.e., adaptable). With the required emission and activity profiles, the types and amounts of land use modifications, technology advancements, and other changes that will be required to transform or morph the present emissions scenario into the future desired emissions scenario are being identified.

D.1.4.3. *University of California - Davis*

Future progress towards the abatement of air pollution in cities throughout the U.S. is uncertain because population expansion and current socioeconomic trends affect pollutant emissions. Further, there is an incomplete understanding of how these factors will combine to influence air quality at the urban and regional scale. The objective of this project is to combine land use forecasting models, water constraint models, travel demand models, emissions models, and a source-oriented air quality model into a modeling system with feedback loops to predict future emissions and associated air quality impacts. The modeling system is being used to assess the sensitivity of emissions inventories to future policy scenarios in the areas of land use policies, transportation investments, technological innovations, air quality regulations, and agricultural practices in the San Joaquin Valley in the year 2030.

D.1.4.4. *Johns Hopkins University*

The amounts, locations, and timing of power sector emissions are sensitive to economic and technological assumptions. The purpose of this project is to develop and demonstrate a methodology for creating geographically and temporally disaggregated emissions scenarios for the electric power sector on a multidecadal time-scale for use with air quality models. This project focuses on power generation for three reasons. First, this sector represents a large share of SOx, NOx, mercury, and CO_2 emissions in the U.S. Moreover, future shares are highly uncertain, depending upon technology change, fuel mix, electric load growth, regulation of the electricity sector, and the evolution of environmental policy. Second, alternative scenarios concerning these key drivers can make huge differences in total emissions and their spatial and temporal distribution. Finally, emissions and associated ambient air concentrations are sensitive to the growth and distribution of electricity demands, which in turn are strongly linked to temperature and other climatic variables that may change significantly over the next few decades.

D.1.4.5. *State University of New York at Buffalo*

The goal of this project is the development of a tool capable of producing long-term (25- to 50-year) projections of stationary- and mobile-source emissions in a metropolitan area. Currently, emission models are used mostly for short time horizons, taking, as given, projections of local economic activity and population change. Instead of simply extrapolating these local trends, this effort models the fundamental behavioral relationships among individuals and firms and links these underlying economic relationships to secular national and international trends in population, economic development, and technological changes relevant to emissions. Among the specific demographic trends to be examined are the aging of the population, reductions in household size, and international immigration. In addition, the possibility of the continued deindustrialization of U.S. manufacturing and its impact on a metropolitan area with considerable manufacturing will be investigated, using the Chicago metropolitan statistical area as a case study. New technologies likely to impact emissions, such as electric vehicles and hydrogen fuel-cell vehicles, as well as electricity/energy production with a higher renewable fuel mix under higher sustained energy prices also will be investigated.

D.1.4.6. *University of North Carolina at Chapel Hill*

Through simulation modeling of land use, transportation, emissions, and air quality, this research project rigorously tests the hypothesis that alternative development patterns, implemented regionally over a planning horizon of 50 years, can substantially influence the quantity and location of emissions from on- and off-road mobile sources and thus affect ozone and PM levels. The development patterns of interest include the type of development and its location (e.g., transit oriented development, dense mixed use development, development supportive of non-motorized transportation modes for non-work trips, neo-traditional suburbs, new urban core development, and redevelopment). A case study will be developed, using recent data for Charlotte (NC), Mecklenburg County, and the multi-county Metrolina region.

D.1.4.7. *University of Washington-Seattle*

The objective of this research is to develop an integrated, Open Source software platform that integrates land use, activity-based travel, and network assignment, and tightly couples this integrated system to current and emerging emissions modeling software (e.g., Mobile6 and its successor, Motor Vehicle Emission Simulator or MOVES). By improving existing models to better reflect and integrate lifestyle, economic production, and public policy factors that drive vehicle miles traveled, this platform will provide a new capacity for integrated land use, transportation, and air quality modeling to support air quality planning in metropolitan areas throughout the U.S. The UW-Seattle group is testing this integrated system in the Puget Sound region, working collaboratively with the Puget Sound Regional Council. They use this integrated model to assess the relative influence of transportation infrastructure, pricing, land use policies—including smart growth, and demographic and economic trends, on VMT and emissions over a 30-year horizon.

D.1.4.8. *University of Texas at Austin*

The objective of this research is to develop and use an integrated transportation-land use model (ITLUM) to investigate the impacts of regional development scenarios and trade policies on the magnitude and spatial distribution of emissions of O_3 precursors. ITLUM-based forecasts are being compared with four pre-determined metropolitan development scenarios: (1) low-density, segregated-use development based on extensive highway provision, (2) concentrated, contiguous regional growth within 1-mile of transportation corridors, (3) concentrated growth in existing and new communities with distinct boundaries, and (4) high-density development and balanced-use zoning. The resulting air quality impacts and predicted human exposures are being evaluated. In addition, ITLUM emission forecasts are compared to those based on the U.S. EPA's post-Clean Air Act Amendment emission scenario projections. The research team is also evaluating whether changes in land use and dry deposition patterns have at least as significant an impact on future air quality as changes in on-road vehicle emission control technologies.

D.1.5. Fire, Climate, and Air Quality

While some attention has been given to the influence of fires on air quality and to the consequences of climate change for wildfires, the focus of this research solicitation was on the integration of the complex interactions of fire, climate, and air quality. In order to produce plausible future emission inventories from fires, critical information must include estimates of location, time, frequency, and fuel characteristics. Due to the inherent uncertainties in predicting the future, this RFA emphasized using a range of scenarios in order to demonstrate which forces and linkages are most important, rather than attempting to develop an exact forecast of the future. Three proposals (Table D-6) were funded under this RFA.

Table D-6. 2004 STAR grant recipients: fire, climate and air quality

Institution	Title
Georgia Institute of Technology	Interaction of Ecosystems, Fires, Air Quality and Climate Change in the Southeast
Harvard University	Investigation of the Effects of Changing Climate on Fires and the Consequences for U.S. Air Quality, Using a Hierarchy of Chemistry and Climate Models
University of North Carolina at Chapel Hill	Investigation of the Interactions between Climate Change, Biomass, Forest Fires, and Air Quality with an Integrated Modeling Approach

D.1.5.1. *Georgia Institute of Technology*

Large amounts of biomass are burned in the Southeast, and fire emissions have been found to significantly affect air quality in the region. It is expected that the effects of fire emissions will change significantly as a result of climate and land-use changes. The objectives of this research are to (1) integrate process-based ecosystem, fire emissions, air quality, and regional climate models to systematically understand the complex interaction of these components in the Southeast, (2) evaluate the integrated modeling system with state fire statistics and ground and satellite observations and understand better the effects of fire emissions on air quality in the Southeast, (3) calculate the sensitivities of the modeling system to major inputs and use these sensitivities to quantify uncertainties in the system results, and (4) assess the impact of regional climate and land use changes and fire management on ecosystems and fire emissions and the consequent effects on air quality in the Southeast.

D.1.5.2. *Harvard University*

Existing studies show that fires in North America can have a significant effect on visibility and air quality in the U.S. on an episodic basis. The Harvard group is exploring the relationships between climate and frequency and intensity of forest fires in North America. Using linear stepwise regression, the best predictors for area burned for different ecosystems, including temperature, relative humidity, wind speed, precipitation, and components of the Fire Weather Index (FWI) system, or of the Fire Weather Danger Rating System (NFSRS) are being determined. The group is using area burned prediction schemes in simulations with the NASA/GISS general circulation model (GCM) to derive estimates of area burned for 2000-2050. Plume heights from fires in North America are related to areas of fires in a study of the effect of present day fires on ozone and PM using the global aerosol-chemistry model, GEOS-CHEM, and CMAQ. Future climate predicted using a general circulation model and relationships between fire and climate is being used to predict future fires in the U.S.. Using global and regional scale chemistry-aerosol transport models, this group is assessing the role of future wild fires on air quality.

D.1.5.3. *University of North Carolina at Chapel Hill*

Forest fires not only change landscapes and destroy property but also emit trace gases and aerosols (e.g., CO, methane, NOx, and black carbon) that affect regional and global air quality. These impacts can be felt over long distances because of the long-range transport of these pollutants both as primarily emitted species and as precursors for other pollutants formed in the atmosphere through photochemical reactions. Recently, the increased frequency of large fires in the U.S. has been thought to be associated with short-term changes in climate variables such as precipitation and temperature that have exacerbated the conditions for fire occurrence. The overall goal of research by the UNC-Chapel Hill team is to assess the impact of climate change and variability on biomass and forest fires, evaluate the impact of evolving emissions from forest fires on O_3 and PM air quality, and determine the regional climate response to these changes in the Southern U.S. using an integrated modeling approach.

D.1.6. Consequences of Global Change for Air Quality

The focus of this RFA was on improving the understanding of linkages between climate, atmospheric chemistry, and global air quality and the ability to assess future states of the atmosphere by coupling local- and regional-scale air quality models with global-scale climate and chemistry models. Predictions of future air quality that rely on global climate simulations will require consideration of how larger scale climatic parameters and processes are transferred to regional models. In addition, accurate prediction of precipitation events is a key challenge to modeling air pollution episodes. Successful predictions of future air quality also require a good understanding of both current and future emissions of pollutants and their precursors. Due to the inherent uncertainties in predicting the future, the RFA emphasized that an explicit treatment of uncertainty, such as using multiple scenarios was desirable. Moreover, the focus of the research should be on exploring a range of scenarios to demonstrate which forces and linkages are most important, rather than an exact forecast of the future. Ten projects (Table D-7) were funded under this RFA.

D.1.6.1. *University of California - Davis*

Ozone and PM standards designed to protect public health are routinely violated in California's South Coast Air Basin surrounding Los Angeles and the San Joaquin Valley (SJV) in central California. The project by the UC-Davis team aims to quantitatively assess the consequences of global change on California air quality by (1) measuring emissions from mobile sources powered by alternative fuels as a function of temperature and humidity, (2) creating a source-oriented PM module for the Weather Research & Forecasting (WRF) model to quantify feedback between air quality and regional meteorology, and (3) calculating California air quality in 2030 for a range of O_3 and $PM_{2.5}$ pollution events. GCM simulations of future climate are being dynamically downscaled to the regional scale using the Weather Research and Forecasting (WRF) meteorological model. A source-oriented PM module is being integrated into WRF to study the interactions between pollution and local meteorology. The new model will be used to compare current air pollution episodes in California with those that are expected to occur in the year 2030. Multiple episodes (~30) will be studied in current and future periods to understand the distribution of possible events.

Table D-7. 2006 STAR grant recipients: consequences of global change for air quality

Institution	Title
University of California - Davis	Impact of Global Change on Urban Air Quality via Changes in Mobile Source Emissions, Background Concentrations, and Regional Scale Meteorological Feedbacks
University of Illinois at Urbana	Impacts of Global Climate and Emissions Changes on U.S. Air Quality (Ozone, Particulate Matter, Mercury) and Projection Uncertainty
University of Wisconsin - Madison	Sensitivity of Heterogeneous Atmospheric Mercury Processes to Climate Change
Desert Research Institute	Effects of Global Change on the Atmospheric Mercury Burden and Mercury Sequestration Through Changes in Ecosystem Carbon Pools
Stanford University	Effects of Future Emissions and a Changed Climate on Urban Air Quality
University of Michigan	Global and Regional-Scale Models for Ozone, Aerosols and Mercury: Investigation of Present and Future Conditions
North Carolina State University	Study the Impact of Global Change on Air Quality Using the Global-Through-Urban Weather Research and Forecast Model with Chemistry
Harvard University	Global Change and Air Pollution (GCAP) Phase 2: Implications for U.S. Air Quality and Mercury Deposition of Multiple Climate and Global Emission Scenarios for 2000-2050
Carnegie Mellon University	Changes in Climate, Pollutant Emissions, and U.S. Air Quality: An Integrating Modeling Study
Washington State University	Ensemble Analyses of the Impact and Uncertainties of Global Change on Regional Air Quality in the U.S.

D.1.6.2. *University of Illinois at Urbana*

The objective of this study by UICU is to quantify and understand the impacts and uncertainties of global climate and emission changes, from the present to 2050 and 2100, on U.S. air quality, focusing on O_3, PM, and mercury. State-of-the-art, well-established ensemble modeling systems that couple a global climate-chemical transport component with a mesoscale regional climate-air quality component is being applied over North America. Both components incorporate multiple alternative models representing the likely range of climate sensitivity and chemistry response under plausible emissions scenarios to rigorously assess uncertainty. These systems are used to quantify the individual and combined impacts of global climate and emissions changes on U.S. air quality. Sensitivity experiments refine understanding of relationships with major contributing source regions and types and uncertainties associated with key conclusions.

D.1.6.3. *University of Wisconsin - Madison*

The goal of the proposed research is to quantify the impact of climate change on key atmospheric processes that control the fate of mercury in transport from emissions to deposition. Researchers at UW-Madison build on existing scientific understanding of atmospheric mercury processes by examining the incremental impact of climate change variables on heterogeneous atmospheric mercury oxidation and depositional processes. Specifically, an integrated laboratory and modeling approach is used to quantify (1) the sensitivity of dry deposition of elemental mercury, reactive gaseous mercury, and particulate mercury to temperature, humidity, O_3, NO_x, and sunlight intensity and (2) the sensitivity of atmospheric mercury oxidation and reduction reaction in fog and cloud water to temperature, sunlight intensity, and the composition of these atmospheric waters. In addition, the oxidation of elemental mercury in the presence of the complex atmospheric reactions that produce photochemical smog and secondary organic aerosols are being investigated. Finally, the group uses a regional chemical transport model to explore the sensitivity of mercury deposition to temperature, precipitation, and atmospheric circulation patterns associated with climate change.

D.1.6.4. *Desert Research Institute*

Terrestrial carbon pools play an important role in uptake, deposition, sequestration, and emission of atmospheric mercury. Biomass and soil carbon pools are highly sensitive to climate and land use changes with potentially serious consequences for the fate of an estimated 50,000 Mg of atmospheric mercury associated within carbon pools. The objective of the research by the Desert Research Institute is to assess how global change over the next 100 years affects mercury cycling processes—atmospheric mercury uptake, sequestration, and emission—associated with vegetation and soil carbon pools. Effects of global change on plant-derived atmospheric mercury inputs to ecosystems via changes in plant productivity, plant senescence, and litterfall are being assessed. In addition, global change impacts on plant, litter, and soil carbon pools and the resulting effects on sequestered mercury within these pools and feedback on the future atmospheric mercury burden are investigated. This effort involves several components including a systematic collection of data on mercury in vegetation and soil carbon pools in terrestrial ecosystems, field and laboratory experimental studies, and modeling.

D.1.6.5. *Stanford University*

This research study examines the effects of changes in emissions on climate and the resulting feedback of climate on air quality in Los Angeles, the Central Valley, and Atlanta during the next 50 years. In addition to applying A1B and B1 IPCC-SRES emission factors to the 2005 U.S. National Emission Inventory to develop future air pollutant scenarios, this project investigates the effects on emissions due to implementing a future fleet of ethanol-gasoline (85% ethanol-15% gasoline), plug-in gasoline-electric hybrids, and wind-electrolysis-hydrogen-fuel-cell vehicles. Of interest is determining whether such vehicles will increase or decrease O_3 and PAN in different parts of the U.S. and how global warming may affect their emissions. Finally, the researchers are considering the contribution of Asian emissions to U.S. pollution. It has been suggested that higher future emissions from Asia will increase urban air quality problems in California and the west , and this research is intended to provide useful information on this issue.

D.1.6.6. *University of Michigan*

This research project investigates the impact of future climate and emissions of air quality in the U.S. with a focus on O_3 and mercury. The University of Michigan uses linked gas-phase and aqueous photochemistry models and a new approach for representing the interaction between aerosols and tropospheric chemistry. Importantly, the meteorology derived from linked global circulation and chemistry/transport models includes event-specific aerosol impacts on climate. Model correlations of O_3 with temperature are being used as a basis for evaluating accuracy of the predicted response to climate. Other species correlations (O_3-CO, O_3-NOy, O_3-PAN) are also investigated as indicators for the effect of global emissions on air quality. For mercury, the project aims to identify the relative impact of local emissions and global transport in two regions where mercury has caused environmental damage (the Great Lakes and Florida). EPA field measurements in those regions will be used to evaluate model accuracy. A series of species correlations will be investigated as possible measurement-based evidence for the impact of local versus global emissions. Finally, correlations between reactive mercury and O_3 are being investigated to determine whether O_3 formation also affects mercury.

D.1.6.7. *North Carolina State University*

An overarching goal of the proposed research is to develop a community global-through-urban model framework that fully couples meteorology and chemistry and contains state-of-the-science treatments for O_3, $PM_{2.5}$, and Hg in both troposphere and stratosphere at all scales. Application of this unified model with consistent physics in a two-way nesting mode allows the researchers to examine the two-way feedbacks between climate changes and air quality and determine their importance in quantifying the impact of global changes on air quality. Sensitivity simulations with respect to inputs, configurations, resolutions, and physics help quantify the uncertainties in these model parameters. In addition, a unified model will improve our scientific understanding of the interactions among multiple pollutants and multiple processes (e.g., transport, chemistry, radiation, removal). Results from this project aim to inform policy makers about current and future integrated emission control strategies for multiple pollutants in a changing world.

D.1.6.8. ***Harvard University***

The proposed research by Harvard University builds on previous work that resulted in the construction of powerful and versatile machinery for investigating the effects of climate change on air quality and mercury deposition. This global-regional model capability will be used to address three critical issues over the 2000-2050 time horizon. First, the potential range of global change impacts on air quality is being assessed through consideration of an ensemble of scenarios for greenhouse gas and air pollutant emissions. Second, a series of sensitivity simulations is being carried out to investigate the effects of global climate and emission changes on intercontinental transport of pollution to the U.S. Finally, taking advantage of the capability for dynamic coupling of mercury between atmospheric, oceanic, and terrestrial reservoirs, the Harvard group examines mercury deposition to ecosystems, including how climate change might perturb the cycling of mercury between the atmosphere and surface reservoir. This set of projects will provide important information to policymakers as they consider issues such as co-benefits of greenhouse gas reductions, long-range transport of air pollutants, mercury deposition, and the effects of global change on regional air quality.

D.1.6.9. ***Carnegie Mellon University***

Future changes in climate, biogenic emissions, and long-range transport of pollution may provide additional challenges to air quality management in the U.S. The goal of the CMU study is to quantify the expected magnitude and range of these impacts on ozone, $PM_{2.5}$, $PM_{2.5\text{-}10}$, and ultrafine PM concentrations, visibility, mercury, and acid deposition. This project builds on previous work by CMU that resulted in a coupled global-regional climate and air pollution modeling system. The system is being extended to incorporate and account for climate-sensitive emissions (e.g., biogenic, ammonia, evaporative emissions, etc.), recent developments in understanding of the formation and partitioning of secondary organic aerosol, and the volatility of primary organic aerosol components, mercury atmospheric chemistry and deposition, and ultrafine aerosol size-composition distribution. The researchers also are using a new approach for screening and selecting climate scenarios for regional air quality simulations: an ensemble of approximately 30 years of future climate is screened to select both "representative" years but also more extreme (colder-warmer, wetter-drier, clearer-cloudier) years for uncertainty analysis. Finally, the CMU group is conducting a range of sensitivity simulations and alternative future scenarios to explore uncertainties associated with future emissions. The ultimate goal of this research is to provide insights and tools to inform air quality management decisions about the impacts of global climate and emission changes on U.S. air quality.

D.1.6.10. ***Washington State University***

This proposal builds on current research by WSU on the effects of global change on continental and regional air quality to include quantitative estimates of uncertainties. An ensemble modeling approach is being used to develop a quantitative measure of the uncertainty in the WSU modeling framework in comparison to current 1990-1999 observations and to project these uncertainties into the future. Bayesian analyses of the coupled global-regional model configurations for a base climate period (1990-1999) are conducted to produce weighted ensemble members based upon their skill in representing observed climate and air quality. Using this analysis, the number of ensemble members for future climate runs will be reduced to those that provide significant skill to the overall composite. In addition, the WSU group is quantitatively addressing the uncertainties that accompany projections of future emissions, including changes in landcover, urbanization, biogenic emissions, and fire emissions. Combining the reduced ensemble set with a range of potential emission scenarios in a factorial design encompasses a number of model/emission scenarios so that quantitative estimates of the air quality impact and uncertainties associated with both modeling errors and emission scenarios are obtained.

APPENDIX E
MODELING APPROACH FOR INTRAMURAL PROJECT ON CLIMATE IMPACTS ON REGIONAL AIR QUALITY

As described in the main body of this report, a number of modeling studies have been developed to support this assessment of potential impacts of climate on air quality. In addition to the extramural projects supported through the National Center for Environmental Research (NCER) (see Appendix 4), an intramural modeling study referred to as the Climate Impacts on Regional Air Quality (CIRAQ) project was initiated in 2002. CIRAQ is organized into two phases: Phase I, where the focus is the impact of future climate on air quality if anthropogenic emission sources remained at current levels and Phase II, where the focus is the impact on air quality both from future climate and future emission scenarios for ozone (O_3) and aerosol-related emissions.

The CIRAQ project was separated into Phase I and Phase II to distinguish the influence of future climate scenarios separately from changes in emissions that effect O_3 and $PM_{2.5}$. In the December 2000 workshop (see Chapter 1 of this report), this approach was discussed, and it was agreed upon as necessary for teasing out these different influences. The schedule for Phase I was organized to contribute results to this 2007 interim report, and Phase II will be completed for the 2010 final report on climate impacts on national air quality. The future emission scenarios that will be used for Phase II of CIRAQ have been under development in the EPA Office of Research and Development (see Appendix 6) while Phase I has been underway.

Another decision made in the design of CIRAQ was that multiple years of simulation were needed to insure that interannual variability would not be misinterpreted as climate change in the comparison of current to future simulations. Interannual variability in meteorological conditions such as temperature and precipitation can have a strong effect on air quality, yet it is driven by periodic patterns such as the El Niño-Southern Oscillation (ENSO) or North American Oscillation (NAO) cycles. These ENSO and NAO cycles are part of natural climate variability and not related directly to climate warming from greenhouse gases. The schedule for this project was used to determine the maximum number of years that could be simulated for the project. Specifically, 10 years of meteorology and 5 years of air quality were modeled each for the current and future periods.

To study potential impacts of future climate on air quality, models are needed to simulate hypothetical future scenarios. These models must include processes that are involved in global-scale climate as well as processes that are involved in regional-scale air quality. A dynamical downscaling approach (Leung et al., 2003) was taken that links global scale climate and chemistry models with regional scale meteorology and air quality models. In this way, global and hemispheric influences on climate and long-range transport of pollutants can be incorporated into the regional predictions. Below, a description of each of these global and regional modeling components is described along with some background on why each of the models or options was chosen.

For the global scale models used in this study, the CIRAQ project coordinated with several extramural projects supported by NCER grants. The global climate model (GCM) is derived from the Goddard Institute for Space Studies (GISS) II' model, as described by Mickley et al. (2004). A benefit from this model is that it also includes a tropospheric O_3 chemistry model (Mickley et al., 1999) that could provide chemical boundary conditions for O_3 and O_3 precursors to the regional scale air quality model. Consistency between the global climate and chemistry was another criterion for the CIRAQ modeling simulations, so that the climate and chemical boundary conditions for the regional model would be consistent. The GCM has a horizontal resolution of 4º latitude and 5º longitude and nine vertical layers in a sigma coordinate system extending from the surface to 10 mb. The global climate simulation covers the period 1950-2055, with greenhouse gas concentrations updated annually using observations for 1950-2000 (Hansen et al., 2002) and the A1B scenario from the IPCC for 2000-2055 (IPCC, 2000). The GISS II’ GCM’s radiation scheme assumes present-day climatological values for O_3 and aerosol concentrations, i.e., without any feedbacks due to future concentration changes. These GCM simulations were developed by Dr. Loretta Mickley at Harvard University, and the GCM simulation is described in Mickley et al. (2004). Support was initially provided by the intramural CIRAQ project for these simulations, and Dr. Mickley is also a co-investigator on the NCER-funded grant at Harvard (PI: Dr. Daniel Jacob), where a new version of the GISS GCM is now being coupled with their GEOS-Chem global chemistry model.

The regionally downscaled climate simulations for the CIRAQ project were developed by Dr. Ruby Leung, who is a leading expert in dynamical downscaling from Pacific Northwest National Laboratory. A regional climate model (RCM) based on the Penn State/National Center for Atmospheric Research (NCAR) Mesocale Model (MM5) (Grell et al., 1994) was used to downscale the GCM output for 1990-2003 and 2045-2055. Climate fields, at a temporal resolution of 6 hours, from Dr. Mickley’s GISS II’ simulations were used as lateral boundary conditions for these RCM simulations, and the same CO_2-equivalent concentrations were used within the RCM domain as used in the GCM simulations. Dr. Leung’s RCM simulations were designed with a two-way nested configuration with 108 km and 36 km horizontal resolution for the outer and inner domains, respectively and 23 vertical layers (Leung and Gustafson, 2005). Unlike standard MM5 simulations for air quality modeling, no assimilation of observational data was used for the current RCM simulations. The primary reasons for this were to evaluate the

RCM simulations under current climate to establish the model performance and to insure consistency between the current and future simulations. MM5 options used included the Grell cumulus parameterization scheme with shallow convection, Reisner1 mixed phase cloud microphysics, the Medium Range Forecast Model (MRF) planetary-boundary-layer scheme, the NOAH land-surface model, and the Rapid Radiative Transfer model (RRTM). Further discussion of the physics parameterizations used is provided in Leung et al., (2003). In general, choices were made to preserve the large-scale dynamical features of the GCM simulation rather than attempt to match present observed climatological patterns. This requirement distinguishes this approach from that taken by Liang et al. (2006) and Hogrefe et al. (2004), where MM5 options were chosen that evaluated best against observational data within the domain.

Dr. Leung provided the RCM hourly outputs to EPA via external hard drives and automated quality assurance steps were taken to check for corrupt or missing data files. This was critical since a total of 4 terrabytes of data were transferred. Leung and Gustafson (2005) provides a comparison of these current and future RCM simulations, where temperature increases over the continental U.S. were consistent with those predicted in the GISS II' simulation at a coarser scale. Leung and Gustafson (2005) identify a difference in the ventilation where the future RCM simulations show increases in ventilation while the GISS II' shows increased stagnation that could lead to increased or longer pollution episodes (Mickley et al., 2004). The fact that the ventilation is different between the global and the regional models is substantial since stagnation is a large driver for pollution events. Once the RCM simulation results were archived at EPA, an extensive evaluation of the RCM results during the current time period was conducted.

Evaluation of the RCM shows that the RCM-derived climate across the western U.S. was generally well simulated for all seasons. The western U.S. weather patterns, temperature, and precipitation from the RCM were similar to the North American Regional Reanalysis (NARR) during all seasons, particularly in the summer. Many of the primary weather patterns that occur over the eastern U.S. were well simulated by the RCM during the winter. However, a main component of the warm season weather patterns over the eastern U.S., the subtropical Bermuda high pressure system off the southeast U.S. coast, was not well simulated by the RCM. This could have been influenced by the Bermuda High being further east in the GCM than typically observed or because of the coarse resolution of the GCM. More detailed information about the RCM evaluation can be found in Gilliam and Cooter (2007) and Cooter et al. (2007).

For the CIRAQ project, the regional-scale air quality simulations were conducted using the CMAQ model version 4.5 (Byun and Schere, 2006) for the two 5-year periods "1999-2003" and "2048-2052." These years are placed in quotes to emphasize that the simulations are climatological representations of present and future air quality under the A1B scenario and are not intended to represent or predict the actual day-to-day variations in pollutant concentrations for either the present or future modeling periods. The 5 years of simulation for the current and the future time periods was the maximum number of years that could be completed on the schedule for this 2007 report and provides the best current estimate of interannual variability when estimating air quality changes with future climate. The current years "1999-2003" were selected because they were prior to the NOx SIP Call that was implemented in May 2004 (U.S. EPA, 2005) and because it represents the most recent emission inventory estimates of 2001. Results do suggest that it was important to consider interannual variability as well as an extended summer season for O_3, where the Leung and Gustafson (2005) RCM simulation scenario suggests an extension of the O_3 season into the fall.

CMAQ options used included the Statewide Air Pollution Research Center (SAPRC) chemical mechanism (Carter, 2000), the Rosenbrock chemical solver (Sandu et al., 1997), and the Regional Acid Deposition Model (RADM) cloud scheme. The domain, slightly smaller than the innermost downscaled MM5 domain, encompassed the entire continental U.S., parts of Canada and Mexico, and the surrounding oceans at a horizontal resolution of 36 km and with 14 vertical layers. The Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (Houyoux et. al., 2000) version 2.2 was used to calculate the plume rise in preparing daily emissions inputs consistent with the meteorology. Biogenic emissions were computed using the Biogenic Emissions Inventory System (BEIS) (Pierce et al., 1998) version 3.13 and the downscaled RCM outputs. Anthropogenic emissions were based on the U.S. Environmental Protection Agency 2001 National Emission Inventory (NEI). NEI inventories typically are developed incrementally for every third year, and 2001 was the most recent time period available for this study.

Chemical boundary conditions for O_3 and O_3precursors were taken from monthly averaged outputs of the tropospheric O_3 chemistry module coupled to the GISS II' GCM. While results included in this report focus on O_3, the CMAQ simulations also included aerosol predictions. Boundary conditions for the aerosols were provided by Dr. Peter Adams from Carnegie Mellon University, who has an NCER grant for climate and air quality. Those boundary conditions were also based on a GISS II'-driven chemistry model for aerosols; however, the GISS II' GCM was driven by the IPCC A2 scenario (Racherla and Adams, 2006). This difference should not be substantial at 2050 since the IPCC climate scenarios do not diverge drastically until post-2050.

Results from the CMAQ simulations were evaluated against observed O_3 data from the Air Quality System (AQS) observational network. These evaluations were based on the comparisons of the observed and modeled distribution of O_3 during the summer season because these climatological simulations were not designed to replicate the actual series of changes in O_3 on specific days. Results showed a substantial over-prediction bias in summertime O_3 that appears to be influenced primarily by the SAPRC chemical mechanism. A secondary cause of the O_3 bias is the meteorological prediction uncertainties from the RCM. Gilliam and Cooter (2007) show that the RCM simulations used in the CIRAQ study, under-predicted precipitation and had a positive bias in temperature in the areas of the Southeast and Midwest, where the over-prediction biases were most evident. The full details from this analysis can be found in Nolte et al. (2007). Since the CIRAQ study is focused on the change in O_3 from current to future climate scenarios, it is anticipated that this O_3 bias would exist in the current and future simulations and, therefore, be cancelled out to some degree.

The SAPRC chemical mechanism was chosen for the CIRAQ CMAQ simulations because it is considered a more detailed, up-to-date mechanism than CB4 (Gery et al., 1989) and because the chemical groupings are more consistent with the chemical families in the Harvard global chemistry model (Mickley et al., 2004). Based on the findings from this study, it would be preferable to include CMAQ simulations using the new CB05 chemical mechanism now available in the most recent release of CMAQ version 4.6 in the second phase of this CIRAQ study. This could require development of current climate CMAQ CB05 simulations for comparison as well; therefore, it would not be possible to follow the 5-year time series approach used in Phase I of this study.

As described earlier, Phase I of this project was only intended to focus on the impacts of future climate on air quality without including any future scenarios for the anthropogenic emissions for O_3 and $PM_{2.5}$. In preparation for Phase II, it was, however, decided that a simplified sensitivity test that adjusted the current anthropogenic emissions based on IPCC scaling factors would be helpful. For the future simulation with emission changes, scaling factors consistent with the A1B AIM scenario for the OECD90 region were applied for all anthropogenic emission sectors, as shown in Table E-1. This control-case approach is admittedly simplistic and is intended to be a minimal sensitivity test of the range of impacts that could result from the A1B scenario.

Results from this sensitivity test with future emissions suggested that substantial decreases in O_3 would occur under the future A1B climate scenario and these A1B AIM OECD90-based reductions in anthropogenic emissions. The modeling results had suggested a 2-5 ppb increase in O_3 with future climate only (i.e., no change in current anthropogenic emissions); therefore, the change in emissions is anticipated to have a much larger influence in the model predicted changes in O_3. While that is not unexpected, the results highlight how important the selection of future emission scenarios will be. If the IPCC A2 scenario had been

Table E-1. Scaling factors for future emissions sensitivity test

Species	A1B AIM 2050 Scaling Factor (relative to 2000)
NOx	0.52
SO_2	0.37
VOCs	0.79
CO	1.5

selected for this study, the conclusions would have been conversely different where future emissions and future climate would results in dramatic increases in O_3, as shown by Hogrefe et al. (2004). While it is far more likely that NOx and SO_2 emissions will be reduced in the future rather than as the A2 scenario suggests, the exact amount of reduction is more uncertain the further into the future these scenarios are developed. Therefore, the conclusion from this analysis is that Phase II of the CIRAQ project needs to focus on multiple 2050 anthropogenic emission scenarios to develop a plausible range of results.

This conclusion that a series of simulations is needed with different options or choices is a common recommendation from the evaluation of the CIRAQ CMAQ results and the sensitivity tests with A1B emission scaling factors described above. It leads to new challenges for Phase II of CIRAQ since 5-year simulations are not feasible for multiple chemical mechanisms and future emission scenarios. Interannual variability in the current series of simulations can be used to help guide selection of shorter time periods that represent extreme and average years. This may be the best approach for reducing the number of simulation years and increasing the range of options and sensitivity tests.

For the 2007 interim report and current manuscripts developed for CIRAQ, the primary focus has been on O_3 rather than $PM_{2.5}$. The current vs. future $PM_{2.5}$ results are more uncertain and complicated since PM is composed of multiple chemical species, the concentrations of which are influenced by different emission sources. Preliminary analyses suggest that the ventilation or stagnation in the future scenarios could have a substantial influence on the results, and discrepancies between the global and regional simulations of future stagnation frequency lend more uncertainty to the future $PM_{2.5}$ change estimates. Further, several factors could influence the future primary $PM_{2.5}$ emissions that can be directly influenced by future climate conditions, such as forest fires and windblown dust. Current emissions from these types of sources are static and do not vary based on changes in climate. Another factor of uncertainty is the influence of future air quality changes on the regional climate, where for example lower concentrations of sulfate aerosols could lead to more positive net radiative forcing. New modeling tools are becoming available, such as WRF-CMAQ, which includes feedbacks from air quality to regional climate. These new modeling tools are needed to better understand how climate and air quality interact in future scenarios and increase our confidence in the future scenarios for $PM_{2.5}$.

E.1. REFERENCES

Byun, D; Schere, KL. (2006) Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. Appl Mech Rev 59:51-77.

Carter, WPL. (2000) Implementation of the SAPRC-99 chemical mechanism into the Models-3 framework. Report to the United States Environmental Protection Agency, January 29, 2000. Available online at http://pah.cert.ucr.edu/ftp/pub/carter/pubs/s99mod3.pdf.

Cooter, EJ; Gilliam, RC; Swall, J; et al. (2007) Evaluation of 700 mb steering level winds from downscaled global climate model results. Part II: Comparison of reanalysis and regional climate model data. J Appl Meteorol Climatol: in NOAA review.

Gery, MW; Whitten, GZ; Killus, JP; et al. (1989) A photochemical kinetics mechanism for urban and regional scale computer modeling. J Geophys Res 94(D10):12,925-12,956.

Gilliam, RC; Cooter, EJ. (2007) Evaluation of the large-scale weather patterns, temperature, and precipitation of a 10-year GISS regional climate simulation. in review

Grell, G; Dudhia, J; Stauffer, DR. (1994) A description of the fifth generation Penn State/NCAR mesoscale model (MM5). NCAR Tech Note, NCAR/TN-398+STR. NCAR (National Center for Atmospheric Research), Boulder, CO. Available online at http://www.mmm.ucar.edu/mm5/documents/mm5-desc-doc.html.

Hansen, J; Sato, M; Nazarenko, L; et al. (2002). Climate forcings in Goddard Institute for Space Studies SI2000 simulations. J Geophys Res 107(D18):4347, doi10.1029/2001JD001143.

Hogrefe, C; Lynn, B; Civerolo, K; et al. (2004) Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. J Geophys Res. 109:D22301, doi:10.1029/2004JD004690.

Houyoux, M.R., J.M. Vukovich, C.J. Coats, Jr., N.W. Wheeler, and P.S. Kasibhatla, (2000). Emission inventory development and processing for the seasonal model for regional air quality (SMRAQ) project. J.. Geophys. Res., Atmospheres, 105(D7): 9079-9090.

IPCC (Intergovernmental Panal on Climate Change). (2000) Special report on emissions scenarios. New York, NY: Intergovernmental Panel on Climate Change. Available online at http://www.grida.no/climate/ipcc/emission/.

Leung, LR; Qian, Y; Bian, X. (2003) Hydroclimate of the western United States based on observations and regional climate simulation of 1981-2000. Part I:Seasonal statistics. J Climate 16(12):1892-1911.

Leung, LR; Gustafson, WI, Jr. (2005) Potential regional climate change and implications to U.S. air quality. Geophys Res Lett 32(16):L16711, doi:10.1029/2005.

Liang X-Z; Pan, P; Zhu, J; et al. (2006) Regional climate model downscaling of the U.S. summer climate. J Geophys Res 111(D10):D10108, doi:10.1029/2005JD006685.

Mickley, LJ; Jacob, DJ; Field, BD; et al. (2004) Effects of future climate change on regional air pollution episodes in the United States. Geophys Res Lett 31:L24103, doi:10.1029/2004GL021216.

Mickley, LJ; Murti, PP; Jacob, DJ; et al. (1999) Radiative forcing from tropospheric ozone calculated with a unified chemistry-climate model. J Geophys Res 104(D23):30,153-30,172.

Nolte et al. (2007), submitted/under peer review.

Pierce, T; Geron, C; Bender, L; et al. (1998) Influence of increased isoprene emissions on regional ozone modeling. J Geophys Res 103(D19):25,611-25,629.

Racherla, PN; Adams, PJ. (2006) Sensitivity of global tropospheric ozone and fine particulate matter concentrations to climate change. J Geophys Res 111(D24):D24103, doi10.1029/2005JD006939.

Sandu, A, Verwer, JG; Blom, JG. (1997) Benchmarking stiff ODE solvers for atmospheric chemistry problems II: Rosenbrock solvers. Atmos Environ 31(20):3459-3472.

U.S. EPA (Environmental Protection Agency). (2005) Evaluating ozone control programs in the Eastern United States: focus on the NO_x budget trading program, 2004. Office of Air and Radiation, Washington, DC: EPA/454/K-05/001. Available online at http://www.epa.gov/airtrends/2005/ozonenbp.pdf.

APPENDIX F
USING MARKAL TO GENERATE EMISSIONS GROWTH PROJECTIONS FOR THE EPA GCRP AIR QUALITY ASSESSMENT

F.1. INTRODUCTION

F.1.1. Background

The U.S. EPA contributes to the U.S. Climate Change Science Program (CCSP) by working to develop an understanding of the potential environmental impacts of anticipated future global changes, including population growth and migration, economic growth, land use change, technology change, climate change, and government actions and policies. As a central component of EPA's contribution to the CCSP, the EPA Office of Research and Development's Global Change Air Quality Assessment is building upon traditional EPA expertise by examining the connection between these global changes and air quality.

Air pollutants of particular concern are tropospheric ozone (O_3) and fine particulate matter ($PM_{2.5}$). These pollutants, which are components of urban smog, contribute to human respiratory problems, damage ecosystems, and reduce visibility, among other impacts. They are formed through atmospheric reactions of precursor emissions. Precursors to O_3 include nitrogen oxides (NOx) and volatile organic compounds (VOCs). In most areas of the U.S., VOCs from vegetation are in sufficient concentration that NOx is the limiting chemical species in O_3 formation. The predominant source of NOx emissions is the combustion of fossil fuels. Fine PM formation can involve many chemical species, but sulfur oxides (SOx), NOx, elemental and organic carbon, and ammonia are common precursors. Coal and diesel combustion are sources of SOx, and carbonaceous PM is most often a product of incomplete combustion.

Human health concerns have led to ambient air quality standards being implemented for O_3 and particulates. Many areas of the country are not currently in attainment with these standards, however, leading to recent air quality legislation, including the NOx SIP Call (U.S. EPA, 2006a), Clean Air Interstate Rule (CAIR) (U.S. EPA, 2005), Heavy Duty Highway Diesel Rule (U.S. EPA, 2007a), and Nonroad Diesel Rule (U.S. EPA, 2004). These regulations are expected to bring most urban areas of the U.S. into attainment by 2015.

The ability of these programs to maintain air quality further into the future is less certain. The U.S. population is projected to continue to grow through 2050 as is the U.S. economy. These factors potentially yield increases in emissions from additional demands for energy and transportation services, among others. Further, climate change projections predict generally warmer temperatures, exacerbating pollution by increasing summer energy demands for cooling and by increasing the photochemical reaction rates that produce tropospheric O_3. Countering these factors, economic and policy drivers will likely result in technology change, including energy efficiency improvements and reduced pollutant emissions rates. Characterizing the relative and combined impact of these factors, thus, is an important step in anticipating future-year air quality and in identifying whether additional technologies or policy measures will be necessary to protect human health and the environment. This characterization is one of the primary products of the Global Change Air Quality Assessment, with contributing work being carried out both through intramural and extramural research activities.

F.1.2. Conceptual Framework

The intramural modeling activities of the Global Change Air Quality Assessment are aimed at evaluating the individual and combined impacts of climate and emissions changes on air quality in 2050. The work described in the main body of the 2007 Interim Assessment Report has largely focused on characterizing climate change impacts. Air quality modeling was carried out with year 2000 emissions for two cases of meteorology thought to be representative of the years 2000 and 2050, respectively. The 2012 Final Assessment Report will augment the 2007 analysis by evaluating the 2050 meteorological case with projected emissions for 2050.

The relationship between the modeling runs is illustrated in Figure F-1. This experimental design is anticipated to allow the meteorological and emissions signals on air quality to be evaluated individually and together.

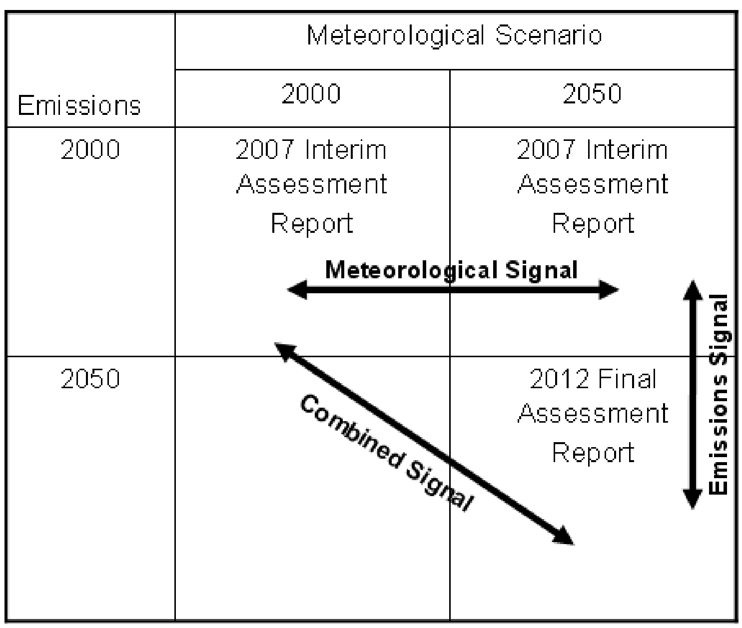

Figure F-1. Experimental design of the global change air quality assessment.

One of the major challenges in carrying out this experimental design is the generation of a realistic and representative emissions inventory for 2050. A step in creating such an inventory was to develop a conceptual model that outlines the various system components and linkages that influence future year emissions and air quality. Figure F-2 is a graphical depiction of this conceptual model.

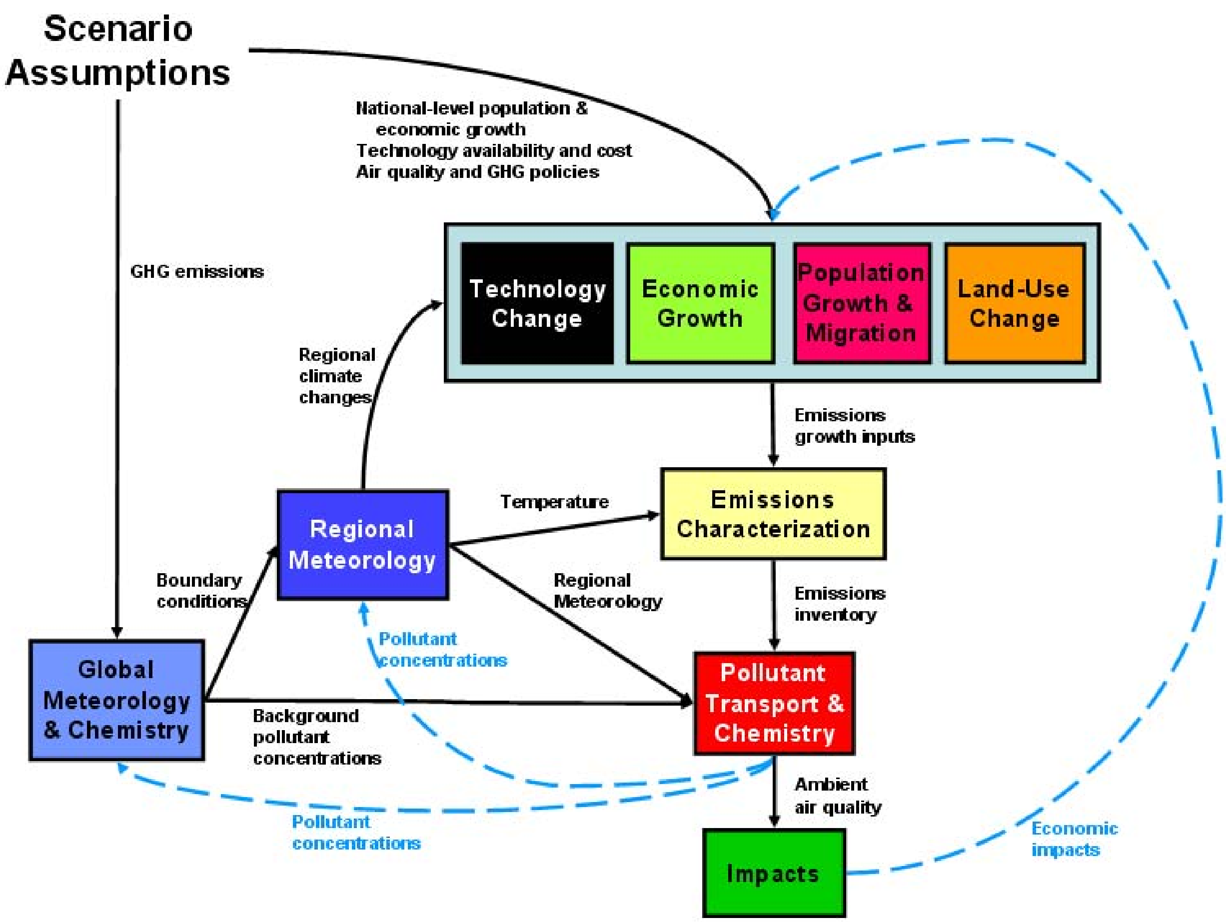

Figure F-2. Conceptual framework outlining the influence of global change factors on air quality.

At this high level, the overall system is driven by various global- and national-scale assumptions. Assumed global greenhouse gas emissions drive global circulation patterns, meteorology, and chemistry. These, in turn, affect regional meteorology, temperature-sensitive anthropogenic and biogenic emissions, and pollutant transport and chemistry. Assumptions also drive technology change, economic growth, population growth and migration, and land-use change which are, themselves, interrelated. These factors have great implications on the quantity and location of pollutant emissions and, thus, on air quality. The blue text and lines represent feedbacks that may be important. For example, pollutants such as aerosols and black carbon have radiative forcings that can affect regional climate. Similarly, health and environmental impacts may lead to better or worse economic conditions and changes in mortality rates, thereby affecting some of the drivers for emissions growth.

In Figure F-3, the box encompassing technology change, economic growth, population growth and migration, and land-use change is examined in more detail.

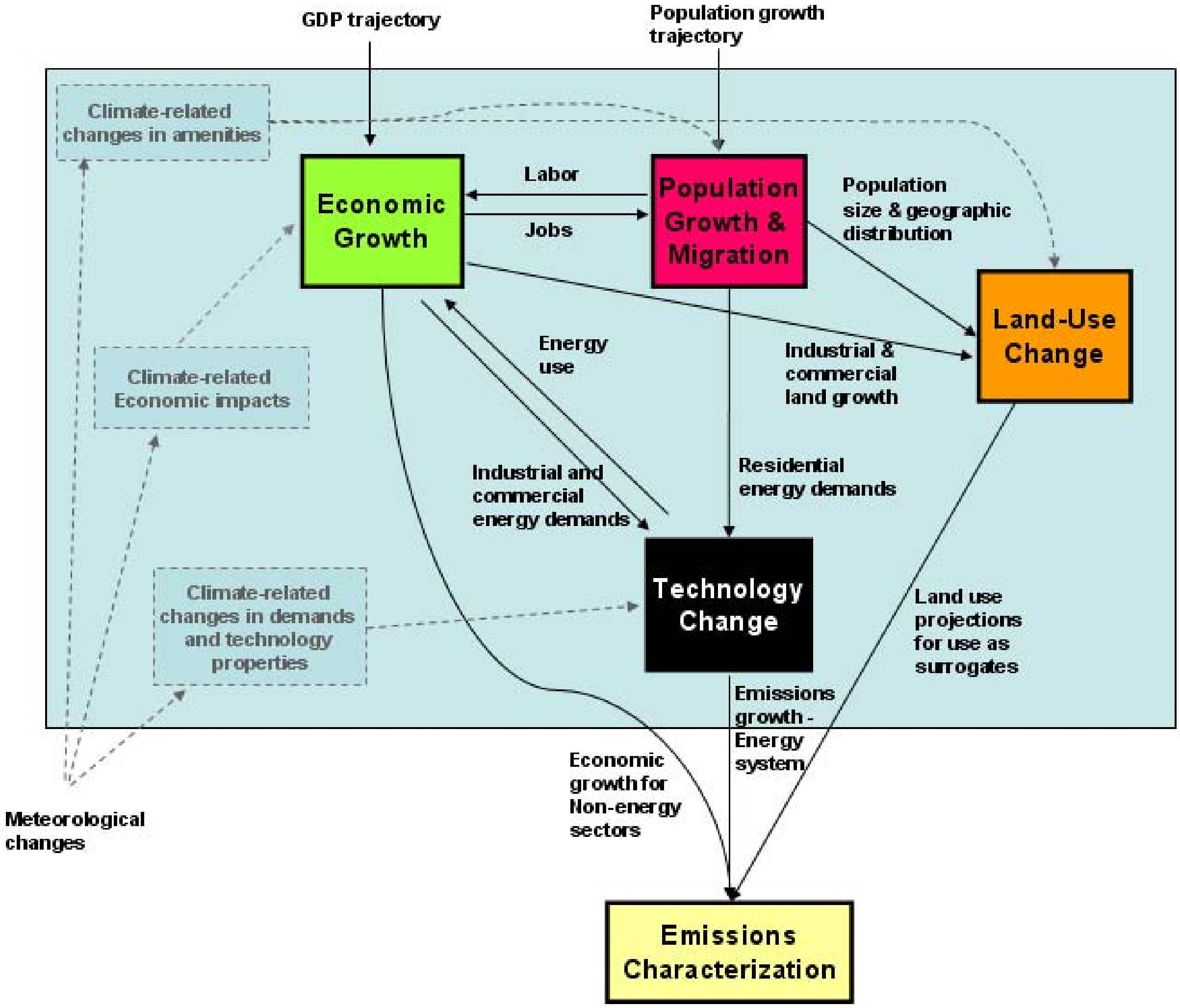

Figure F-3. Conceptual model detail on the factors affecting future-year emissions growth.

This figure indicates the relationship between economic growth and population changes. Economic growth is a function of the cost of labor while population migration is affected by the availability of jobs. Both economic growth and population changes drive energy demands and may indirectly influence changes in the technologies. Population growth and migration have an effect on land use, including the transformation of rural, agricultural, and forest land to accommodate housing. These changes, in turn, affect the quantity, nature, and geographic distribution of both biogenic and anthropogenic emissions. Climate change has the potential to impact processes represented within many of these components. For example, climate changes can change the attractiveness of living in various areas, the ability to use land for agricultural and recreational purposes, and demands for energy services such as heating and cooling. The feedbacks indicated in Figure F-2, including the effects on the economy and population resulting from air quality impacts, are not included in Figure F-3.

F.1.3. Intramural Emissions Modeling Effort for the 2010 Assessment Report

Developing emissions projections for the 2010 assessment report involves realizing the conceptual model illustrated in Figures F-2 and F-3 with a modeling methodology. The level of available resources necessitates the leveraging of existing expertise, models, and tools. For example, within its ongoing regulatory and research air quality modeling applications, EPA uses the Sparse Matrix Operator Kernel Emissions (SMOKE) processing model, the MM5 regional-scale meteorological model, and the CMAQ air quality model. Given future-year projections of meteorology and emissions, these models readily can be applied to evaluate a 2050 emissions scenario.

Generating a 2050 emissions inventory for input into SMOKE is not straightforward, however. EPA typically uses the Integrated Planning Model, or IPM, to model fuel use and emissions from the electricity production sector. IPM has been applied to model past and present emissions, as well as to project emissions to a near-term future year, such as 2007, 2015, or 2020. IPM was not developed with the goal of producing emissions projections to 2050. Similarly, EPA's current methods for generating near-term emissions projections for mobile, residential, commercial, industrial, and biogenic emissions, among others, have a limited ability to account for many types of changes that are expected over a nearly 50-year time period. These include changes such as the introduction of new technologies (e.g., advanced nuclear power, coal gasification with carbon capture and sequestration, plug-in gasoline-electric hybrids, and hydrogen fuel cell vehicles), growth and redistribution of population and industries, expansion of urban and suburban areas, and changes in heating and cooling demands related to population shifts and climate change. Accounting for these factors requires the development of a new emissions projection methodology.

To this end, an emissions projection methodology is being developed that includes the EMPAX economic model, which is a state-level computational general equilibrium model of the

U.S.; the ICLUS (Integrated Climate and Land Use Scenario) system, a modeling system that links a population growth and migration model with a land use change model; and, MARKAL (MARKet ALlocation), an energy system model that projects the penetration of technologies and their associated emissions. These models and their data linkages are shown in Figure F-4.

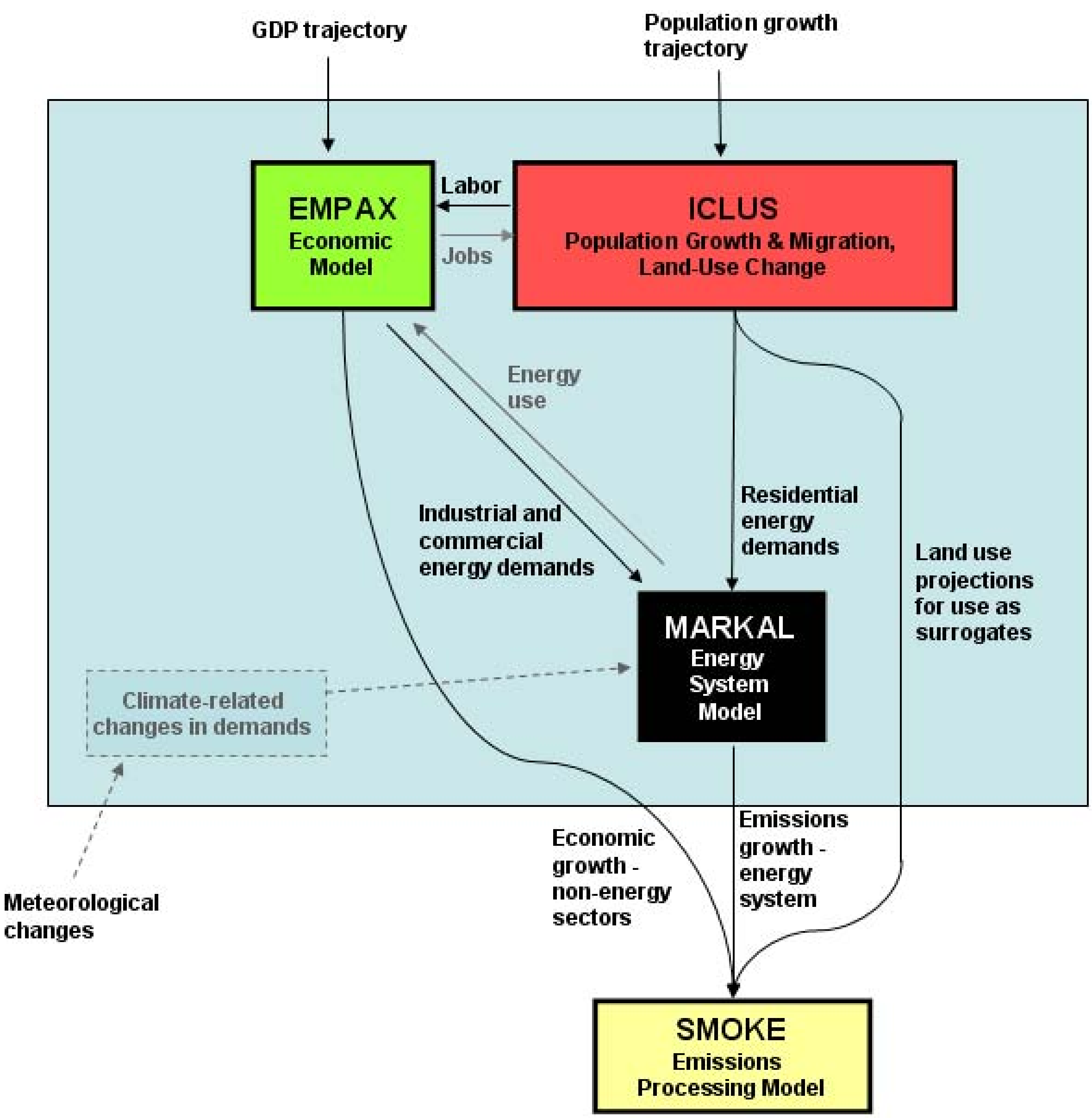

Figure F-4. Models and linkages for developing emissions growth factors.

In Figure F-4, the “Jobs,” “Labor,” and “Energy Use” linkages are deemphasized to indicate that these linkages may or may not be included in the 2012 Assessment Report, depending on available time and resources. The feasibility of including the additional climate-related linkages and feedbacks shown in Figures F-2 and F-3 is being evaluated.

The focus of this appendix is to describe the MARKAL energy-modeling component. Results from a MARKAL run illustrate the types of outputs that the model produces. The appendix concludes with a description of the process by which the MARKAL results are converted to emissions growth factors for use in SMOKE.

F.2. ENERGY SYSTEM MODELING

F.2.1. The MARKAL Energy System Model

In modeling the role of technology change on future-year emissions, the focus here is on the U.S. energy system. The energy system includes the fuels and technologies that extend from the import or extraction of fuel resources, to the conversion of these resources to useful forms, to their use in meeting energy service demands. The energy system is selected for special consideration because of the large amount of pollutant emissions that it produces. For example, current demands for transportation and electricity are met largely through the combustion of fossil fuels. Based on an analysis of the EPA's 2001 National Emissions Inventory, combustion in the U.S. is estimated to contribute approximately 95% of anthropogenic emissions of nitrogen oxides (NOx) and carbon monoxide (CO), 89% of sulfur oxides (SOx), and 87% of mercury.

Figure F-5 provides a simplified depiction of an energy system in which fossil fuels dominate. Major air pollutant emissions from each component of the system are shown.

While much of the energy system in the U.S. may be dominated by fossil fuels, renewables and advanced technologies may play an increasing role in the future. These include advanced nuclear reactors, wind and solar power, biomass and coal gasification, combined cycle natural gas systems, hydrogen fuel cell vehicles and plug-in hybrids. An alternative energy future, emphasizing renewable and advanced technologies is depicted in Figure F-6. The extent to which the future energy system evolves toward this or other alternatives will have important implications on future pollutant emissions and air quality.

For the 2012 assessment, the MARKAL model is being used to identify and evaluate the pollutant emissions associated with alternative future realizations of the U.S. energy system. The MARKAL model was developed in the late 1970s at Brookhaven National Lab in response to the oil crisis of the mid-1970s. In 1978, the International Energy Agency adopted MARKAL and created the Energy Technology and Systems Analysis Programme (ETSAP) to oversee its ongoing development (ETSAP, 2006). In addition, the U.S. Department of Energy's Energy Information Administration (EIA) made MARKAL the basis for the System for the Analysis of Global Energy Markets (SAGE) model (U.S. DOE, 2003a). SAGE is used to produce EIA's

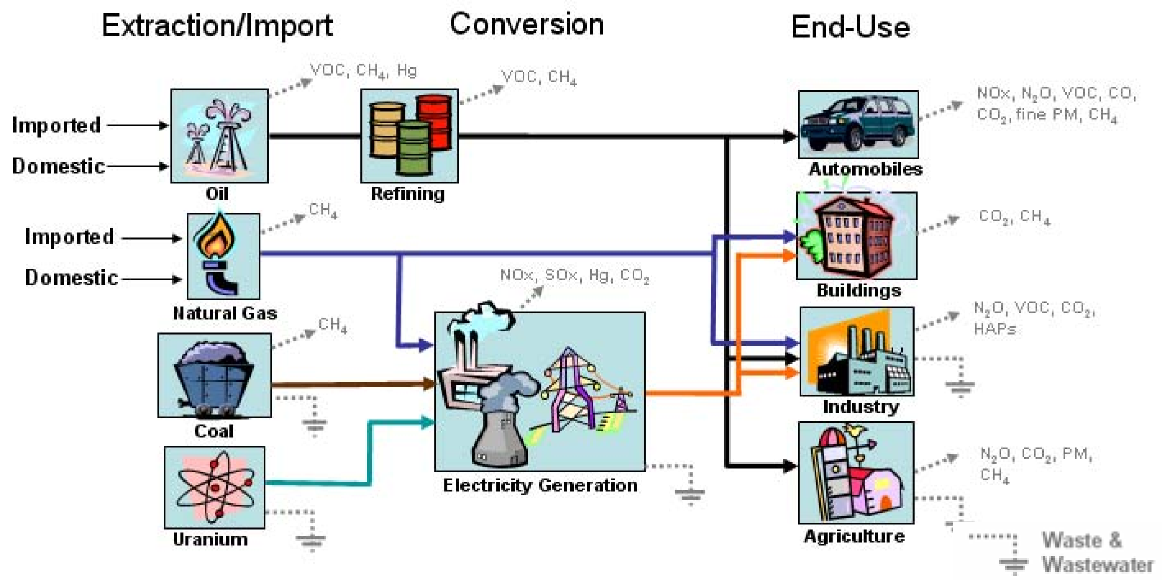

Figure F-5. A simplified depiction of an energy system, in which energy demands are largely met by fossil fuel resources and conventional nuclear technologies.

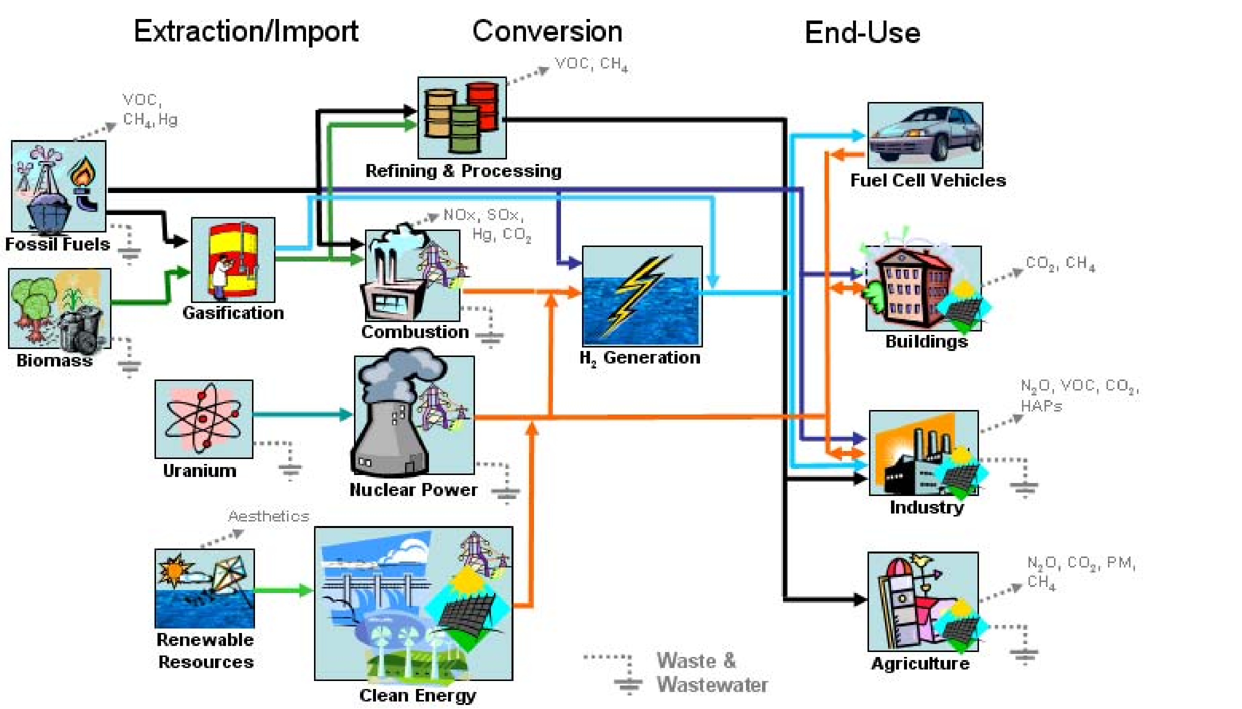

Figure F-6. A depiction of an alternative future energy system that has an increased emphasis on renewables and advanced technologies.

Annual International Energy Outlook (U.S. DOE, 2006). Altogether, MARKAL and its variants are used in approximately 40 countries around the world.

MARKAL, a data-driven, optimization model, includes a representation of the structure of an energy system. Data must be provided to characterize the specific energy system being modeled. This typically involves developing a representation of the current energy system, as well as projections of resource supplies, energy demands, and technology characteristics over a modeling horizon of 20 to 50 years. Depending on the application, the input database may scale from representing a single sector (e.g., transportation or electricity generation) to representing all energy-related sectors in the economy (e.g., transportation, residential, commercial, industrial, agricultural, and electricity production). Further, the database can define a single region, such as the continental U.S., or it can represent the system at a finer resolution, such as at the regional- or state-level, explicitly modeling resource supplies, energy demands, and technology characteristics within regions, as well as the trade of electricity and fuels among modeled regions.

Given a mathematical representation of the system as input, MARKAL uses linear or mixed-integer linear programming solution techniques to calculate the least cost technology pathway for meeting demands. Outputs of the model include a projection of the technological mix at intervals into the future, estimates of total system cost, energy demand (by type and quantity), and estimates of criteria pollutant and greenhouse gas emissions. If multiple sectors of the energy system are represented, then MARKAL can be used to identify cross-sector dynamics. For example, the introduction of a large number of vehicles powered by compressed natural gas would drive demand for natural gas. This would impact the competition for natural gas and could potentially influence the adoption of technologies within the electricity generation, residential, and commercial sectors. MARKAL can provide insight into these interactions.

MARKAL features a number of options that can be useful in tailoring it toward particular investigations. For example, MARKAL can be configured to account for demand elasticities and endogenous technological learning as well as to represent consumer hesitancy to adopt new technologies through hurdle rates. While MARKAL, by default, is configured to examine all steps of the modeling time horizon simultaneously (e.g., the model has perfect foresight in identifying the least cost technology pathway), it also can be applied in a myopic manner in which it examines the technological choices to be made for each subsequent time step independently. Further, when using this latter approach, a market share algorithm can be applied in which the market penetration of alternative technologies is a function of their relative marginal costs. An additional MARKAL option is an implementation of a methodology called Modeling to Generate Alternatives, or MGA (Brill et al., 1990). The MGA algorithm allows MARKAL to generate a set of alternative technology pathways to achieve the modeled objectives and constraints. These alternatives are constrained to be within a small cost increment of the least cost pathway. The individual solutions may be of interest while the similarity or difference among the alternatives provides an indication in the flexibility available in meeting future energy demands.

MARKAL also accommodates the consideration of uncertainties in future technology characteristics, energy service demands, and policies. The stochastic optimization option allows alternative states of the world in the future to be specified. For example, these states may differ by characteristics such as oil supply, availability of advanced nuclear power, or viability of coal capture and sequestration technologies. MARKAL then identifies the optimal short-term, least cost technology pathway that is robust given the myriad of potential futures that were represented.

The EPA has integrated MARKAL into a modeling framework that supports Monte Carlo simulation, as well as parametric and global sensitivity analyses. This framework allows sensitivities of the energy system to input assumptions and uncertainties in model outputs to be examined. Results provide powerful insight into the dynamics of the energy system that are difficult to examine using deterministic approaches alone. For example, a single deterministic optimization run may suggest that a technology is not economically competitive and thus will not penetrate the market. Global sensitivity analysis, however, can be used to identify the conditions under which that technology is competitive and the technologies with which it competes.

To apply MARKAL to the 2012 assessment, EPA is developing a regionalized U.S. EPA MARKAL database, referred to as EPA9R. The database represents the energy demands and technologies in the major sectors in the U.S. energy system, including the commercial, industrial, residential, transportation, and electricity generation sectors. These data are represented at a regional-level, with the nine modeled regions being analogous to the nine U.S. Census Bureau census divisions, shown in Figure F-7. Alaska and Hawaii are included in the Pacific region in the EPA9R database.

The EPA9R database extends from 2000 to 2050 in 5-year increments. In the process of developing a 9-region database, EPA first developed a one-region, national-scale database referred to as EPANMD (U.S. EPA, 2006b). EPANMD was released to the public in 2006, and several groups are now using the model. EPANMD, which has recently extended to 2050, is used for the MARKAL run described in this appendix. The final 2012 Assessment Report and related modeling are expected to make use of EPA9R, allowing regional energy supply and demands to be considered.

The primary source of data for populating EPANMD has been the U.S. Department of Energy's 2005 Annual Energy Outlook (AEO) report (U.S. DOE, 2003b). Versions of

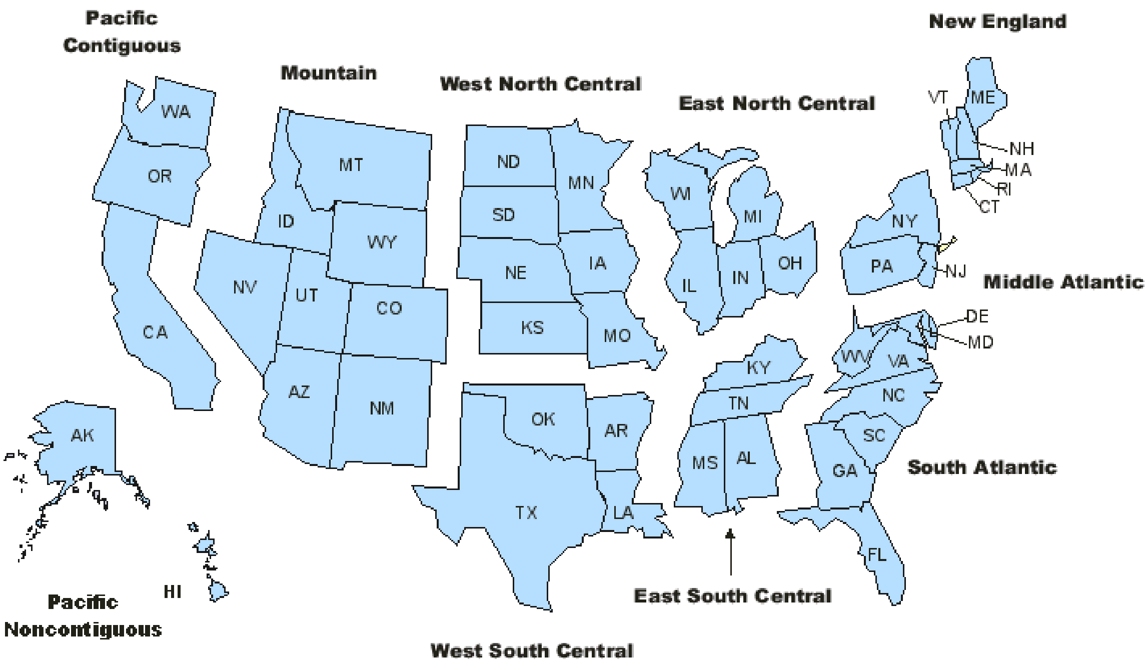

Figure F-7. Census divisions represented in the EPA9R MARKAL database.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels.

EPANMD have been updated to reflect AEO 2006 and are currently being updated to incorporate data from AEO 2007. Data for many of the technologies not represented in the AEO were derived from other widely recognized authoritative sources (e.g., the Electric Power Research Institute's Technical Assessment Guide [EPRI, 2003]) while the data characterizing light duty transportation options were obtained from the U.S. EPA's Office of Transportation and Air Quality (U.S. DOE, 2002). Most pollutant emissions factors used within the model were derived from the EPA's Air Quality and Emissions Trends Report (U.S. EPA, 2006c) and AP 42 listings (U.S. EPA, 2007b).

In 2004, EPA used an earlier version of EPANMD to produce a report that demonstrated the use of MARKAL in carrying out scenario-based analyses of the transportation sector. In 2006, a companion piece focusing on electricity generation was completed. The 2006 analysis also demonstrated how parametric and global sensitivity analysis techniques could be used to identify how the model responds to changes to various inputs. This, in turn, provides useful information in understanding model dynamics and in identifying the key inputs that drive outputs of interest (e.g., high levels of emissions).

Compared to the 2004 and 2006 reports, results presented in this appendix to the 2007 Interim Assessment Report reflect updated technology, demand, and resource supply data. Further, the electric sector has been calibrated to represent the electricity generation mix and emissions control technologies through 2020 that were included in EPA's 2006 analysis of the national ambient air quality standards for particulate matter. Major regulatory drivers included in that analysis were CAIR and the on- and off-road diesel regulations. As with the previous work, the database represents the U.S. as a single region.

F.3. APPLICATION

F.3.1. Scenario Analysis

MARKAL is a useful tool for carrying out scenario analyses of the energy system. Scenarios are internally consistent depictions of how the future may unfold, given assumptions about economic, social, political, and technological developments, as well as consumer preferences (Schwartz, 1996). Scenarios explore plausible futures by using a model or models to generate an outcome (or set of alternative outcomes) consistent with a set of motivating assumptions, sometimes called a "storyline." It is important to stress that a scenario is not a prediction but instead represents one realization of the wide-ranging potential futures.

Scenario analysis, involving the evaluation of a small number of such scenarios, aims to examine how changes in model parameters (inputs) affect outputs across sets of related storylines, rather than focusing on the results from a particular scenario. No attempt is made to consider every possible future. These comparative analyses alternately look forward ("What-if?") to examine how competing sets of input assumptions drive technology adoption and emissions, and backward ("How-could?") to identify the energy technology pathways available to meet some future environmental or technological goal. Scenarios, therefore, facilitate assessment of the consequences of varying assumptions, the range of possible futures, and trade-offs and branch points that govern choices among these futures. Results from a selected set of scenarios will serve as input to the ORD 2012 Air Quality Assessment Report.

F.3.2. Illustrative Application

To demonstrate the use of MARKAL and the types of outputs that can be generated from a scenario, a reference case storyline was identified and evaluated. While the storyline is called a reference case, it represents only one of many possible futures. The reference case was calibrated such that sectoral energy demands and fuel use through 2020 approximate projections in the U.S. Department of Energy's 2006 Annual Energy Outlook (AEO). Electric sector emissions through 2020 were constrained to approximate the EPA's 2006 PM NAAQS analysis, and thus included CAIR, the Heavy Duty Highway Diesel Rule, and the Nonroad Diesel Rule.

F.3.3. Reference Case

Outputs from MARKAL include technology penetrations for meeting various energy service demands as well as the fuel use, emissions, and costs associated with individual technologies, sectors, and the entire system. Results from the reference case are provided graphically in Figures F-8 through F-14.

Figure F-8 characterizes the system-wide primary energy use. Units are in petajoules (PJ =1015 J). The oil and petroleum category includes both imported crude oil and imported petroleum products such as gasoline. "Other" is primarily natural gas liquids. The "renewables" category includes biomass, wind, solar, hydropower, geothermal, and landfill gas combustion.

The model indicates increases in demand for each fuel category although coal use levels, to some extent, after 2035 as new electricity demands are met by other fuels.

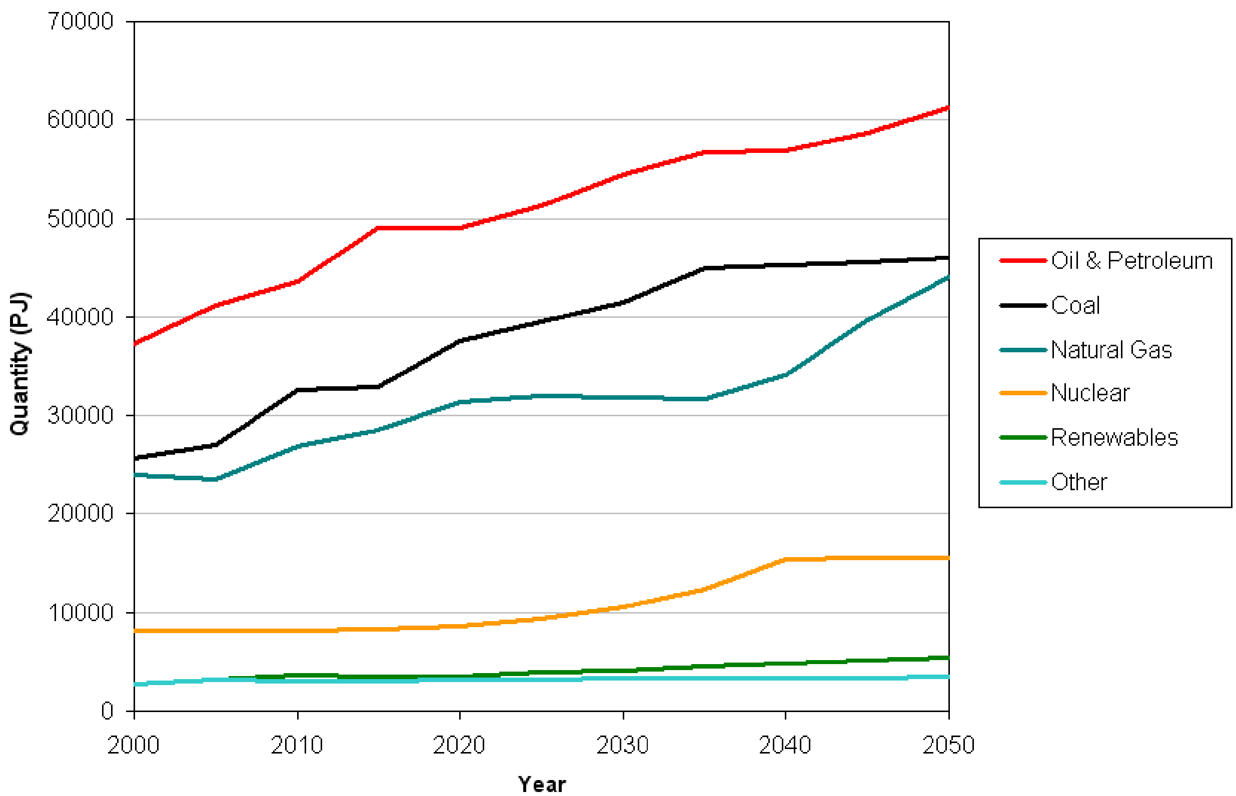

Figure F-8. System-wide energy inputs. All values are net, accounting for exports.

Figure F-9 depicts the amount of electricity generated via different types of fuels. Natural gas, coal, and nuclear power are the three major fuels used to meet increasing electricity demands.

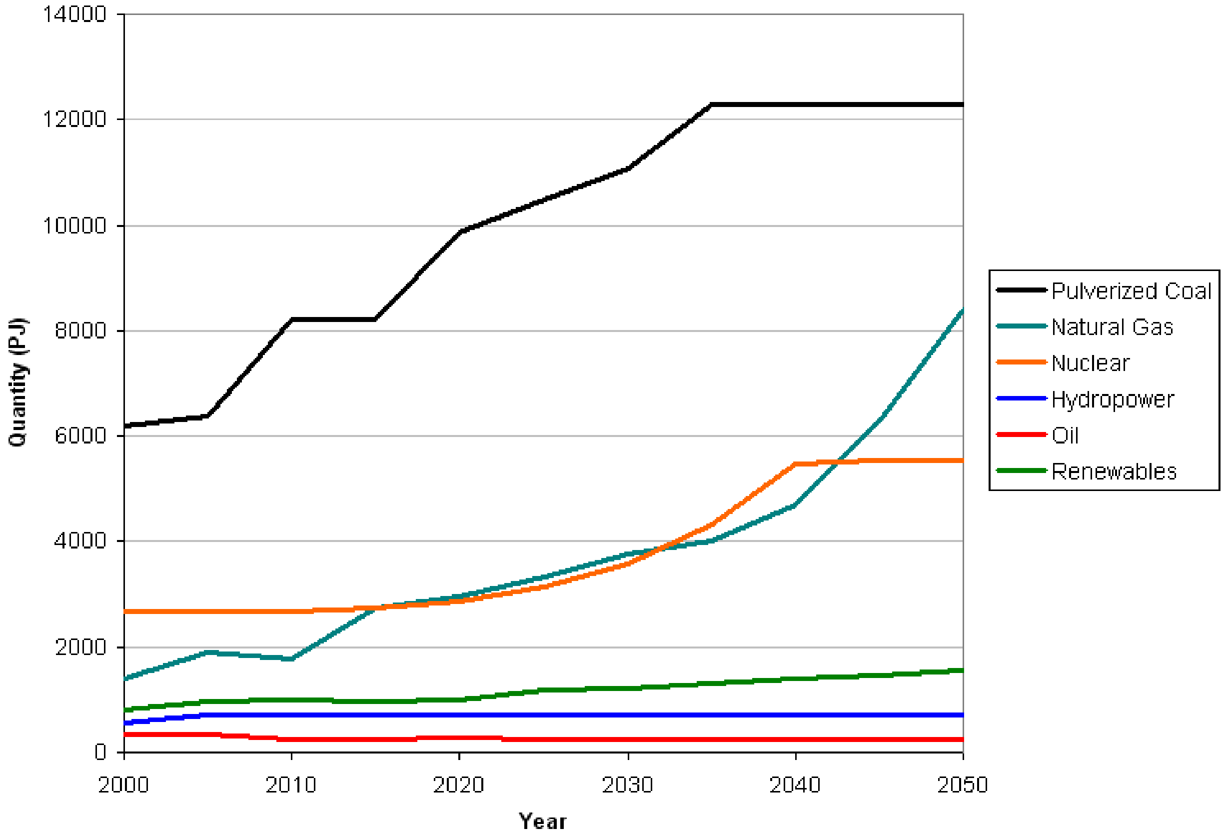

Figure F-9. Electricity generation by type of fuel. A breakdown of the renewables category is provided in Figure F-10.

Figure F-10 provides a detailed look at the amount of electricity produced by different types of renewables. Hydropower has the largest penetration of the renewable options. Constraints on hydropower resources limit its use, however. The increase in hydropower from 2000 to 2005 is an artifact of optimization as the model attempts to make maximum use of existing resources. Wind and geothermal capacities appear to increase substantially while electricity from solar power is limited until the later years in the modeling horizon.

Figure F-11 shows the mix of vehicle technologies in the light-duty fleet. In this scenario, fuel price pressures lead to the adoption of vehicles with advanced internal combustion engines (ICEs) that achieve higher efficiencies than conventional and diesel ICEs. Hybrid gasoline-electric vehicles achieve some degree of penetration, but this does not exceed 7% over the modeling period.

Figure F-12 shows the fractional change in NOx, SO_2, and CO_2 emissions over the modeling horizon, compared to 2000. System-wide, NOx emissions decline by approximately 40% from 2000 through 2050. Sulfur dioxide emissions follow a less-discernable trend and are slightly

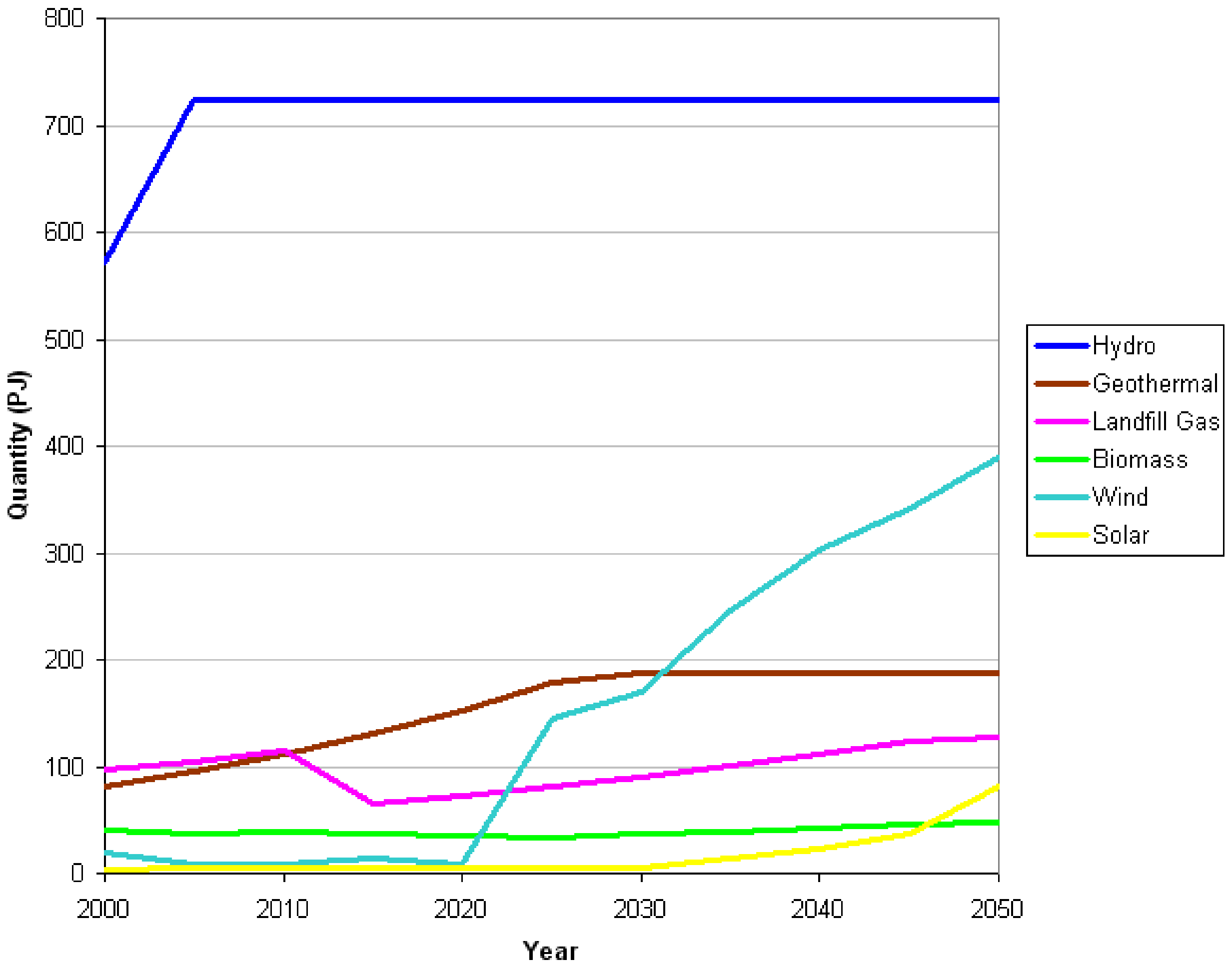

Figure F-10. Use of renewables in electricity production.

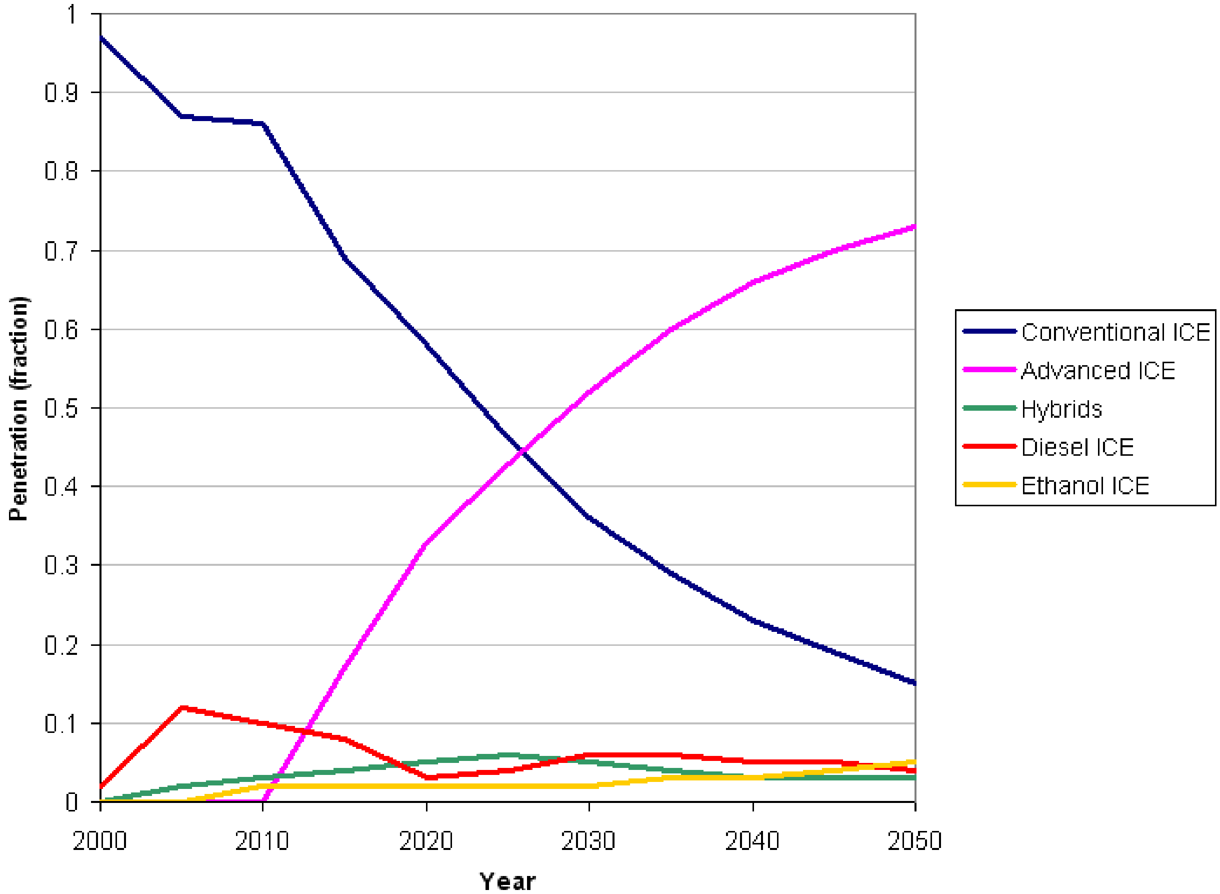

Figure F-11. Technology penetration into the light duty vehicle fleet.

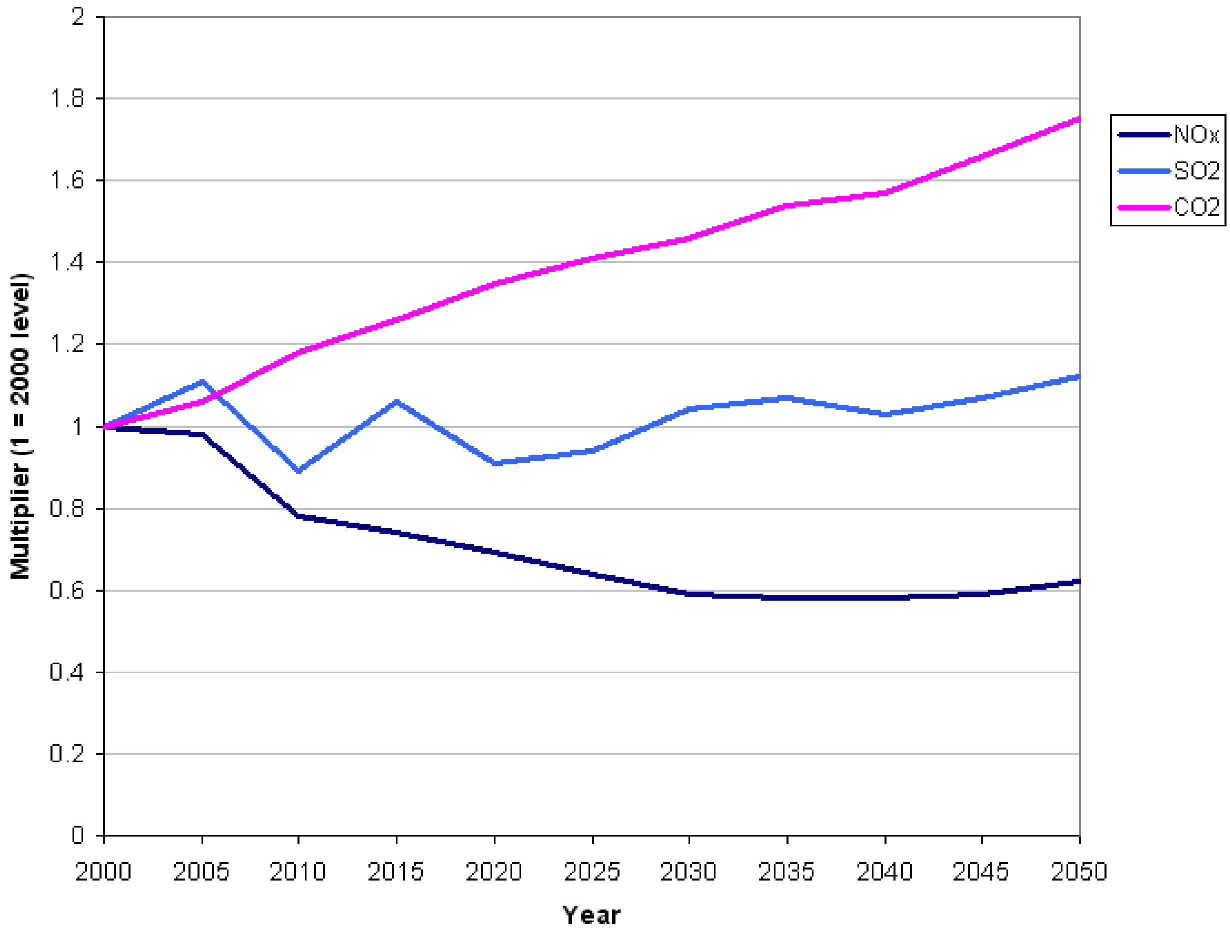

Figure F-12. Reference case scenario emissions relative to 2000.

higher at the end of the modeling horizon. CO_2 emissions increase steadily as energy demands and the related combustion of fossil fuels increase across sectors.

Figure F-13 provides a more detailed look at NOx emissions. The overall decrease in NOx is driven by large reductions in electricity production resulting from CAIR and by reductions in transportation sector, much of which is attributable to the EPA's on-road and off-road diesel rules.

Figure F-14 characterizes the reference-case scenario's use of domestic and imported energy. Exports are also shown. An increasing fraction of energy inputs is imported over the time horizon.

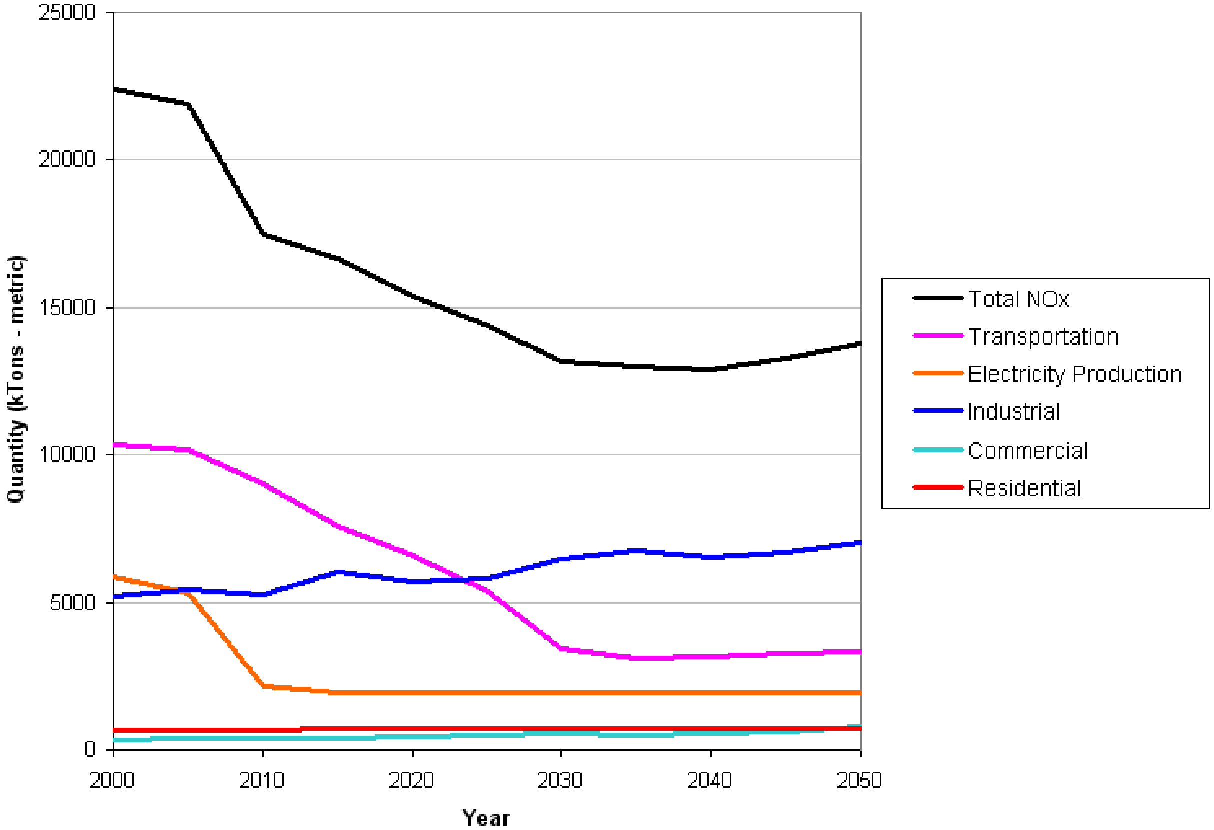

Figure F-13. System-wide and sectoral NOx emissions.

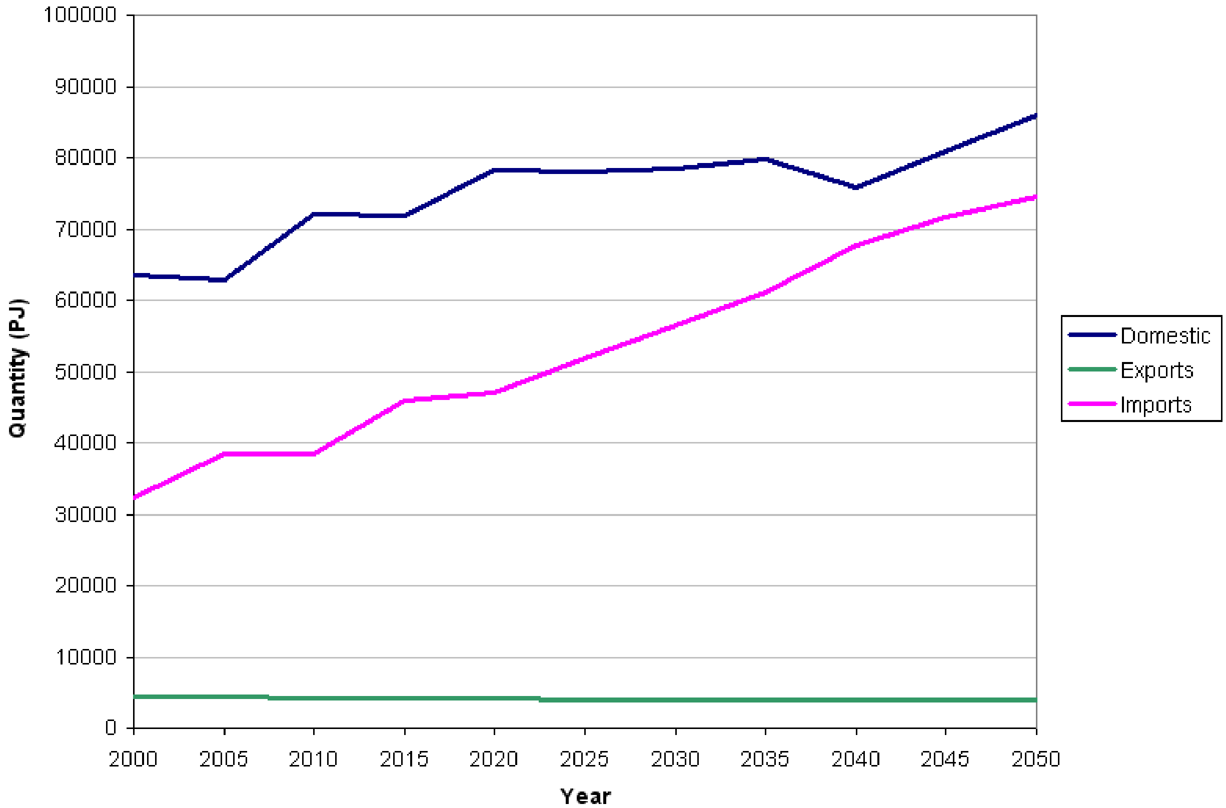

Figure F-14. Domestic fossil fuel utilization, imports, and exports.

F.3.4. Discussion

The results presented in this section represent one realization of the future and are highly dependent on assumptions regarding future technology characteristics, the costs of obtaining fuels, and other factors. Many of these factors are uncertain. One approach for incorporating consideration of uncertainty is to conduct a scenario analysis where widely ranging scenarios encompass a range of futures considered. The use of parametric and global sensitivity analysis techniques is also important in characterizing the model's response to changes in inputs. These techniques allow important model interactions to be identified, including those that may not be anticipated. Scenario and sensitivity analysis will be incorporated into the 2012 Final Assessment Report.

While MARKAL results provide insight into future energy technology pathways, they are nonetheless based on a model, and all models have limitations. For example, MARKAL is a mixed integer linear programming model as opposed to a nonlinear programming model. As a result, objectives and constraints in the model must be represented as linear functions. Many real-world characteristics of the energy system are nonlinear, such as resource supply curves, so detail is lost in a linear representation. Linearity has an advantage in modeling, however, since linear and mixed integer linear programming models are typically much easier to solve than nonlinear models. Another caveat is that MARKAL is an optimization model and not a simulation model. Optimization models identify the least cost approach to achieve a desired objective. MARKAL solutions thus represent those of a rational social planner acting to minimize costs. Typically in MARKAL, this decision-maker has perfect foresight over the time horizon, although MARKAL's myopic solution mode can be used to limit this foresight to each model time period. In contrast, simulation models are designed to represent more complex and realistic human behaviors.

F.4. GENERATION OF INPUTS TO THE AIR QUALITY ASSESSMENT

The SMOKE emissions processing model generates a future-year inventory by applying technology- or industry-specific multiplicative factors to sources within a base-year inventory. Emissions sources are classified by codes. Source Classification Codes (SCCs) are eight- and 10-digit codes that represent point and non-point sources emissions technologies, respectively. Source Identification Codes (SICs) are four-digit codes that represent the type of industry. Growth factors for SCCs or SICs are included in a growth and control file that is input into SMOKE.

MARKAL does not produce SCC or SIC growth factors as output, and the aggregation of technologies within MARKAL is different than that in the emissions inventory. Thus, MARKAL outputs must be post-processed to derive emissions growth factors. Post-processing to develop SCC growth factors involves the following steps:

Step 1 Emissions of NOx, sulfur, and PM by year and technology are extracted from a MARKAL output file

Step 2 A "crosswalk" that links MARKAL technologies to SCCs is used to assign MARKAL emissions to SCC categories.

Step 3 For each SCC, the change in emissions between the base year (e.g., 2000) and the future year (e.g., 2050) is calculated and a multiplicative factor is determined

Step 4 Emissions growth factors by pollutant are output to the growth and control factor file.

This process provides emissions growth factors for NOx, SOx, and PM from energy system technologies. The proportion of emissions of VOCs from the energy system is low. Thus, emissions growth factors for these sources will be generated outside of MARKAL, and likely will be linked to population or economic growth estimates.

Emissions growth factors can be applied within SMOKE across the entire inventory or at the state or county level. The EPA9R database produces results at a census division level. Thus, the emissions growth factors for a MARKAL region will be applied to all states within that region.

Compared to the current state-of-the-art approach for projecting emissions, the methodology outlined here is differentiated by

- representation of current and expected technology characteristics (e.g., cost, efficiency, and emissions controls) for major energy-system source categories explicitly;
- estimation of technology change endogenously;
- portrayal of increased energy service demands, resource limitations, and current and anticipated emissions and air quality policies;
- identification of cross-sector implications of changes in the demands for various fuels.

F.5. REFERENCES

EPRI (Electric Power Research Institute). (2003) Technology assessment guide: advanced technologies. Palo Alto, CA: Electric Power Research Institute; Product ID:1004976.

ETSAP (Energy Technology Systems Analysis Program). (2006) Energy technology systems analysis program (ETSAP) [September 2006]. Available online at http://www.etsap.org/index.asp.

Brill, E.D, Jr., Flach, J.M., Hopkins, L.D., Ranjithan, S. (1990). MGA: A decision support system for complex, incompletely defined problems. IEEE Transactions on Systems, Man and Cybernetics 20(4): 745-757.

Schwartz, P. (1996). The art of the long view: planning for the future in an uncertain world. New York, NY: Doubleday.

U.S. DOE (Department of Energy). (2003a) Model documentation report: system for the analysis of global energy markets (SAGE) - Volume 1: model documentation. Energy Information Administration, U.S. Department of Energy, Washington, DC; DOE/EIA-M072(2003)/1. Available online at http://tonto.eia.doe.gov/FTPROOT/modeldoc/m072(2003)1.pdf.

U.S. DOE (Department of Energy). (2003b) National energy modeling system: an overview 2003. Energy Information Administration, U.S. Department of Energy, Washington, DC; DOE/EIA-0581(2003). Available online at http://www.eia.doe.gov/oiaf/aeo/overview/index.html.

U.S. DOE (Department of Energy). (2002) Program analysis methodology: quality metrics 2003, final report. Office of Transportation Technology, U.S. Department of Energy. Available online at http://www1.eere.energy.gov/ba/pdfs/facts_quality_metrics_2003.pdf.

U.S. DOE (Department of Energy). (2006) International energy outlook 2006. Energy Information Administration, U.S. Department of Energy, Washington, DC; DOE/EIA-0484(2006). Available online at http://www.fypower.org/pdf/EIA_IntlEnergyOutlook(2006).pdf.

U.S. EPA (Environmental Protection Agency). (2004) Clean air nonroad diesel – tier 4 final rule [September 2006]. Office of Transportation and Air Quality, Washington, DC. Available online at http://www.epa.gov/nonroad-diesel/2004fr.htm.

U.S. EPA (Environmental Protection Agency). (2005) Clean air interstate rule [September 2006]. Office of Aire and Radiation, Washington, DC. Available online at http://www.epa.gov/cair/.

U.S. EPA (Environmental Protection Agency). (2006a) Finding of significant contribution and rulemakings for certain states in the ozone transport assessment group region for the purposes of reducing regional transport of ozone ("NOx SIP Call") [September 2006]. Technology Transfer Network: oxone implemention. Office of Transportaion and Air Quality. Available online at http://www.epa.gov/ttn/naaqs/ozone/rto/sip/index.html.

U.S. EPA (Emvironmental Protection Agency). (2006b) EPA U.S. national MARKAL database: database documentation. U.S. Environmental Protection Agency, Washington, DC; EPA/600/R-06/057. EIMS ID: 150883.

U.S. EPA (Environmental Protection Agency). (2006c) Air trends reports [September 2006]. Office of Air and Radiation, Washington, DC. Available online at http://www.epa.gov/air/airtrends/reports.html.

U.S. EPA (Environmental Protection Agency). (2007a) Clean diesel trucks, buses, and fuel: heavy-duty engine and vehicle standards and highway diesel fuel sulfur control requirements (the "2007 heavy-duty highway rule") [September 2006]. Office of Transportation and Air Quality, Washington, DC. Available online at http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm.

U.S. EPA (Environmental Protection Agency). (2007b) AP 42, fifth edition: compilation of air pollutant emission factors [September 2006]. Technology Transfer Network. Available online at http://www.epa.gov/ttn/chief/ap42/.

APPENDIX G
CHARACTERIZING AND COMMUNICATING UNCERTAINTY: THE NOVEMBER 2006 WORKSHOP

G.1. INTRODUCTION

An effective scientific assessment process must explicitly address uncertainty to solidify the credibility of the research effort underlying the assessment and to assure that the assessment products fulfill the need of the intended users for accurate information. The U.S. EPA Global Change Research Program (GCRP) Assessment of the Impacts of Global Change on Regional U.S. Air Quality is, in part, a bounding exercise to determine whether or not the impacts of climate and other drivers of change on air quality are significant enough that they must be folded into planning and management. An analysis of the uncertainty in the assessment findings is needed to determine if they are sufficient to answer to the questions originally posed.

However, complex, model-based environmental assessments, including climate change impacts assessments, present unique challenges to characterizing and communicating scientific uncertainty. Challenging elements include reliance on linked systems of detailed models at multiple spatial and temporal scales, leading to the propagation of nonlinear model sensitivities through the linked simulations; the presence of uncertainty about the state of our knowledge; the characterization of this knowledge into a model; and the most appropriate values for the inputs and empirical parameters within that model and the inherently multidisciplinary nature of the problems considered, each discipline with its own norms for treating uncertainty. There is no "best practice" guidance for handling uncertainty in this type of assessment.

EPA organized and conducted a workshop in November 2006 to solicit advice from assembled experts about issues related to characterizing and communicating uncertainty in such assessment in general, and the ongoing global change-air quality assessment in particular. The goal was to begin identifying and developing principles and practices to apply in the current and future assessments.

The rest of the report documents the workshop and summarizes preliminary findings that emerged. Development of a comprehensive strategy for addressing uncertainty based on these findings, as well as identifying and applying the formal uncertainty analysis techniques most appropriate for the problem of global change impacts on air quality, are important future steps.

G.2. WORKSHOP GOALS, PARTICIPANTS, AND STRUCTURE

The "Workshop on Uncertainty in the U.S. EPA Assessment of the Impact of Global Change on U.S. Air Quality" took place on November 1-2, 2006, at the Millennium Hotel in

Durham, North Carolina, conducted by EPA's National Center for Environmental Assessment (NCEA). The workshop goals were to provide

- A foundation for EPA to develop a strategy to properly track, quantify, and communicate uncertainty in complex, model-based assessments, particularly concerning the impacts of global change and
- Specific recommendations for how EPA can best track, quantify, and communicate uncertainty in its current global change-air quality assessment.

EPA invited approximately 75 experts from academia and other government agencies, covering various scientific disciplines and affiliations, to attend the workshop. These disciplines included

- Regional climate modeling
- Global climate modeling
- Social sciences (e.g., urban and regional economists, energy economists, transportation economists)
- Technology development (energy, transportation)
- Energy projections
- Vegetation modeling
- Global scenario development
- Emissions modeling
- Regional air quality modeling
- Global chemistry modeling.

In addition, key stakeholders from the EPA Office of Air Quality Planning and Standards (OAQPS) and regional air quality planning and management entities were present and actively involved in the discussions. Their perspective was crucial to help frame the context of the uncertainty discussions and provide a focus on the questions most relevant for policy needs.

The two-day workshop began with an opening plenary session during which invited speakers presented background information on EPA's GCRP, the global change-air quality assessment, and discussions of general methods for evaluating uncertainty in complex model-based systems. Speakers and their presentations during this plenary session were

- *Welcome and Opening Remarks*: Anne Grambsch, EPA ORD/NCEA

- *Decision Making in the Face of Uncertainty*: Lydia Wegman, EPA Office of Air and Radiation (OAR)/OAQPS
- *Overview of EPA's Global Change-Air Quality Program*: Anne Grambsch, EPA ORD/NCEA
- *Research Summaries by EPA Science to Achieve Results (STAR) Grantees*: Various STAR Grantees
- *Modeling Ozone Sensitivities to Future Climate*: Alice Gilliland, EPA ORD/National Exposure Research Laboratory (NERL)
- *Evaluating Uncertainty in Linked Climate and Air Quality Modeling*: Steve Hanna, Hanna Consultants
- *Responses to National Academy of Sciences (NAS) and Office of Management and Budget (OMB) Recommendations and Guidelines for Probabilistic Uncertainty Assessment in OAQPS's Regulatory Analyses*: Bryan Hubbell, EPA OAR/OAQPS.

Following the opening plenary, the participants split into three breakout groups that were all given the same charge to provide EPA feedback on three topic areas: (1) tracking and quantifying uncertainty in complex, model-based global change impacts assessments, (2) effectively communicating uncertainty associated with these assessments, and (3) addressing uncertainty specifically in EPA's global change-air quality assessment. Discussions on these topics addressed issues raised in "key discussion questions" included in the workshop handouts and "framing questions" that EPA distributed to participants prior to the workshop. While the three breakout groups had the same general charge, which allowed for comparisons across the groups to identify areas of common ground, the focus of the discussions during the workshop varied across the breakout groups. The workshop concluded with a second plenary session during which the workshop participants commented on materials developed by the breakout groups.

The workshop was not designed to seek consensus on any topic or to prioritize the participants' many suggestions. The ideas presented were viewed as a collection of ideas set forth for EPA's further consideration and were not necessarily to be viewed as formal recommendations.

G.3. PRELIMINARY FINDINGS

Complex, model-based environmental assessments, particularly assessments of climate and global change impacts, offer substantial challenges. The challenges in global change impacts assessments include the need to simulate interconnected global-scale human and natural processes through to distant time horizons, the need to minimize the computational burden of these complex simulations by combining models with widely differing temporal and spatial resolution, the complexities of the modeling tools required, and the multi-disciplinary nature of the problems. Addressing the conceptual and linguistic differences, through dialogue at the workshop, between the intellectual disciplines, and between the science and policy communities involved in the assessment, is a key workshop outcome.

G.3.1. General Findings

A general finding of the workshop is that characterization and quantification of uncertainty cannot be separated from the overall assessment process. A well-designed assessment includes the following basic elements:

- A healthy, iterative, process between the scientists and the stakeholders (including decision makers, policy planners, and resource managers). This process is a two-way flow of information about needs and capabilities, including discussion of the level of uncertainty in the assessment findings as they emerge. This dialogue is ongoing throughout the assessment. In a fundamental sense, the process, not any particular uncertainty analysis, is the product.
- A well-defined decision context that is informed by both the science and the stakeholder imperatives. This context determines the variables and metrics upon which to focus, the spatial and temporal resolutions at which they are needed, the scenarios of interest, and the acceptable levels of uncertainty required (i.e., risk tolerance). Important considerations in this aspect of the assessment process include differences in the criteria and perspectives between stakeholders and scientists concerning the nature of reliable knowledge. The discussion process must either reconcile or accommodate any such differences. The type of information that is considered to be useful by the stakeholder community may range from the direction of the effect, e.g., positive or negative with respect to the current level, to orders of magnitude, to quantification of an effect at high precision.
- A set of preliminary analyses (scoping analyses) to identify and prioritize the major and minor uncertainties likely to be present when attempting to meet the needs of the particular decision context. These analyses might include examinations of the existing body of knowledge on the topic, elicitations of expert judgments, and sensitivity studies.
- A conceptual diagram of all components of the problem. The conceptual diagram is then realized (to the extent possible) with the models that are available or that are developed for the project. Comparing this realization to the original conceptual diagram yields important insights into the compromises made in modeling that may yield uncertainty.

Based upon the requirements of the decision context and the findings from the preliminary analyses, the extent and rigor of the uncertainty analysis needed can then be determined, i.e., comprehensive and quantitative or back-of-envelope and qualitative. Resources sufficient to carry out the required uncertainty analysis, which in the case of climate and air quality modeling includes sufficient computing power, must be factored into the cost of the assessment.

G.3.2. Findings on Technical Issues Specific to the Global Change-Air Quality Modeling Systems

- It is not appropriate to think of such systems as "prediction" tools. They are "*scenario analysis"* tools, and must be used as such for decision support purposes.
- Formal, quantitative uncertainty analysis of the linked climate-air quality model system that explores the whole parameter space is at this stage of technological development extremely expensive and time-consuming. Efficiency in using available computational resources is, therefore, paramount.
- As a subset of a full Monte Carlo analysis, an example approach to qualitative uncertainty analysis, ensemble methods are likely the most appropriate for linked climate-air quality modeling systems (Hanna et al., 2007).
- The role of the preliminary analyses, including tapping current scientific knowledge in the literature, expert elicitation, and simplified sensitivity studies of different types, is extremely important to intelligently guide more sophisticated, formal uncertainty analyses to be performed if feasible (e.g., winnowing down the parameter space for choosing the most relevant ensemble members).
- All analyses must include evaluating the predictive skill of model system versus observations specifically for the air quality metrics of interest (as opposed to simply long-term average climate variables, for example). The identified limits of the system's predictive skill contribute to the uncertainty in the assessment projections.
- The temporal and spatial resolution of the analysis needs to be chosen in a manner that maximizes the utility of the results to the client, e.g., a resolution that does not result in uncertainties beyond the acceptable limit for the policy application. Again, these quantities are identified via the iterative communication process discussed above.
- Effective coordination of research efforts across groups contributing the scientific findings to the assessment is crucial, for example, in the consistency of scenarios and modeling assumptions used to allow "apples to apples" comparisons.
- The role of reduced form models, simplified models, tailored policy planning tools, etc., is unclear. The workshop revealed a broad range of views with no consensus.

G.3.3. Findings on Communication Strategies

- Lead with what is known (i.e., more certain), then move to what is unknown (i.e., less certain).
- Account for the different norms of communication between scientists (e.g., limitations, caveats) and decision makers.

- Use clear, unambiguous language to express likelihood and level of confidence. For example, see the Intergovernmental Panel on Climate Change (IPCC) and U.S. Climate Change Science Program (CCSP) practices.
- Establish the credibility of the findings by communicating the respect of the community for the participating scientists and the extent of the peer-review process.
- Take advantage of creative visualization methods.

Finally, the workshop closed with a call for future meetings to focus on the specific technical issues discussed above, with narrower questions and smaller groups of participants.

G.4. REFERENCES

Hanna, S; Weaver, CP; Hemming, B. (2007) A review and framework for evaluating uncertainties in the assessment of the impacts of global climate change on U.S. air quality. J Air Waste Manage Assoc: to be submitted.