Chapter 2

Decision Support for Air Quality

Lead Author: Daewon W. Byun

1. Introduction

Our ability to understand and forecast the quality of the air we breathe, as well as our ability to understand the science of chemical and physical atmospheric interactions, is at the heart of models of air quality. Air quality is affected by and has implications for the topics in our other chapters: air quality is affected by energy management and agricultural practices, for instance, and is a major factor in public health. Models of air quality also provide a means of evaluating the effectiveness of air pollution and emission control policies and regulations.

While numerous studies examine the potential impact of climate change on forests and vegetation, agriculture, water resources and human health (e.g., Brown et al., 2004; Mearns, 2003; Leung and Wigmosta 1999; Kalkstein and Valimont 1987), attempts to project the response of air quality to changes in global and regional climate have long been hampered by the absence of proper tools that can transcend the different spatial and temporal scales involved in climate predictions and air quality assessment and by the uncertainties in climate change predictions and associated air quality changes.

~~Air quality is affected by meteorological processes and by changes in the meteorological processes associated with climate change processes at scales that are much smaller than those resolved by global climate models (GCMs), which are typically applied at a resolution of several hundred kilometers. Air quality is most affected by meteorological processes at regional and local scales.~~ Current-day regional climate simulations, which typically employ ~~a~~ horizontal resolution of 30 - 60 km, are insufficient to resolve small-scale processes that are important for regional air quality, ~~such as~~ low-level jets, land-sea breezes, local wind shears, and urban heat island effects. In addition, climate simulations place enormous demands on computer storage. As a result, most climate simulations only archive a limited set of meteorological variables, the time interval for the archive is usually 6-24 hours, and some critical information required for air quality modeling is missing.

~~Another issue is the~~ interaction and feedback between climate and air chemistry. Climate and air quality are linked through atmospheric chemical, radiative, and dynamic processes at multiple scales. For instance, aerosols in the atmosphere may modify atmospheric energy fluxes by attenuating, scattering, and absorbing solar and infrared radiation, and may also modify cloud formation by altering the growth and droplet size distribution in the clouds. The changes in energy fluxes and cloud fields may, in turn, alter the concentration and distribution of aerosols and other chemical species. Although a few attempts have been made to address the issues, our understanding of climate change is based largely on modeling studies that have neglected these feedback mechanisms.

~~Also of concern is the~~ impact of climate change on air emissions. Changes in temperature, precipitation, soil moisture patterns, and clouds due associated with global warming may directly alter emissions ~~such as~~ biogenic emissions (e.g., isoprene and terpenes). Isoprene, an important natural precursor of ozone, is emitted mainly by deciduous tree species. Emission rates are dependent on the availability of solar radiation in visual range and are highly temperature sensitive. Emissions of terpenes (semi-volatile organic species) may induce formation of secondary organic aerosols. The accompanying changes in the soil moisture, atmospheric stability, and flow patterns complicate these effects and it is difficult to predict ~~if~~ climatic change will eventually lead to increased levels of surface ozone and aerosol concentrations ~~or not~~.

This chapter discusses the U.S. Environmental Protection Agency's Community Multiscale Air Quality (CMAQ) modeling system. CMAQ has as its primary objectives to (1) improve the ability of environmental managers ~~in~~ evaluat~~ing~~ the impact of air quality management practices for multiple pollutants at multiple scales, and (2) enhance scientific ability to understand and model chemical and physical atmospheric interactions (http://www.epa.gov/asmdner/CMAQ/ ~~(accessed May 2007)~~. It is also used to guide the development of air quality regulations and standards and to create state implementation plans. Various observations from the ground~~,~~ in situ and satellite platforms are used in CMAQ almost at every step of the decision support system (DSS) processing

2. Description of CMAQ

The U.S. EPA CMAQ modeling system (Byun and Ching, 1999; Byun and Schere, 2006) has the capability to evaluate relationships between emitted precursor species and ozone at urban~~/~~regional scales (Appendix W to Part 51 of 40CFR: Guideline on Air Quality Models). CMAQ uses state-of-the-science techniques for simulating all atmospheric and land processes that affect the transport, transformation, and deposition of atmospheric pollutants. The primary modeling components in the CMAQ modeling system include: (1) a meteorological modeling system (e.g., MM5) or a regional climate model (RCM) for the description of atmospheric states and motions; (2) inventories of man-made and natural emissions of precursors that are injected into the atmosphere; and (3) the CMAQ Chemistry Transport Modeling (CTM) system for the simulation of the chemical transformation and fate of the emissions. The model can operate on a large range of time scales from minutes to days to weeks as well as on numerous spatial (geographic) scales ranging from local to regional to continental.

The base CMAQ system is maintained by the U.S. EPA. The Center for Environmental Modeling for Policy Development (CEMPD), University of North Carolina at Chapel Hill (UNC), is contracted to establish a **Community Modeling and Analysis System** (CMAS) (http://www.cmascenter.org/) for supporting community-based air quality modeling. CMAS helps development, application, and analysis of environmental models and helps distribution of the DSS and related tools to the global modeling community. Table 1 lists Earth observations (of all types~~–~~remote sensing and *in situ*) presently used in the CMAQ DSS.

Within this overall DSS structure as shown in Table 1, CMAQ is an emission-based, three-dimensional (3-D) air quality model that does not utilize daily observational data directly for the model simulations. The ~~base~~ databases utilized in the system represent typical surface conditions and demographic distributions (e.g., land use and land cover as well as the demographic and socioeconomic information in the BELD3 database). At present the initial conditions are not specified using observed data even for those species routinely measured as part of the controlled criteria species listed in the National Clean Air Act and its Amendments (CAAA) in an urban area using a dense measurement network. This is because of the difficulty in specifying the multi-species conditions that satisfy chemical balance in the system, which is subject to the diurnal evolution of radiative conditions and of the atmospheric boundary layer as well as temporal changes in the emissions that reflect constantly changing human activities.

The main output of the CMAQ and its DSS is the concentrations and deposition amount of atmospheric trace gases and particulates at the grid resolution of the model, usually at 36-km for CONUS (continental) domain, and 12-km or 4-km for regional or urban scale domains. The end users of the DSS want information on the major scientific uncertainties and our ability to resolve them subject to the information on socioeconomic context and impacts. They seek information on the implications at the national, regional, and local scales and on the baseline and future air quality conditions subject to climate change to assess the effectiveness of current and planned environmental policies. Local air quality managers would want to know if the DSS could help assess methods of attaining current and future ambient air quality standards and evaluate opportunities to mitigate the climate change impacts. Through sensitivity simulations of the DSS with different assumptions on the meteorological and emissions inputs, the effectiveness of such policies and uncertainties in the system can be studied.

3. Potential Future Uses and Limits

One of the major strengths of CMAQ is its reliance on the first principles of physics and chemistry. The present limitations in science parameterizations and modeling difficulties will continuously be improved as new understanding of these phenomena are obtained through various measurements and model evaluation/verification. ~~A case in point is the~~ development of the chemical mechanism~~,~~ Carbon Bond 05 (CB05), which recently replaced CB-4~~.~~ The quality of emission inputs for the system, both at the global and regional scales, depends heavily on socio-economic conditions ~~and~~ such estimates are obtained using projection models in relevant socio-economic disciplinary areas. The CMAQ DSS user/operators may not always have domain expertise to discern the validity of such results.

CMAQ needs to have the ability to utilize available observations to specify more accurately critical model inputs, which are arbitrarily defined at present. A data assimilation approach is one approach that may be used to improve the system performance at different processing steps. For example, research has been undertaken to use satellite remote sensing data products together with high-resolution land use and land cover (LULC) data to~~.~~

Table 1. Input data used for operating the CMAQ-based DSS.

Data Set	Type of Information	Source	Usage
Regional Climate Model Output	Simulation results from a regional climate model (RCM) used as a driver for CMAQ modeling. It is processed through MCIP (meteorology-chemistry interface processor)	RCM modeling team. PNNL, UIUC, NCEP, EPA, Universities	Regional climate characterization, Driver data for air quality simulations, emissions processing
Land Use Land Cover, Subsoil category, & Topography Data, topography for meteorological modeling	Describes land surface conditions and vegetation distribution for surface exchange processes.	Various sources from USGS, NASA, NCEP EPA, states, etc.	Usually the data is associated with RCM's land surface module. Need to be consistent with vegetation information such as BELD3 if possible.
Biogenic Emissions Land Use Database version 3 (BELD3)	Land use and biomass data, vegetation/tree species fractions;	EPA	Processing of biogenic emissions; Used to provide activity data for county-based emission estimates; Now also used for Land surface modeling in RCM
Air Emissions Inventories: National Emissions	Amount and type of pollutants into the atmosphere. Includes: - Chemical or physical identity of pollutants	EPA, Regional Program Organizations (RPOs), states, and	Preparation of model-ready emission inputs. Perform speciation for the chemical mechanism used.

Inventories (NEI) and state/special inventories. Often called as "bottom-up" inventories	- Geographic area covered - Institutional entities - Time period over which the emissions are estimated - Types of activities that cause emissions	local government; foreign governments.	Used to evaluate "top-down" emissions (i.e., from inversion of satellite observations though air chemistry models)
Chemical Species Initial and Boundary Conditions	Clean species concentration profiles initial input and boundary conditions used for CMAQ simulations; originally from observations from clean background locations	EPA (fixed profiles), GEOS-Chem (Harvard & Univ. Houston), Mozart (NCAR); dynamic concentrations with diurnal variations (daily, monthly or seasonal)	CMAQ simulations. Fixed profiles are used for outer domains where no significant emissions sources are located
AQS/AIRNow	Near real-time (AIRNow) and archived datasets (AQS) for ozone, PM, and some toxics species	Joint partnership between EPA & state and local air quality agencies	Measurement data used for model evaluations. Report and communicate national air quality conditions for

improve the land-surface parameterizations and boundary layer schemes in the RCMs (e.g., Pour-Biazar, et al., 2007). Active research in chemical data assimilation is currently conducted with the GEOS-Chem modeling program, which utilizes both *in situ* and satellite observations (e.g., Kopacz, et al, 2007; Fu et al., 2007). Because of the coarse spatial and temporal resolutions of the satellite data collected in the 1960s through the 1980s most of research in this area has been performed with global chemistry-transport models. As the horizontal footprint of modern satellite instruments reach~~es~~ the resolution suitable for regional air quality modeling, these data can be used to evaluate and then improve the bottom-up emissions inputs in the regional air quality models. However, they ~~still~~ do not provide required ~~detailed~~ vertical information except ~~from the solar~~ occultation instruments, ~~but with very limited spatial coverage. However,~~ ~~a~~dditional in *situ* and remote sensing measurements from ground and aircraft platforms could be used to augment the satellite data in these data assimilation experiments.

Utilization of the column-integrated satellite measurements in a high-resolution 3-D grid model like CMAQ poses serious challenges ~~to~~ distribut~~e~~ the pollutant vertically, separating those within and above the atmospheric boundary layer. Because similar problems exist for the retrieval of meteorological profiles of moisture and temperature, ~~these~~ experiences can be adapted for a few well-behaved chemical species. The same tool can be used to improve the initial and boundary conditions with various in *situ* and satellite measurements of atmospheric constituents. At present, however, an operational assimilation system for CMAQ is not yet available although prototype assimilation codes have ~~just~~ been generated (Hakami, et al., 2007; Zhang et al., 2007). Should these data assimilation tools become part of the DSS, various conventional and new satellite products, ~~such as from AURA/~~Tropospheric Emission Spectrometer (TES) ozone profiles, GOES hourly total ozone column (GhTOC) data, OMI TOC, CALIPSO attenuated backscatter profiles, and OMI AOT data can be utilized to improve the urban-to-regional scale air quality predictions.

Because of the critical role of the RCM as the driver of CMAQ in climate change studies, ~~the~~ results ~~of RCM~~ for the long-term simulations must be verified thoroughly. ~~Until now, for the air quality related operations,~~ evaluation of the RCM has been performed only for relatively short simulation periods. For example, the simulated surface temperature, pressure, and wind speed must be compared to surface observations to determine how well the model captures the mean land-ocean temperature and pressure gradients, the mean sea breeze wind speeds, the average inland penetration of sea-breeze, the urban heat island effect, and the seasonal variations of these features. Comparisons with rawinsonde soundings and atmospheric profiler data would determine how well the model reproduces the averaged characteristics of the afternoon mixed layer heights and of the early morning temperature inversion, as well as the speed and the vertical wind shears of the low-level jets. In addition to these mesoscale phenomena, changes in other factors can also alter the air pollution patterns in the future and need to be carefully examined. These factors include the diurnal maximum, minimum, and mean temperature; cloud cover; thunderstorm frequency; surface precipitation and soil moisture patterns; boundary layer growth and nocturnal inversion strength.

As demonstrated in ~~the~~ global model applications, satellite measured biomass burning emission~~s~~ data should be utilized in ~~the~~ regional air quality modeling (e.g., Duncan et al. 2003; Hoelzemann, et al., 2004). Duncan et al. (2003) presented a methodology for estimating the seasonal and interannual variation of biomass burning~~,~~ designed for use in global chemical transport models using fire-count data from the Along Track Scanning Radiometer (ATSR) and the Advanced Very High Resolution Radiometer (AVHRR) World Fire Atlases. The Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) data product was used as a surrogate to estimate interannual variability in biomass burning. Also Sprak~~e~~len et al. (2007) showed that wildfire~~s~~ contribution to the interannual variability of organic carbon aerosol can be studied using the area burned data and ecosystem specific fuel loading data. A similar fire emissions data set at the regional scales could be developed for use in the climate impact on air quality study. For retrospective application, a method similar to that used by the NOAA's Hazard Mapping System (HMS) for Fire and Smoke (http://www.ssd.noaa.gov/PS/FIRE/hms.html) may be used to produce a long-term regional scale fire emissions inventories for climate impact analysis.

4. Uncertaint~~y~~

The CMAQ modeling system as currently operated has several sources of uncertainty in addition to those associated with ~~some of~~ the limits ~~of CMAQ as~~ described in the previous section. In particular, when CMAQ is used to study of the effects of climate change and air quality, improvements in several areas are necessary to reduce uncertainty ~~in the CMAQ modeling system~~. First, the regional air quality models employ limited modeling domains and as~~,~~ such they are ignorant of ~~the~~ air pollution events outside the domains unless proper dynamic boundary conditions are provided. Second, because the pollutant transport and chemical reactions are ~~vastly~~ affected by the meteorological conditions, improving both the global climate and regional climate models and the downscaling methods by evaluating~~/~~verifying physical algorithms implemented with observations ~~must be accomplished~~ to improve the systems overall performance. Third, the basic model inputs, ~~such as~~ land use/vegetation cover descriptions and emissions inputs ~~in the system~~ must be improved. Fourth,~~ but not the least,~~ the issue of incommensurability of modeling the nature, as well as the grid resolution problems, as suggested by Russell and Dennis (2000), needs to be addressed. These factors are the principal cause of simulation/prediction errors.

Although the models incorporated in the DSS are first-principle based environmental models, they have difficulties in representing forcing terms in the system, in particular the influence of the earth's surface, long-range transport, and uncertainties in the model inputs such as daily emissions changes due to anthropogenic and natural events. There is ample opportunity to reduce uncertainties associated with CMAQ through model evaluation~~/~~verification using current and future meteorological and atmospheric chemistry observations. Satellite data products assimilated in the GCTM could provide better dynamic lateral boundary conditions for CMAQ. Additional opportunities to reduce the model uncertainty include: comparison of model results with observed data at different resolutions~~,~~ quantification of effects of initial and boundary conditions and chemical mechanisms; application of CMAQ to estimate the uncertainty of input emissions data; and ensemble modeling (using a large pool of simulations among a variety of models) as a means to estimate model uncertainty.

A limitation in CMAQ applications, and therefore a source of uncertainty, has been the establishment of initial conditions. The default initial conditions and lateral boundary conditions in CMAQ are provided under the assumption that after spin-up of the model, they no longer play a role, and in time, surface emissions govern the air quality found in the lower troposphere. Song et al. (2007) showed that the effects of the lateral boundary condition differ for different latitude and altitude, as well as season~~, for a long-term simulation~~. In the future, dynamic boundary conditions can be provided by fully integrating the GCTMs as part of the system. Several research groups are actively working on this, but the simulation results are not yet available in the open literature. A~~lso, a~~ scientific cooperative forum the Task Force on Hemispheric Transport of Air Pollution (http://www.htap.org/index.htm) endeavor~~s~~ to bring together the national and international research efforts at ~~the~~ regional, hemispheric, and global scales to develop a better understanding of air pollution transport in the Northern Hemisphere. The task force is currently preparing ~~the~~ 2007 Interim Report addressing various long-range transport of air pollutant issues (http://www.htap.org/activities/2007_Interim_Report.htm). Although the effort ~~is~~ not directly address~~ing the~~ climate change issues, many of findings and tools used are very much relevant to ~~the~~ meteorological and chemical downscaling issues.

Ultimately, ~~application of~~ CMAQ should consider all the uncertainties in the inputs. The system's response may be directly related to the model configuration and algorithms (structures, resolutions and chemical and transport algorithms), compensating errors, and the incommensurability of modeling nature, as suggested by Russell and Dennis (2000).

5. Global Change Information and CMAQ

CMAQ could be used to help answer several questions about the relationship between air quality and climate change:

1) How will global warming affect air quality in a region?

2) How will land use change due to climate, urbanization, or intentional management decisions affect air quality?

3) How much will climate change alter the frequency, seasonal distribution, and intensity of synoptic patterns that influence pollution in a region?

4) How sensitive are the air quality simulations to uncertaint~~y~~ in wild fire projections and to potential land management scenarios?

5) How might the contribution of the local production and long-range transport of pollutants differ due to different climate change scenarios?

6) Will future emission~~s~~ scenarios or climate changes affect the frequency and magnitude of high pollution events?

To provide answers to these questions, CMAQ ~~will~~ rely heavily on climate-change-related information. In addition to the influence of greenhouse gases and global warming, ~~other~~ forcing functions include population growth and land use changes. Different scenarios can be chosen either to study potential impacts or to estimate the range of uncertainties of the predictions. The two upstream climate models, GCMs and RCMs, generate the climate change data that drive a GCTM and CMAQ. Both the GCMs and RCMs are expected to represent future climate change conditions while simulating historic climate conditions that can be verified with comprehensive reanalysis datasets. The meteorology simulated by the climate models represents ~~that in a typical~~ future year scenario, reflecting ~~the~~ changing atmospheric conditions. ~~Furthermore, e~~mission~~s~~ inputs used for the GCTM and CMAQ must reflect the natural changes and/or anthropogenic developments related to climate change.

In recent years, the EPA Science to Achieve Results (STAR) program has funded several projects ~~on~~ the possible effects of climate change on air quality and on ecosystems. Many of these projects have adopted CMAQ as the base tool ~~for the study~~. Figure 1 provides a general schematic of the potential structure of a CMAQ-based climate change decision support system (DSS). The figure show potential uses of CMAQ for climate study; most climate-related CMAQ applications are not yet configured as fully as indicated in the figure.

The projects linking CMAQ and climate study have used upstream models and downstream tools ~~such as~~ those identified in Table 2. Related projects that use regional air quality models other than CMAQ are also listed~~ as reference information~~. For the GCMs, NCAR's CCM (Kiehl et al., 1996), NASA's GISS (e.g., Hansen et al., 1997; 2005), and NOAA GFDL's CM2 (Delworth et al., 2006) are most popular global models for providing meteorological inputs representing climate change events. A recent description for the GISS model can be found~~, for example,~~ in Schmidt et al. (2006) (http://www.giss.nasa.gov/tools/) and for the CCM in Kiehl et al. (1996) and from the webpage http://www.cgd.ucar.edu/cms/ccm3/. A newer version of the CCM was released on May/17/2002 with a new name~~--~~the Community Atmosphere Model (CAM). The CAM web page ~~is available from:~~ http://www.ccsm.ucar.edu/models/atm-cam ~~and t~~he model ~~are~~ described in Hurrell et al. (2006).

Table 2. Potential Uses: modeling components and upstream and downstream tools for a CMAQ-based Climate Change Impact Decision Support System.

Component	Functions	Owner	Users
Global Climate Models (GCMs)	Performs climate change simulations over the globe for different SRES climate	CCM (Community Climate Model): NCAR	Climate research institutes, Universities, Government

	scenarios. Typical resolution for a long-term (50 yr) is at 4° x 5° lat. & long.	***GISS (Goddard Institute for Space Studies) GCM: NASA*** CM2: Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA	institutions
Global Chemistry Transport Models (GCTMs)	Computes global scale chemical states in the atmosphere. Uses same resolution as GCM.	GEOS-Chem: NASA, Harvard University MOZART: NCAR (ESSL/ACD)	Global chemistry research organizations, Universities, Government institutions
Regional Climate Models (RCMs)	Simulates regional scale climate and meteorological conditions downscaling the GCM output. For US application ~36 km resolution used	MM5-based: NCAR, PNNL, UIUC, others WRF-based: NCAR, UIUC Eta-based: NCEP	Regional climate research groups, Universities, Government institutions
Regional Air Quality Models (AQMs)	Performs air quality simulations at regional and urban scales at the same resolution as the RCM	CMAQ (Community Multiscale Air Quality): EPA CAMx (Comprehensive Air quality Model with Extensions): Environ WRF-Chem: NOAA/NCAR STEM-II: University of Iowa	Regional, State, and local air quality organizations, Universities, Private industries Consulting companies
Downstream tools for decision	Performs additional computations to help	CMAQ/DDM: GIT CMAQ/4Dvar: CalTech/VT/UH	Universities, Consulting companies

support	decision support, such as sensitivity and source apportionment studies, exposure studies	Stochastic Human Exposure and Dose Simulation (SHEDS): EPA Total Risk Integrated Methodology (TRIM): EPA	
Upstream tools for representing climate change impacts on input data	Performs additional computations to generate model inputs that affect simulations	Land surface models SLEUTH: USGS, UC-Santa Barbara (captures urban patterns) CLM (community land model): NCAR (used for RCM and biogenic emission estimates after growth)	Universities, Consulting companies

As shown in Table 2, for climate change studies, CMAQ is linked with upstream models such as a global climate model (GCM), a global tropospheric chemistry model (GTCM), and a regional climate model (RCM) to provide emissions sensitivity analysis, source~~-~~apportionment, and data assimilation to assist policy and management decision~~-~~making activities including health impact analysis. One of the EPA STAR projects (Hogrefe, 2004, 2005; Knowlton, 2004; Civerolo, 2007) utilized the CMAQ-based DSS to assess ~~if the~~ climate change would affect the effectiveness of current and future air pollution policy decisions subject to the potential changes change in local and regional meteorological conditions. In other EPA STAR projects (Tagaris, 2007; Liao, 2007a,b), global climate change information from the simulation results of GCM with ~~the~~ well-mixed greenhouse gas ~~concentrations~~ – CO2, CH4, N2O, and halocarbons – updated yearly from observations for 1950–2000 (Hansen et al., 2002) and for 2000-2052 following the A1B SRES scenario from the Intergovernmental Panel on Climate Change (IPCC 2001), but with ~~fixed~~ ozone and aerosol concentrations in the radiative scheme at present-day climatological value (Mickley, et al., 2004), was employed.

To resolve the meteorological features affecting air pollution transport and transformation ~~in~~ a regional scale, the coarse scale meteorological data representing the climate change effects by a GCM are downscaled using a RCM.~~.~~ An RCM is often based on a limited-domain regional mesoscale model, such as MM5, RAMS, Eta, ~~and~~ WRF/ARW ~~and~~ WRF/NMM. An alternative method for constructing regional scale climate change data is through a statistical downscaling, which evaluates observed spatial and temporal relationships between large-scale (predictors) and local climate variables ~~(predictands)~~ over a specified training period and domain (Spak~~,~~ et al., 2007). Because of the need to use ~~the~~ meteorological driver that satisfies constraints of dynamic consistency (i.e., mass and momentum conservation~~s~~) for ~~the~~ regional scale air quality modeling (e.g., Byun, 1999 a and b), the CMAQ modeling system relies exclusively on the dynamic downscaling method.

~~,~~Regional chemistry models like CMAQ are better suited for regional air quality simulations than ~~a~~ global Chemical Transport Model (CTM) because of the acute air pollution problems that are managed and controlled through policy decisions at specific geographic locations. Difficulty in prescribing proper boundary conditions (BCs) is one of the deficiencies of CMAQ simulations of air quality~~, especially in the upper troposphere~~ (e.g., Tarasick et al., 2007; Tang et al., 2007). Therefore, one of the main roles of the global CTM is to provide proper dynamic boundary conditions for CMAQ to represent temporal variation of chemical conditions that might be affected by the long-range transport of pollution events outside the regional domain boundaries. The contemporary EPA funded projects on climate change impact on air quality mainly use two GCTM models: the NASA/Harvard~~'s~~ GEOS-Chem (Bey et al., 2001) and the National Center for Atmospheric Research (NCAR) Model of Ozone and Related Chemical Tracers (MOZART) (Brasseur et al., 1998; Horowitz et al., 2003).

The GEOS-Chem model (http://www-as.harvard.edu/chemistry/trop) is a global model for predicting tropospheric composition. The model was originally driven by the assimilated meteorological observation data from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office (GMAO). For climate studies, the NASA GISS GCM meteorological outputs are used instead. Emission inventories include a satellite-based inventory of fire emissions (Duncan et al., 2003) with expanded capability for daily temporal resolution (Heald et al., 2003) and the National Emissions Inventory for 1999 (NEI 1999) for the US with monthly updates in order to achieve adequate consistency with the CMAQ fields at the GEOS-C~~HEM~~/CMAQ interface (Jacob, personal communication).

MOZART (http://gctm.acd.ucar.edu/mozart/models/m3/index.shtml) is built on the framework of the Model of Atmospheric Transport and Chemistry (MATCH) that can be driven with various meteorological inputs and at different resolutions such as meteorological reanalysis data from the National Centers for Environmental Prediction (NCEP), NASA GMAO, and the European Centre for Medium-Range Weather Forecasts (ECMWF). For climate change applications, meteorological inputs from the NCAR CCM3 are used. The model includes a detailed chemistry scheme for tropospheric ozone, nitrogen oxides, and hydrocarbon chemistry, semi-Lagrangian transport scheme, dry and wet removal processes, and emissions inputs. Emission inputs include sources from fossil fuel combustion, biofuel and biomass burning, biogenic and soil emissions, and oceanic emissions. The surface emissions of NOX, CO, and NMHCs are based on the inventories described in Horowitz et al. (2003), aircraft emissions based on Friedl (1997), and lightning NOx emissions that are distributed at the location of convective clouds.

GCTMs are applied to investigate numerous tropospheric chemistry issues, ~~including~~ CO, CH4, OH, NOx, HCHO, isoprene~~,~~ and inorganic (sulfates and nitrates) and organic (elemental carbons, organic carbons) particulates. ~~As such,~~ various in situ, aircraft, and satellite-based measurements are used to provide the necessary inputs, to verify the science process algorithms, and to perform general model evaluations. They include ~~the~~ vertical profiles from aircraft observations as compiled by Emmons et al. (2000), multi year analysis of ozonesonde data (Logan, 1999), and those available at the Community Data website managed by the NCAR Earth and Sun Systems Laboratory (ESSL) Atmospheric Chemistry Division (ACD);and multiyear surface observations of CO reanalysis (Novelli et al., 2003). Current and previous atmospheric measurement campaigns are listed in web paged by NOAA ESRL (Earth Systems Research Laboratory), http://www.esrl.noaa.gov/; NASA, Tropospheric Integrated Chemistry Data Center; and NCAR ESSL (Earth and Sun Systems Laboratory) Atmospheric Chemistry Division (ACD) Community Data, http://www.acd.ucar.edu/Data/. These observations are used to set boundary conditions for the slow reacting species, ~~such as~~ CH4, N2O, and CFCs and to evaluate other modeled species, ~~such as~~ CO, NOx, PAN, HNO3, HCHO, acetone, H2O2, and nonmethane hydrocarbons. In addition, ~~several~~

satellite measurements from the GOME, ~~SCHIAMCHY~~, and OMI ~~of CO, NO2, HCHO~~ have been used extensively to verify the emissions inputs and performance of the GCTM.

The grid resolutions used in the studies discussed above are much coarser than those used in the air quality models for studying emission control policy issues such as evaluating state implementation plans (SIPs). SIP modeling typically utilizes over 20 vertical layers at around 4-km horizontal grid spacing to reduce uncertainties in the model predictions near the ground and around high emission source areas ~~like~~ urban and industrial centers. Although Civerolo et al.~~,~~ (2007) applied CMAQ at a higher resolution, the duration of the CMAQ simulation was too short a time scale to evaluate the regional climate impacts in detail.

One of the additional key limitations of using the CMAQ for climate change studies is that the linkages between climate and air quality and from the global scale to regional scale models are only one-way (i.e~~.~~., no feed~~-~~back). To represent the interactions between atmospheric chemistry and meteorology, ~~such as~~ radiation and cloud/precipitation microphysics, particulates and heterogeneous chemistry, a two-way linkage must be established between the meteorology and chemistry models. An on-line modeling approach ~~like~~ WRF-chem is an example of such linkage, but still there is a need to develop a link between the global and regional scales. A multi-resolution modeling system such as demonstrated by Jacobson (2001 a, b) might be necessary to address truly the linkage between air pollution forcing and climate change and to provide the urban-to-global connection. In addition, there ~~are~~ significant benefits ~~of~~ linking other multimedia models describing ~~the~~ subsoil conditions, vegetation dynamics, hydrological processes, ~~as well as the~~ ocean dynamics, including the physical/chemical interactions between the ocean micro-sublayer and atmospheric boundary layer. An attempt to generate such a megamodel under one computer coding structure would be impractical because of the existence of extremely different state variables in each multimedia model that require substantially different data models. Furthermore interactions among the multimedia models require multidirectional data inputs, quality assurance check-points, and ~~the~~ decision support entries. A more generalized on-line and two-way data exchange tool~~s~~ currently being developed under the **Earth System Modeling Framework** (ESMF) (http://www.esmf.ucar.edu/) may be a viable option.