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The Application of Satellite-Derived, High-Resolution Land Use/Land Cover Data to Improve Urban Air Quality Model Forecasts

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EXECUTIVE SUMMARY

Under the Clean Air Act (CAA), local and state agencies are responsible for developing state implementation plans (SIPs) aimed at attaining and maintaining the National Ambient Air Quality Standards (NAAQS). Typically, the decision support systems (DSSs) used for this purpose utilize numerical models to simulate the physical and chemical processes that govern the formation and transport of criteria pollutants and their precursors within the region of interest. Within these models, the specification of land use plays an important role in controlling land surface energy and water fluxes, which in turn affects the near-surface meteorology and emissions. Accurate land use characterization has the potential to improve the accuracy of the modeling results and would thus be of great value to federal and state agencies. The National Aeronautics and Space Administration (NASA) Earth Science Applications Program has a mission to work with Government agencies to facilitate the use of Earth science research results and observations to improve the performance of DSSs. The systems engineering approach used to meet this objective consists of three phases: Evaluation, Verification and Validation (V&V), and Benchmarking. Researchers from the NASA Marshall Space Flight Center (MSFC) have worked with the Georgia Environmental Protection Division (GA EPD) to incorporate an improved high-resolution land use characterization dataset (LandPro99 merged with National Land Cover Data (NLCD)), within the modeling system. This project was aimed at improving the Air Quality Modeling Decision Support System (AQMDSS) for the Atlanta metropolitan area through incorporation of high-resolution land use/land cover (LULC) data and to assess the meteorological and air quality impacts of Urban Heat Island (UHI) mitigation strategies (i.e., highly reflective roofing and increased tree canopy) developed by local stakeholders. The NLCD dataset provides coverage for the conterminous U.S. and was developed from Landsat Thematic Mapper (Landsat TM) data from the early 1990s. LandPro99 was developed by the Atlanta Regional Commission (ARC) for the metropolitan Atlanta area using aerial photography from 1999–2001. The dataset provides a more accurate representation of the current land use. It also allows a more robust assessment of future land use changes in the region through the use of the Spatial Growth Model (SGM). In the Benchmarking phase of this project, meteorological and air quality forecasts made using the high-resolution land use data for two summertime high ozone episodes in 1999 and 2000 were compared against forecasts made using the lower resolution, traditional land use data previously used in the AQMDSS. Using the traditional land use data, daytime near-surface air temperatures predicted by the meteorological model were found to be $\approx 3\,^{\circ}\mathrm{C}$ colder than observed. Use of the high-resolution data improved performance of the model substantially, with the overall daytime cold bias reduced by over 30%. The air quality model performance for ozone did not show an improvement. Increased boundary layer mixing simulated using the high-resolution land use data negates the effects of warmer near-surface air temperatures, with the net effect on ozone being near zero. In additional, land use changes in the Atlanta area due to urbanization were predicted through 2030 using the SGM. Modeling simulations with the projected land use predicted higher urban air temperatures. The incorporation of UHI mitigation strategies partially offset this warming trend. Although Atlanta has been the focal study area for this effort, the data and modeling methods used for the AQMDSS reported on here are generally applicable to other cities in the United States (U.S.). Recommendations and lessons learned from this research are also articulated in this Technical Publication (TP).

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LIST OF ACRONYMS AND SYMBOLS

AQI	Air Quality Index
AQMDSS	Air Quality Modeling Decision Support System
ARC	Atlanta Regional Commission
ATLANTA	ATlanta Land use ANalysis: Temperature and Air quality
AWIPS	Advanced Weather Information Processing System
BAU	business as usual
BEIS–3	Biogenic Emissions Inventory System
BELD–3	Biogenic Emissions Land Use Database
CAA	Clean Air Act
CEM	Continuous Emissions Monitoring
CMAQ	Community Multiscale Air Quality
CO	carbon monoxide
CTM	Chemical Transport Model
DEM	digital elevation map
DOT	Department of Transportation
DSS	Decision Support System
DST	Decision Support Tool
EDAS	Eta Data Assimilation System
EGAS	Economic Growth and Analysis System
EGU	Electricity Generating Units
EOS	Earth Observing System
EPA	Environmental Protection Agency
FAQS	Fall-line Air Quality Study
FDDA	Four-Dimensional Data Assimilation
GA	Georgia
GA EPD	Georgia Environmental Protection Department
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
HNO_3	nitric acid
HONO	nitrous acid
hPa	hectopascals

LIST OF ACRONYMS AND SYMBOLS (Continued)

HPMS	Highway Performance Monitoring System
ISBA	Interactions between Soil, Biosphere, and Atmosphere
ISS	Integrated Systems Solution
IWGEO	Interagency Working Group on Earth Observations
LAI	leaf area index
Landsat TM	Landsat Thematic Mapper
LDT	local daylight time
LSM	land surface model
LULC	land use/land cover
m AGL	meters above ground level
MCIP	Meteorology Chemistry Interface Processor
MEBI	Modified Euler Backward Iterative
MM5	Mesoscale Meteorological Model
MNB	mean normalized bias
MNE	mean normalized error
MSA	Metropolitan Statistical Area
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NEI	National Emissions Inventory
NH_3	ammonia
NLCD	National Land Cover Data
NOAA	National Oceanic and Atmospheric Administration
NAAQS	National Ambient Air Quality Standard
NCEP	National Centers for Environmental Prediction
NO_x	nitrogen oxides
PBL	planetary boundary layer
PM	particulate matter
ppb	parts per billion
PPM	piecewise parabolic method
ppm	parts per million
RADM	Reactive Acid Deposition Model
RRTM	Rapid Radiative Transfer Model
SGM	Spatial Growth Model

LIST OF ACRONYMS AND SYMBOLS (Continued)

SIP	State Implementation Plan
SMOKE	Sparse Matrix Operator Kernel Emissions
SOA	secondary organic aerosol
SO_2	sulfur dioxide
UHI	Urban Heat Island
USEPA	United States Environmental Protection Agency
USGEO	United States Group on Earth Observations
USGS	United States Geological Survey
USRA	Universities Space Research Association
VMT	vehicle miles traveled
VOC	volatile organic compounds
V&V	Verification and Validation
WMO	World Meteorological Organization

TECHNICAL PUBLICATION

THE APPLICATION OF SATELLITE-DERIVED, HIGH-RESOLUTION LAND USE/LAND COVER DATA TO IMPROVE URBAN AIR QUALITY MODEL FORECASTS

1. INTRODUCTION

In 2001, NASA, Universities Space Research Association (USRA), and their Georgia (GA) partners began work on a joint project titled *Development and Validation of an Improved Urban Air Quality Modeling System Using High-Resolution Remote Sensing Data*. The project was aimed at improving the AQMDSS for the Atlanta metropolitan area through incorporation of high-resolution LULC data and to assess the meteorological and air quality impacts of UHI mitigation strategies (i.e., highly reflective roofing and increased tree canopy) developed by local stakeholders. Two air pollution episodes were simulated using meteorological, air quality, and emissions models to investigate the effectiveness of high-resolution LULC data for a more accurate characterization of physical and chemical processes that occur in an urban environment. An SGM was used to predict future (i.e., 2030) land use around Atlanta using estimates of population, employment, and transportation network growth. Meteorological modeling simulations using current and projected land use were conducted to evaluate the effects of urbanization on local meteorology and effectiveness of UHI mitigation strategies.

1.1 NASA Application Traceability and Link to NASA Mission

NASA supports research related to air quality modeling and observations through its Earth science mission, which includes atmospheric composition as one of six focus areas. Within this area, NASA's focus is to provide improved satellite observations of atmospheric constituents and surface properties and states, conduct field experiments, and support meteorological and air quality model development.

The objective of the NASA Applied Sciences Program is to expand and accelerate the economic and societal benefits from Earth science, information, and technology. In achieving this objective, the primary goal of the Applied Sciences Program is to enhance decision support capabilities on an organizational basis by enabling the expanded use of Earth science results, information, and technology to serve management and policy responsibilities to society.[1]

One of twelve elements of the Applied Sciences Program is air quality management, which has the objectives of facilitating collaboration with other agencies such as the National Oceanic and Atmospheric Administration (NOAA) and U.S. Environmental Protection Agency (EPA) and extending observations and results to these agencies to enhance applications of NASA's Earth science research for improving decision-making tools in those agencies and at the state and local levels. The Air Quality Management element addresses research and operational issues related to air quality planning, compliance, and forecasting. The roadmap for the Air Quality National Application theme defines the direction, identifies key factors, and identifies and communicates the evolutionary path to reach this theme's objectives. The project and its products discussed in this TP relate to two of the Decision Support Inputs as defined by the Air Quality Roadmap:

1. Aerosol transport loops in EPA AIRNow/Air Quality Index (AQI) for regional forecasts; support EPA-developed tools for states/locals on regional haze; evaluate exceptional events for effects on NAAQS violations; EPA particulate matter (PM) transport rule making.

2. States assess emissions-control options and emissions strategies to build attainable SIPs and improve air quality; public health and economic development opportunities; States claim waivers for foreign-born pollutants.

In relation to point no. 1 above, we have examined how high-resolution NASA satellite data can be used to improve modeling of meteorological constituents that feed into the Community Multiscale Air Quality (CMAQ) model (i.e., DSS) that is used by the EPA as a standard for assessing air quality within the overall context of the NAAQS. As related to point no. 2 above, we have used NASA high-resolution satellite data within the perspective of various modeling schemes to assess how changes in LULC, as well as increases in albedo (i.e., surface reflectivity) and vegetation, affect air quality, specifically ground level ozone. Moreover, we have demonstrated how the improvements to air quality modeling within the purview of an Integrated System Solution architecture adds substantial value and benefits from the modeling efforts conducted by EPA in assessing the state and impacts of air quality constituents as part of an emerging air quality forecasting system at an urban to regional level.

Additionally, our work directly relates to the overall construct of the Interagency Working Group on Earth Observations (IWGEO) wherein air quality monitoring and forecasting is a major thrust of the IWGEO and the United States Group on Earth Observations (USGEO) plan. IWGEO and USGEO seeks to:

- Assess the current condition of the environment.
- Inform models.
- Understand relationships among Earth processes, environmental health, and human health and well-being.
- Support decision-making.
- Involve stakeholders more effectively in environmental decision-making.

The work described in this TP contributes to the mission of IWGEO/USGEO by contributing to the enhancement of a DSS already in place and used extensively in the U.S. to monitor and model air quality and decision-support making. The work discussed here also contributes to a better understanding—and the implementation of better tools and models—of the attributes that can be afforded by using high-resolution NASA satellite data for air quality modeling, and ultimately for public health decision-making.

1.2 Brief Introduction to Decision Support System

Figure 1 illustrates the architecture that is the fulcrum for the Applied Sciences Program as related to an Integrated System Solutions (ISS) construct. The flow of the process as indicated in the figure is such that NASA as a research and development agency extends the observations, model predictions, and computational techniques from Earth science research to support partner agencies. The right side of the diagram relates to the engagement of partner agencies and organizations that develop and operate decision support tools (DSTs) to analyze scenarios, identify alternatives, and assess risks as part of their respective decision-making processes. Federal agencies, for example, use these tools to support their responsibilities to the public, such as resource management, security, regulations, public health, and economic development. In the middle of the diagram are DSTs. DST here refers to assessments and DSSs that serve policy and management decisions. Typically, DSSs are interactive, computer-involved systems that provide organizations with methods to retrieve information, analyze alternatives, and evaluate scenarios to gain insight into critical factors, sensitivities, and possible consequences of potential decisions. DSSs as inputs and synthesizers of great quantities of Earth science data and computationally demanding scientific models exist as systematic mechanisms to incorporate data products and document the value derived from inputs into the DSS process. In this project, the Air Quality Modeling DSS is enhanced with NASA LULC data to improve our ability to simulate urban meteorology and air quality and to evaluate the impacts of UHI mitigation strategies on meteorology and air quality. The ultimate goal is to enable better air quality policy and management decisions.

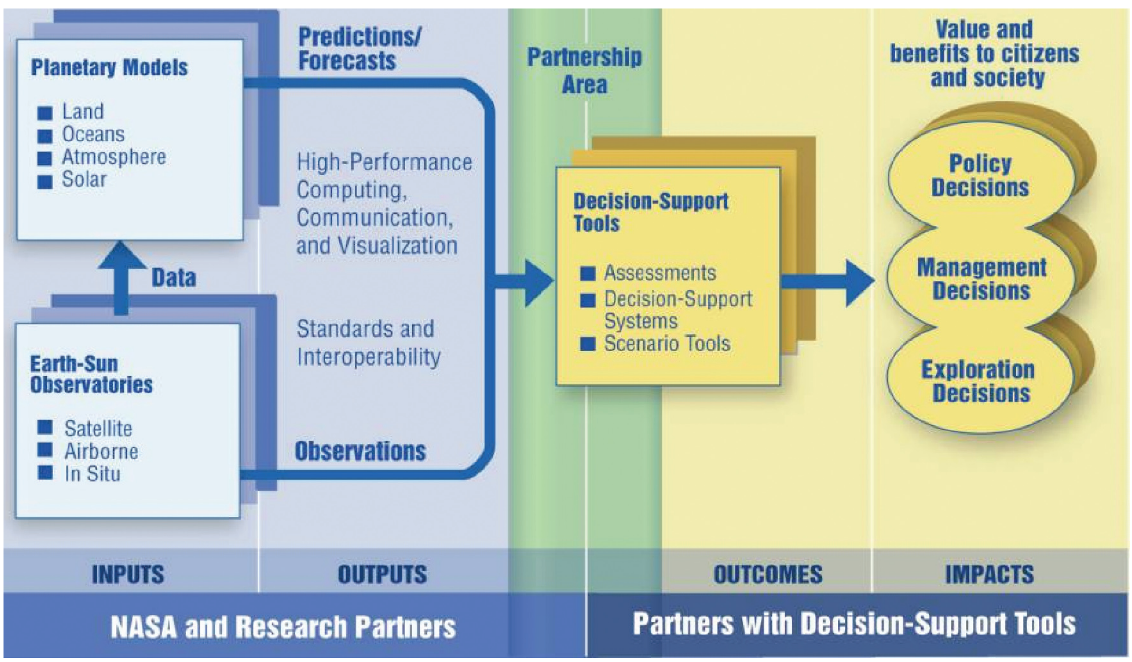

Figure 1. Flow diagram of the ISS architecture. (Source: NASA Earth Science Applications Plan, 2004.)

The ISS architecture process employs a systems engineering approach to achieve both functionality and consistency across a variety of Earth science applications. Embedded within this systems engineering schema are critical junctions in the process relating to Evaluation, V&V, and Benchmarking. The Evaluation phase provides an initial assessment of user-defined requirements relative to Earth science research results. Typically, this includes identifying decision-support tools associated with an application area, assessing the potential value and technical feasibility of current and future Earth science results within the purview of a DST concept, and assessing partner commitment and project value versus benefit relative to the Applied Sciences Program's funding and objectives. As part of Evaluation from a DSS perspective, a decision is made as part of this phase to continue on with collaboration into the V&V phase.

V&V focuses on the developing prototype products to address requirements, devise system integration approaches, and resolution of technical issues related to the introduction of the Earth science products into DSTs. Paramount in this systems engineering phase is the measurement and performance characteristics of Earth science products, i.e., NASA outputs, to meet the input requirements of the DSTs by addressing issues associated with bringing data and model outputs into the partners' internal systems. Here the ultimate purpose of V&V is to ensure that the end-to-end system meets the intended objectives with the new inputs; i.e., that the system functions properly given the ingestion of new Earth science data and models. Verification determines how the actual performance of an observation, prediction, or other Earth science product meets the user-defined requirements within a specific tolerance range. Validation determines if the performance of the algorithms (or logic or rationale) using Earth science data or models can accomplish the stated intended outcomes.

The Benchmarking phase involves the application of a rigorous process to compare the performance of a DST using Earth science products to a standard, recognized criteria or set of criteria, as well as a current practice or reference scenario to document the value of Earth science products within the scope of the DST. If partners have existing metrics and performance standards to evaluate their tools and decisions, these are used as the standard within the Benchmarking phase. The robust documentation of procedures and guidelines that describe the steps to access and utilize Earth science data and results is a requisite part of this systems engineering phase.

The three phases embodied within the systems engineering concept provide a systematic approach to follow the integrated systems solutions architecture and apply NASA's data and models within an Integrated Systems Solutions methodology. This TP documents our efforts at improving a nationally recognized AQMDSS using the process flows and robustness defined by the NASA Applied Sciences Program's Integrated Systems Solutions architecture.

In the existing AQMDSS, there is a need for improved meteorological, emissions, and air quality modeling capabilities, especially in urban areas. Improvements can be made in several areas—physics of meteorological and air quality models, emissions inventories, linkages between model components, and LULC characterization. This project focused on the use of high-resolution NASA satellite data to improve the LULC characterization. The LULC datasets that have been used traditionally in air quality modeling are not well suited for the purpose due to their low-spatial resolution—1 km or coarser—and poor differentiation of urban LULC types. Our initial premise was that the use of high-resolution LULC data could be beneficial for representing in a more realistic way the urban landscape at subgrid scale variability, i.e., at finer scales than can be resolved explicitly in the modeling system.

There is a further need for the capability to evaluate how changes in the urban landscape will affect urban meteorology and air quality. We have addressed this using the SGM to project LULC for Atlanta to 2030 based on projections of population, employment, and transportation networks. By incorporating better LULC data and the SGM into the AQMDSS, we have improved the system in its ability to simulate both current and future air quality conditions.

The enhanced AQMDSS addressed here has successfully passed through the Evaluation, V&V, and Benchmarking phases and now exists as a DSS that is ready for wider application at a national level. Throughout the evolution of this AQMDSS, we have diligently worked with our partner to ensure that the NASA data and models used herein are integral to the overall functioning of the AQMDSS and represent a substantial and clear improvement over what has been used as a standard in the past. A complete description of the AQMDSS construct and its functionality are given later in this TP.

The study area—including counties located with the Atlanta metropolitan statistical area (MSA) that are designated as nonattainment as well as the location of the central business district—is shown in figure 2. The Atlanta area was selected for this project to build on previous research focused on characterization of the UHI, the relationship of LULC to UHI development, UHI impact on regional climate, and air quality modeling. Project ATlanta Land use ANalysis: Temperature and Air quality (ATLANTA), a NASA Earth Observing System (EOS) research effort, attempted to resolve how urban growth in the Atlanta metropolitan area over approximately the last 25 yr has impacted the region's meteorology and air quality.[2] Characterizing the spatiotemporal changes in land cover and measuring the spatial distribution of surface temperature using remote sensing and characterizing the relationship among the two properties were intrinsic to this research. These data were then used in large-scale assessment of air quality and showed that UHI mitigation strategies could reduce peak ozone levels in Atlanta's nonattainment area by ≈7 ppb or 5% of current levels.[3] Although this modeling was based on broad assumptions and gross generalizations with regard to land cover changes, urban planners, government officials, and other interested parties are utilizing this information to initiate plans regarding the future of Atlanta's overall environment.[4] This project builds upon the results achieved in Project ATLANTA by refining the UHI characterization technique by utilizing more LULC and related information from NASA and other Earth science observation providers and developing and validating a coupled modeling system for improved air quality assessment.

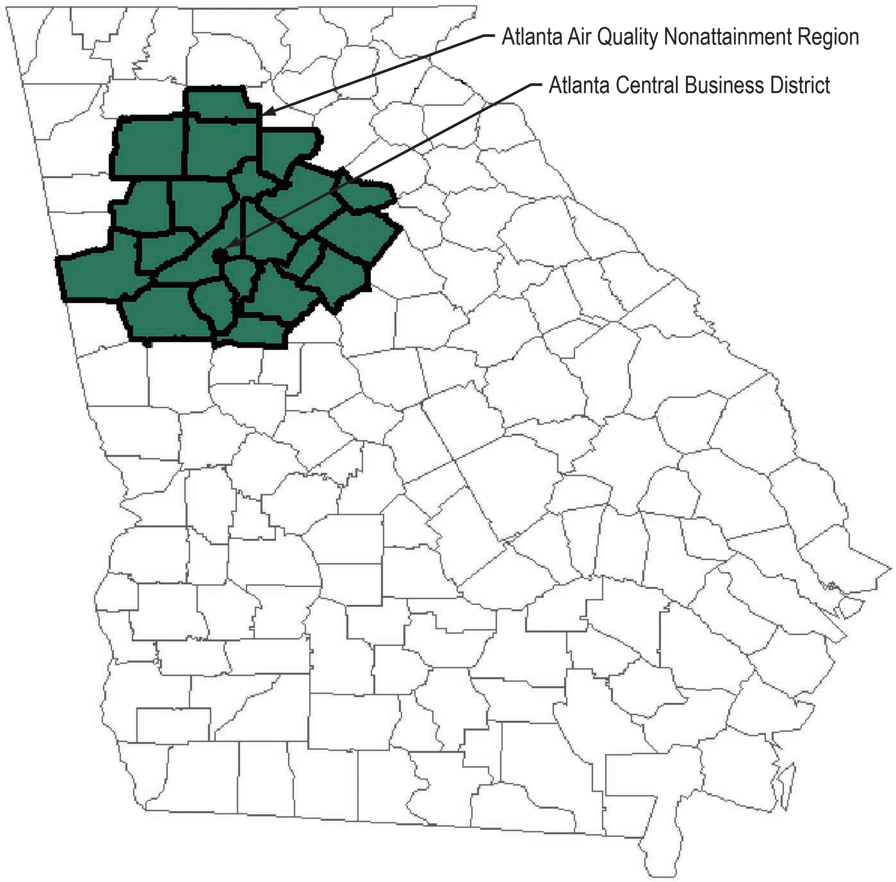

Figure 2. Location of the 21-county Atlanta Air Quality Nonattainment Region and the Atlanta Central Business District.

2. SYSTEMS ENGINEERING APPROACH

2.1 Definition of Problem

Ozone and other air pollutants pose a major health problem in the U.S. and are therefore regulated by the EPA. It is the role of state and local agencies to develop SIPs detailing plans to comply with the NAAQS. A key component of the process for developing and implementing a SIP is a numerical modeling system, i.e., a DSS, to simulate meteorological and air quality processes and evaluate the impacts of current or planned air quality control measures. In this project we have worked with partners in Georgia to improve upon the DSS used there to address air quality reduction controls.

2.1.1 Ozone

2.1.1.1 Ozone Formation. Ozone is not emitted directly into the air, but at ground level is created by a chemical reaction between oxides of nitrogen (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. Motor vehicle exhaust and industrial emissions, gasoline vapors, and chemical solvents also contribute to ozone formation. Ozone has the same chemical structure whether it occurs in the stratosphere or at ground level and can be good or bad, depending on its location in the atmosphere. Good ozone occurs naturally in the stratosphere ≈10–30 mi above the Earth's surface and forms a layer that protects life on Earth from the Sun's harmful rays. In the Earth's lower atmosphere, ground-level ozone is considered bad.

Sunlight and hot weather cause ground-level ozone to form in harmful concentrations in the air. As a result, it is known as a summertime air pollutant. Peak ozone levels typically occur during hot, dry, stagnant summertime conditions which are exacerbated in metropolitan areas by the UHI effect. The length of the ozone season varies from one area of the U.S. to another. Southern and southwestern states may have an ozone season that lasts nearly the entire year.

Many urban areas tend to have high levels of ground-level ozone, but even rural areas are subject to increased ozone levels because wind carries ozone and pollutants that form it hundreds of miles away from their original sources. Millions of Americans live in areas where ozone levels exceed EPA's health-based air quality standards, primarily in parts of the Northeast, the Lake Michigan area, parts of the Southeast, southeastern Texas, and parts of California. Figure 3 depicts the physical processes that result in the development of ground-level ozone, including the particular contributions from both the urban and vegetated LULC surfaces.

2.1.1.2 Impacts on Human Health and Vegetation. Exposure to ambient ground-level ozone, even at low levels, may trigger a variety of health problems, especially in vulnerable populations such as children, the elderly, and those with pre-existing respiratory disease. Health problems as a result of ozone exposure include irritation of lung airways, breathing difficulty during exercise or outdoor activities, and permanent lung damage.[5]

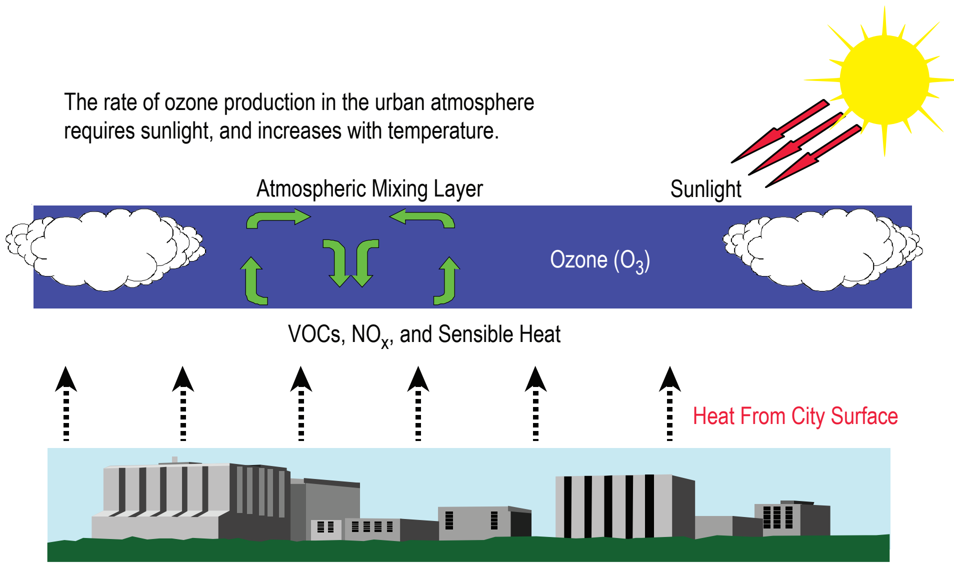

Figure 3. Ozone formation in the urban atmosphere.

Ozone pollution can damage vegetation and ecosystems within and downwind of cities. Ozone damages the foliage of trees and other vegetation, tarnishing the visual appeal of ornamental species and urban green spaces. In addition, ozone transported downwind of cities can reduce crop and forest yields. This makes them more susceptible to disease, insects, other pollutants, and harsh weather.

To address ground-level ozone pollution, EPA has traditionally focused on local control strategies in areas of the country with high measured levels of ozone in the air. In recent years, EPA and the states have recognized the need for more aggressive programs to reduce ozone and other pollutants such as NO_x that cause ozone problems hundred of miles away. In 1998, EPA issued a rule intended to significantly reduce regional NO_x emissions in 22 states and the District of Columbia, and in turn, reduce the regional transport of ozone. Some regional strategies for reducing ground-level ozone include:

- Reducing NOx emissions from power plants and industrial combustion sources.
- Introducing low-emission cars and trucks.
- Using cleaner gasoline.
- Improving vehicle inspection programs.[6]

There are a number of steps that communities can take to lessen the impacts of heat islands. These heat island reduction strategies include:

- Installing higher albedo roofs.
- Installing vegetated green roofs.
- Planting trees and vegetation.
- Switching to higher albedo paving materials.

The extent to which urban areas can benefit from heat island reduction strategies depends on several factors. Some of these factors, like prevailing weather patterns, geography, and pollution transported from upwind regions, are largely beyond the influence of local policy. However, factors such as land use patterns, road and building construction materials, and the coverage of urban trees and vegetation can be directly affected by decision makers who can initiate policies and programs to reduce the impacts of UHIs and achieve related environmental and energy-saving goals.[7]

2.1.2 Clean Air Act

The CAA requires the EPA to set NAAQS for common air pollutants. The standards are to be set at levels that protect public health with an adequate margin of safety to protect the health of sensitive groups of people. The standards drive the Nation's air pollution control programs and must be reviewed every 5 yr to ensure that public health issues are being adequately addressed. The CAA requires the states and EPA to develop strategies for reducing pollution from cars, factories, and power plants in order to meet the air quality standards.

In 1997, the EPA updated the health standards for particulate matter and ozone (soot and smog). The EPA action was based on an explosion of scientific evidence linking health problems with exposure to air pollution at levels below the preexisting standards. EPA established for the first time a standard for very fine particles that can lodge in the airways of the lungs, based on evidence of respiratory illness and early death. The standard for ozone was changed to protect children against the adverse effects of exposures over an 8-hr period. The new standards were supported by the American Lung Association and other public health experts, but they were opposed by many industry groups including the electric utility, oil, auto, mining, and trucking industries. Current standards for ozone are 0.08 parts per million (ppm) over an 8-hr period and 0.12 ppm over a 1-hr period. EPA is now engaged in the next 5-yr review of the health standards for particulate matter and ozone.[8]

2.2 Description of Air Quality Modeling Decision Support System

The AQMDSS used in this research work consists of the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Meteorological Model Version 5 (MM5), Sparse Matrix Operator Kernel Emissions (SMOKE), CMAQ Chemical Transport Model (CTM or Models–3). The system has been used in a large number of projects and studies related to air quality in the last 6 yr with satisfactory results. Through this work we have added the SGM to the AQMDSS. The following sections provide a brief description of the existing modeling system and the input data requirements.

2.2.1 Mesoscale Meteorological Model Version 5

Mesoscale Meteorological Model Version 5 (MM5)[9,10] is the latest in a series of models that were developed from a mesoscale model in the early 1970s[11] and is used to simulate local and synoptic scale meteorological conditions prevalent during the period of interest. Since inception, MM5 has undergone many changes designed to broaden its usage. These include (1) a multiple-nest capability, (2) nonhydrostatic dynamics that allow the model to be used at a few-km scale, (3) multitasking capability on shared and distributed memory machines, (4) four-dimensional data assimilation (FDDA) capability, and (5) multiple physics options.[12] It has been extensively used to develop meteorological fields for air quality models and its performance has been thoroughly evaluated and found adequate for air quality model applications.

Required data inputs include:

- Topography and LCLU data.
- Gridded atmospheric fields of sea-level pressure, wind, temperature, relative humidity, and geopotential height at the following pressure levels: 1,000; 850; 700; 500; 400; 300; 250; 200; 150; and 100 mb.
- Observation data including soundings and surface reports.

LULC is used as input directly to MM5 to provide surface boundary conditions such as albedo, soil moisture availability, surface roughness, and canopy height. It is a critical element in the AQMDSS because of its influence on surface fluxes and consequently boundary layer states—primarily air temperature, relative humidity and the wind field, as well as air quality formation and transport. Any improvement in the characterization of the land surface has the potential to substantially improve air quality simulations.

It is important to point out that meteorological fields simulated by MM5 are used as an input to the emissions and air quality models. Their accuracy is thus of considerable importance. The predicted meteorological variables are compared against meteorological data collected at observation stations in an effort to determine the accuracy of the modeling system. The meteorological model performance evaluation methodology and associated tools are thus an integral part of the meteorological modeling system.

2.2.2 Sparse Matrix Operator Kernel Emissions

Emission inventories are typically available with an annual or daily total emissions value for each emissions source. Air quality models such as CMAQ, however, require emissions data on an hourly basis for each model grid cell and species. Consequently, emission processing requires processing of the emission inventory through temporal allocation, chemical speciation, and spatial allocation, to achieve the input requirements of the air quality model. The SMOKE processor[13,14] is capable of creating gridded, temporalized, and speciated emission files for use in air quality models such as CMAQ. SMOKE is capable of generating temperature-sensitive mobile source emission factors using EPA's MOBILE6 emission factors model. It is also capable of generating a biogenic emissions inventory using the Biogenic Emissions Inventory System Version 3 (BEIS–3)[15,16] that utilizes the Biogenic Emissions Land use Database Version 3 (BELD–3). SMOKE requires a large amount of source specific emissions data. Since meteorological fields affect biogenic, point, and mobile source emissions, emission processing for these source categories requires certain meteorological variables; these include daily surface temperature for calculating mobile source emission factors; temperature and radiation fields for calculating biogenic emissions; surface planetary boundary layer (PBL) height, surface heat fluxes, wind speed, and temperature for estimating plume rise for point sources.

2.2.3 Community Multiscale Air Quality-Chemical Transport Model

EPA's CMAQ-CTM or Models–3[17] is an extensively used air quality modeling system that contains state-of-the-science parameterization of atmospheric processes affecting transport, transformation, and deposition of such pollutants as ozone, particulate matter, airborne toxics, and acidic and nutrient pollutant species. With the atmospheric science in a continuing state of advancement and review, the modeling structure of CMAQ is designed to integrate and test future formulations in an efficient manner, without requiring the development of a new modeling system. This fact alone makes CMAQ-CTM a suitable candidate for development and evaluation of emission control strategies.

CMAQ incorporates output fields from the meteorological (MM5) and emissions (SMOKE) modeling systems and several other data sources through special processors. These meteorological data are processed using Meteorology Chemistry Interface Processor (MCIP), initial and boundary conditions through modules ICON and BCON. Photolysis rates are calculated in JPROC, which generates the photolysis rate lookup table under clear sky conditions using modified extraterrestrial radiation data from the World Meteorological Organization (WMO) and O_2 and O_3 absorption cross-section data from NASA.[18]

Figure 4 illustrates the connections between the various datasets and models composing the AQMDSS. Remotely-sensed data include the National NLCD merged with the LandPro99 (an LULC dataset developed for the Atlanta region) used as surface boundary conditions. This merged dataset is described in more detail in section II.D. Large-scale meteorological data obtained from the National Centers for Environmental Prediction (NCEP) are used as lateral boundary conditions in MM5. Outputs from MM5 are used as inputs to SMOKE and CMAQ. As stated before, SMOKE incorporates within it, the BEIS–3, and mobile source emission factors model (i.e., MOBILE6). Major datasets used by the these models include: the Biogenic Emissions Land use Database Version 3 (BELD–3); traffic volume data either from the Highway Performance Monitoring System (HPMS) of the U.S. Department of Transportation (DOT) or from the Travel Demand Model maintained by the Regional Planning Organization (in this case the ARC); and continuous emissions monitoring (CEM) data for the electric generating units (EGU) available from the EPA.

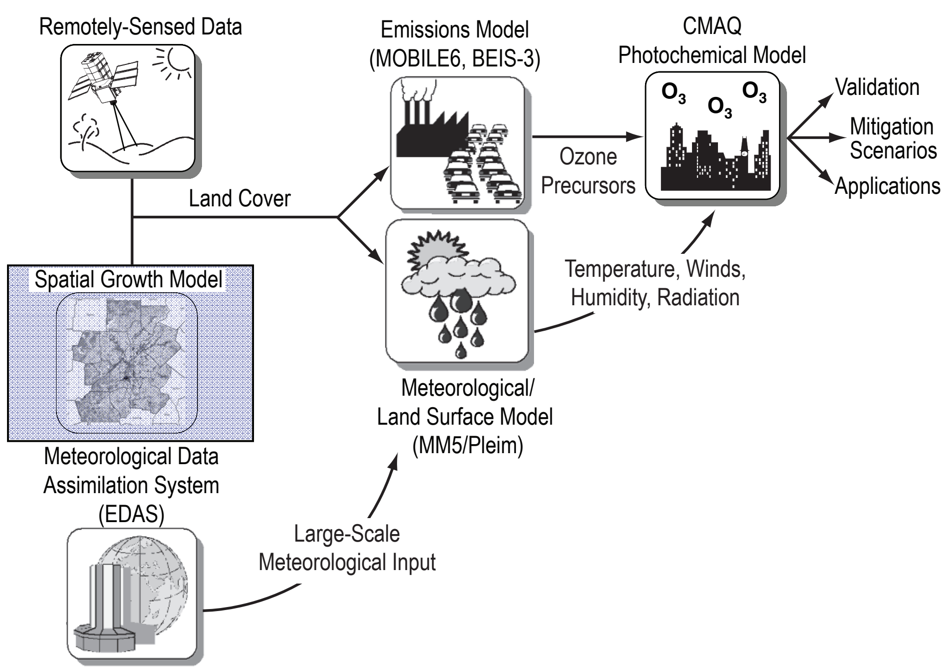

Figure 4. Schematic of the enhanced AQMDSS.

2.3. History and Limitations of Low-Resolution Land Cover Data Inputs for MM5 and CMAQ Modeling in an Urban Environment

The LULC data that have been used previously in MM5 modeling and in the GA EPD Air Quality DSS are the United States Geological Survey (USGS) 4-km 24 category LULC data. This data product specifies five forest types, five agricultural types, three grassland or shrubland types, water, wetlands, savanna, and other miscellaneous types. There is only one urban LULC class, which typically captures only the most heavily urbanized regions. Suburban areas are typically classified as agricultural or grasslands. The ramifications of this misclassification are discussed below in the Evaluation section.

There are two primary limitations to the USGS LULC data with respect to use in an air quality modeling DSS. The first is the spatial resolution of 4 km. While this resolution is consistent with the scale at which modeling is typically performed, information about the subgrid scale distribution of land cover types and associated land surface properties is lost. Because the data represent only the dominant land cover type for each 4-km cell, other classes, which are not dominant but which may cover a sizable minority of the area, are completely ignored. Use of the dominant land cover class can lead to significant errors in the characterization of land surface properties. LULC data at 30-m resolution such as the NLCD/LandPro99 dataset used in this study can be very useful in representing information at the subgrid scale (see next section for more details).

The second limitation of the USGS LULC data is the limited representation of urban and suburban land use. This scheme includes a single urban class, while the LandPro99 classification contains seven classes of developed land. As discussed in the Evaluation section 2.5, the LandPro99 LULC data allow a more robust and useful characterization of urban areas.

2.4 Enhancement to the Air Quality Modeling Decision Support System

By comparison to the USGS land use data, use of high-resolution data such as NLCD/LandPro99 provides very useful information at the subgrid scale; this information was utilized in our model simulations. An illustration of how use of subgrid scale information can impact grid-scale land surface properties is shown in figure 5. In the left panel, albedo is determined via a look-up table based on the dominant land use type on a 4 km grid. Values range from 15% for commercial/industrial and transportation land uses up to about 20% for crops and pastures. In the right panel, albedo is calculated using the same look-up table but using the proportions of each land use type (at 30-m resolution) within each 4-km cell. This results in an albedo field that is smoother, slightly lower, and spatially more realistic with a range of only about 15–18%.

The detailed land use provided by the LandPro99/NLCD data also allows a more robust assessment of future land use through the use of any spatial growth and analysis model. The SGM, developed by our collaborators at Prescott College was used to project land use in the Atlanta region. SGM is a rule-based growth simulator. Developed in ArcView, it has been used in a diverse set of applications across various spatial scales. The spatial arrangement of growth as portrayed in the SGM output is ultimately controlled by nondeterministic interplay of constraining and promoting facets of the ruleset. Typically, planning and development professionals familiar with trends within the study area perform a visual evaluation of the

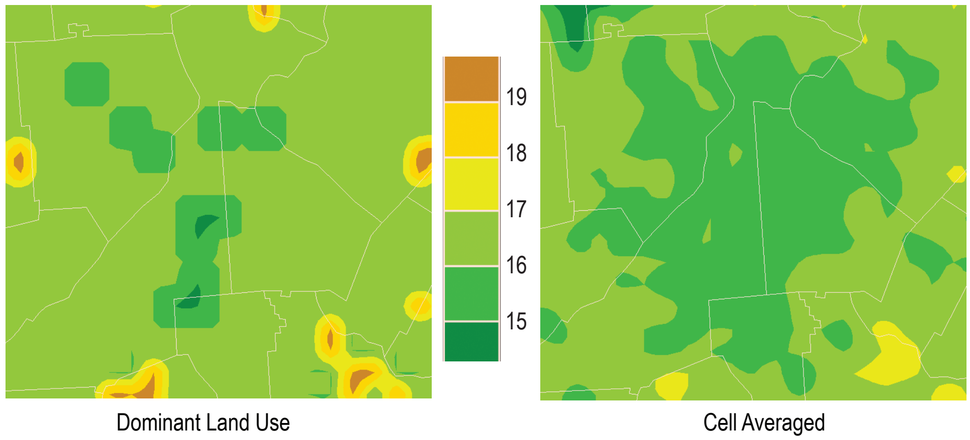

Figure 5. Illustration of the impact of subgrid scale land use data on grid-scale surface albedo. On the left, albedo is based on a look-up table for each 4-km grid cell. On the right, the look-up table is applied to the land use type at 30-m resolution, and the mean albedo calculated across the 4-km cell.

plausibility of a specific output landscape to verify that the macroscale structure of growth is consistent with previous trends and with the constraints on growth within the region. The predicted land use was used in future year meteorological, emissions, and air quality modeling simulations. Depicted as a shaded box in figure 4, this is a major enhancement to the AQMDSS currently employed by federal, state, and local agencies. Using NASA's ISS architecture, the models used, data, outcomes, and impacts are described in figure 6.

2.5 Evaluation

2.5.1 Technical Specifications and Feasibility for Using NASA Data to Improve Decision Support System

As the primary role of the LULC is to provide boundary conditions in MM5 and CMAQ, the main control on the model simulations and the DSS is through its influence on surface energy fluxes and boundary layer meteorological states. Consequently, the primary consideration in selecting an LULC data input is in the accuracy with which these processes and properties can be simulated using the data. Secondarily, the dataset's spatial resolution and ability to differentiate between the many types of LULC typical of an urban environment are considered metrics of the dataset in that these characteristics dictate the flexibility with which the data can be applied. For example, one of the objectives in the Atlanta Air Quality Modeling Study was to project, using a growth model, land use change for the region over the next 30 yr. In order to do this, it was important to have as a starting point a LULC dataset that represented current land use with some complexity. Another objective was to test UHI mitigation strategies in which surface albedo and vegetation cover were modified in the modeling system to test the impact of such changes on air temperature and quality under assumptions of aggressive efforts to reduce the UHI effect over the next 30 yr. The USGS LULC dataset was not suited for these purposes. Therefore, we utilized a LULC dataset that was developed by merging the NLCD and the LandPro99 dataset. The former is a 21-class land cover

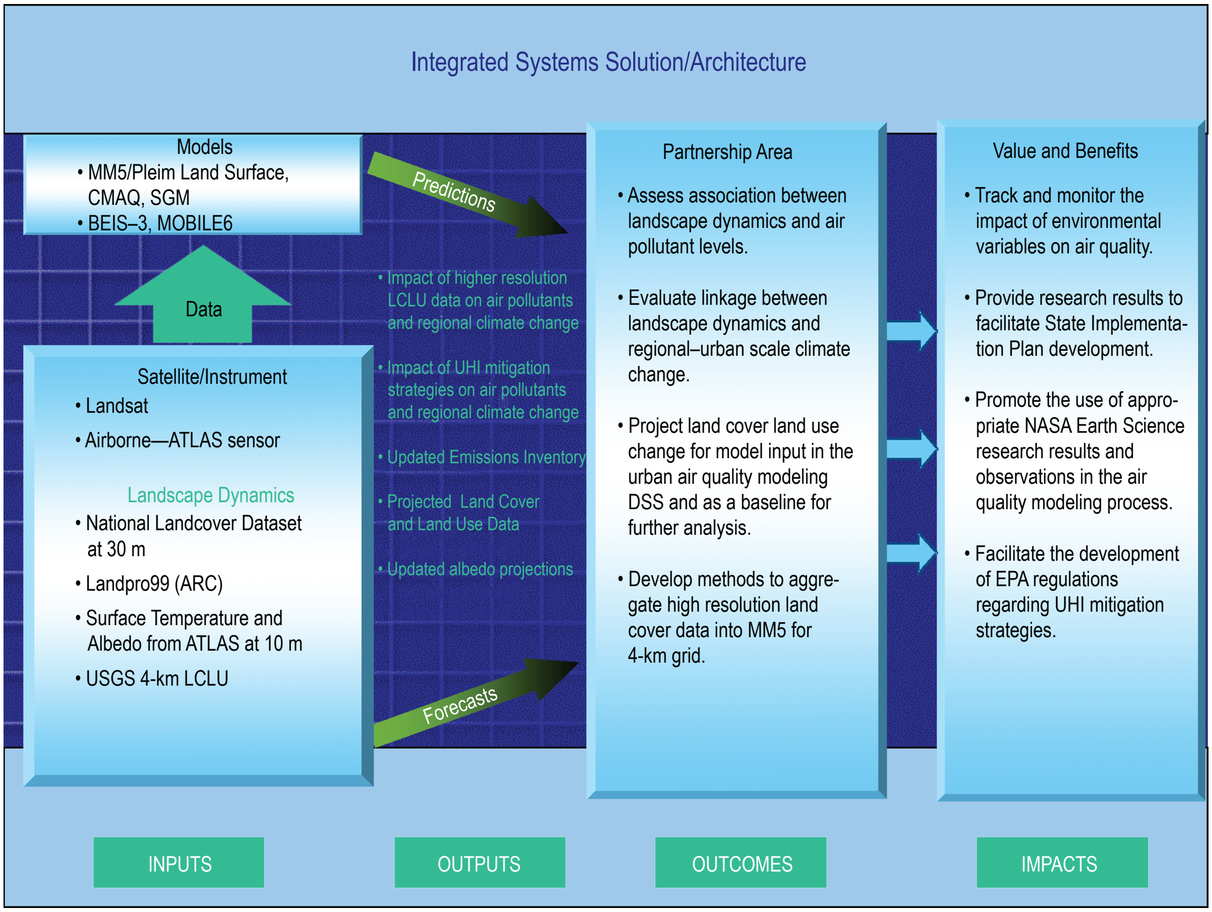

Figure 6. ISS flowchart of AQMDSS enhancement.

classification that provides coverage for the conterminous U.S. and was developed from Landsat TM data from the early 1990s. The LandPro99 data were developed by the ARC for the 13-county metropolitan Atlanta area using aerial photography from 1999–2001.[19] The merged NLCD/LandPro99 data applies the LandPro99 within the 13-county area and NLCD outside of this domain. Efforts were made to make the land cover classes from the two data sources as similar as possible. The LULC classes are compared with the USGS scheme in figure 7. From this starting point we were able to generate realistic LULC growth scenarios that were invaluable in performing future UHI and air quality modeling simulations. Note that in the suburban Atlanta areas, land use is identified in the USGS data as “dry cropland/ grassland,” while in the NLCD/LandPro99 data, much of these areas are depicted as “medium-density residential.” The latter is a much more accurate representation of this area; this is corroborated by the large population and rapid growth in these suburban counties.

Differences between the USGS and NLCD/LandPro99 LULC data are illustrated in figure 8, which shows the frequency distributions of LULC classes across the 13-county metropolitan Atlanta area. For the 13-county area, the NLCD/LandPro99 LULC data are actually defined solely by the LandPro99 data. A major difference is evident in the total forested area, estimated as 53% in the USGS data and 38% in LandPro99. The area used for agriculture is estimated to be much higher by USGS (35%, almost all

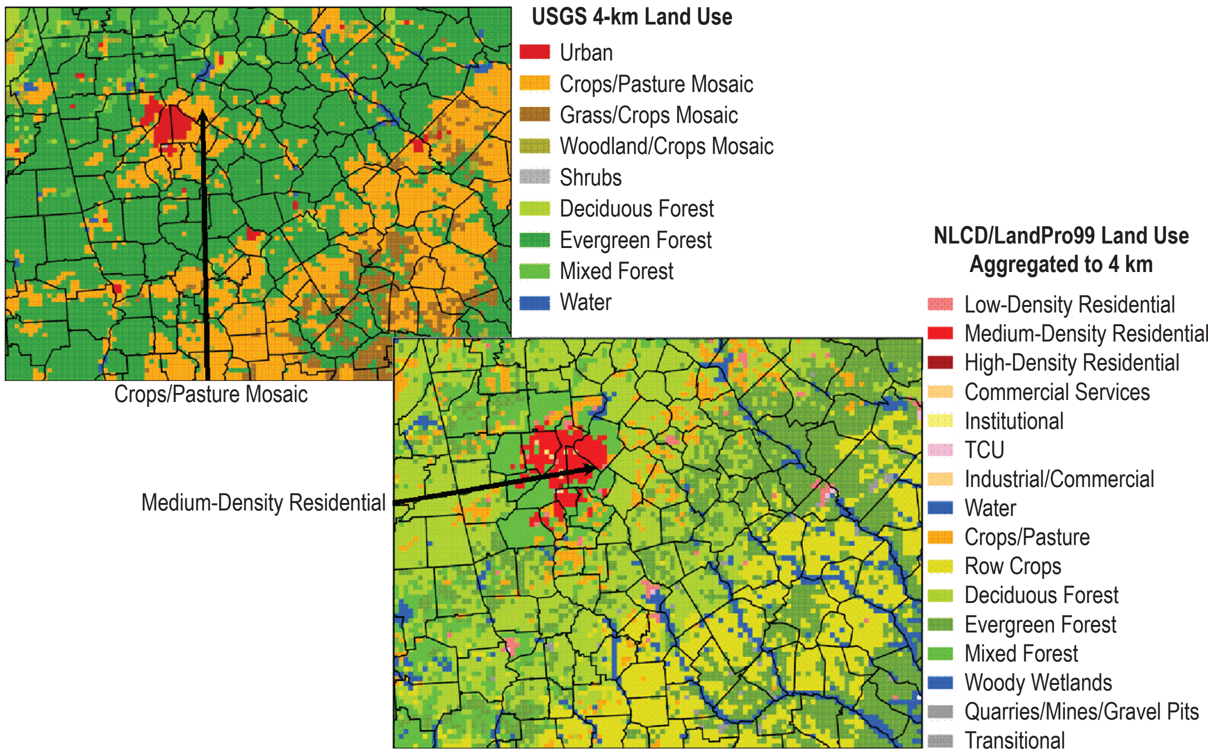

Figure 7. Comparison of the USGS and NLCD/LandPro99 land use classification schemes over the 4-km modeling domain.

of which is dry cropland/grassland), than by LandPro99 (13%), while urban land use makes up only 11% in the USGS data but 28% in the LandPro99 dataset, excluding low-density residential land use that is 10% of the area.

2.5.2 Community Multiscale Air Quality Changes to Make Albedo a Function of Wavelength and Land Use/Land Cover

Use of the NLCD/LandPro99 LULC data allowed us to make another improvement in the AQMDSS. In the JPROC module, surface albedo is typically treated identically for all land surface types, i.e., the spectral reflectance function is the same for all land surfaces. Also, the spectral curve is very simple, with constant values for wavelengths >0.66 microns. We modified this such that albedo is a function of LULC class, and improved the representation of reflectance for longer visible and near-infrared wavelengths. Spectral reflectances for each LULC class were obtained from Eck, Oke, Asrar, Walter-Shea and Biehl, and Herman and Celarier.[20–24] These are shown, along with the original JPROC spectral reflectance function, in figure 9. Due to its more discriminating representation of land-use types within the urban and suburban areas, NLCD/LandPro99 provides, at least in a qualitative sense, an improved albedo specification than could be provided using the USGS LULC data. Calculation of a broad-band albedo from these spectral functions gives a broad-band albedo of 0.12 for the original JPROC function, but most natural land surfaces have higher albedos. Based on the functions used in this study, broad-band albedos for agriculture, rangeland, barren, open shrub, and rock surfaces are in the range of 0.18–0.19 and forests values range from 0.12 to 0.14.

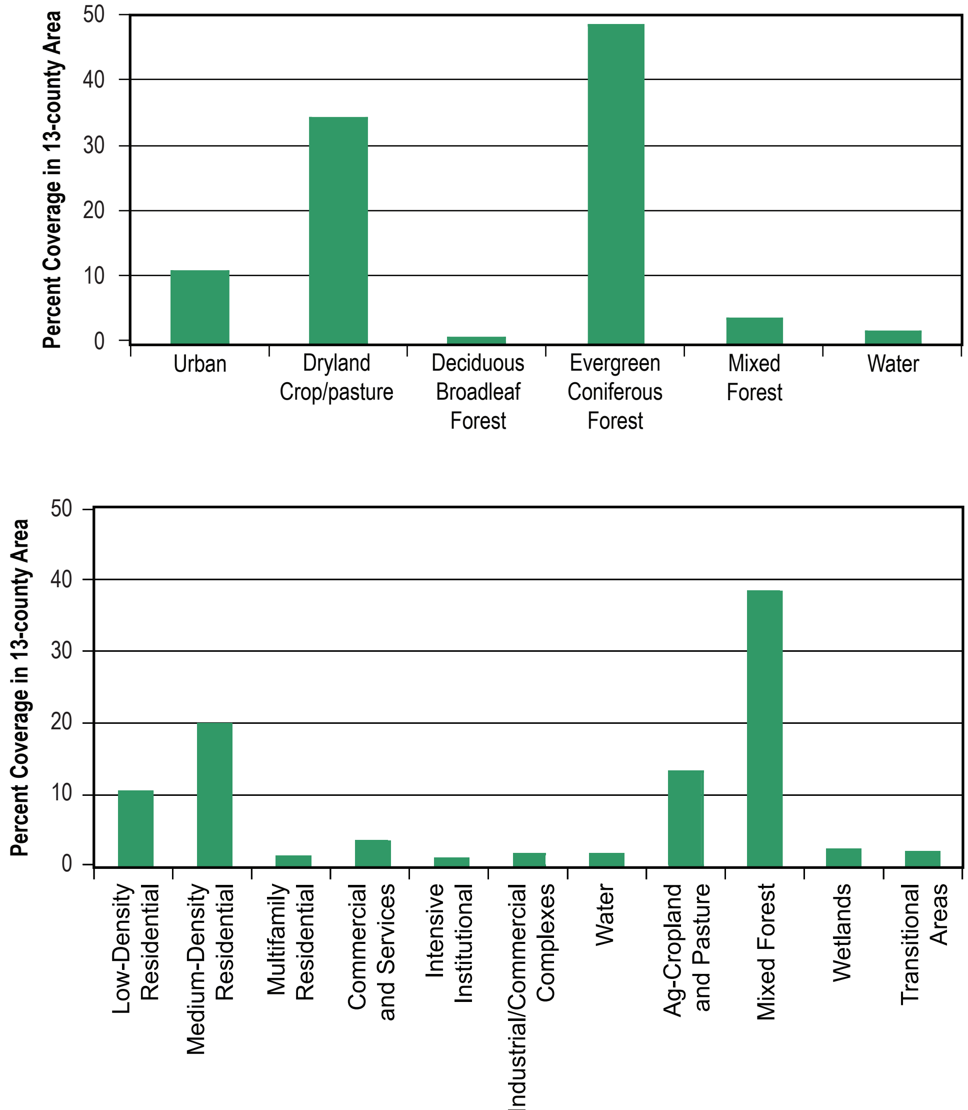

Figure 8. Distributions of land use types represented by the USGS (top) and NLCD/LandPro99 (bottom) land use classification schemes over the 13-county metropolitan Atlanta area.

The importance of albedo in JPROC is that the amount of solar radiation reflected by the surface and subsequently passing through the atmosphere affects photolysis rates and hence ozone formation. A comparison of photolysis rates for the original JPROC configuration with those for each LULC class in the modified version is shown in figure 10. For some surface types, photolysis rates are lower than the constant previously used, while for some types the rates are higher. We investigated the effects of changes in JPROC computations on air quality modeling results but found that the net effect on ozone concentrations was very small.

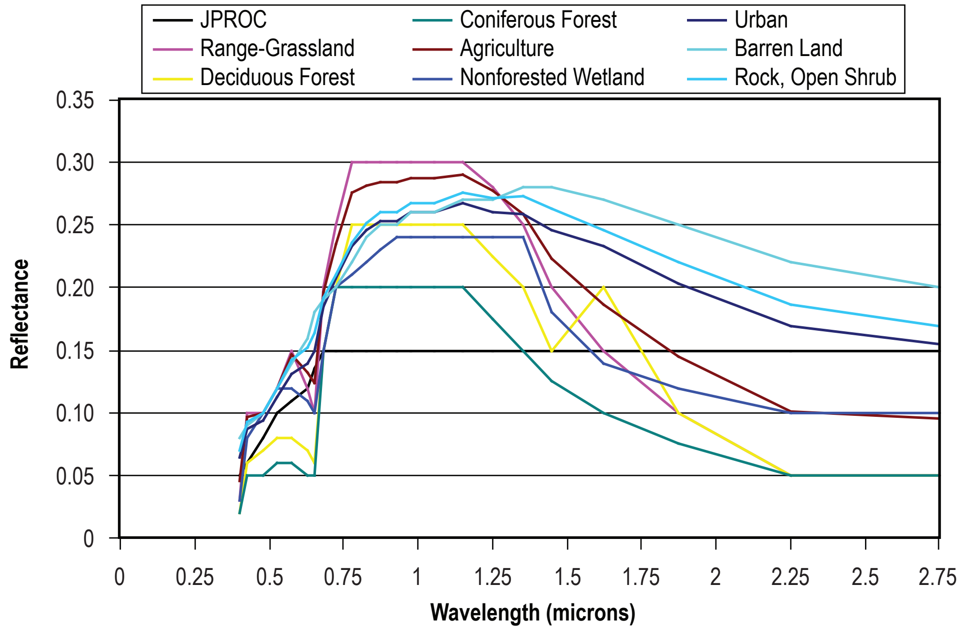

Figure 9. Spectral reflectance of various USGS land surface types compared to the original JPROC spectral reflectance function.

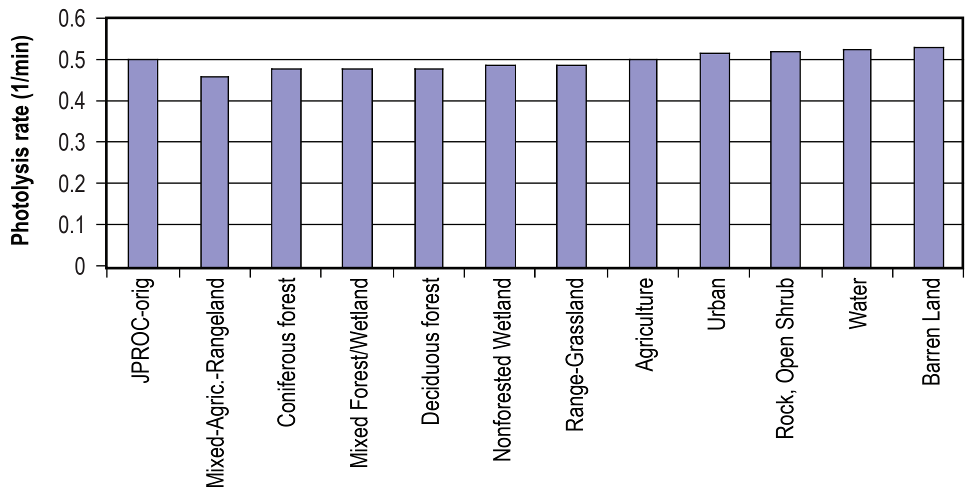

Figure 10. Photolysis rates for the original JPROC configuration and for each USGS land-use class with modified treatment of spectral reflectance.

2.6 Land Use Projections With the Spatial Growth Model

The SGM extends the capability of the AQMDSS to simulate projected changes in LULC related to urbanization, deforestation, or other anthropogenic forcing. In order to run the model, the spatial extent of the study area was matched to the extent of available input data. Land within the study area was divided into grid cells and assigned LULC categories based on the LandPro99 LULC classes. Grid cells not classified as developed land use represent the stock of available land for future development. A set of decision rules was created to control and direct land use changes in the model. These rules were defined by expected rates of land utilization to accommodate population and economic growth and other physical and demographic changes.

The SGM can be modified to handle a variety of data types. Model inputs used to make projections for the Atlanta region (13 counties) were projected population, employment and transportation network, the LULC classification, and physical land features (e.g., topography, water sources, and floodplains). The ARC provided data on current and projected population and employment as well as the existing land cover/land use. The Georgia Department of Transportation (GDOT) provided plans for future transportation system improvements. Data on physical land features were obtained from the Georgia Geographic Information System (GIS) Clearinghouse and included digital elevation maps (DEMs) and floodplain delineations. Landsat-derived NLCD classes at 30-m spatial resolution were used to supplement the LandPro99 LULC data outside the 13 core counties. NLCD data, being used only outside of the 13-county Atlanta area, were not projected in time; however it was used in both baseline and future model runs. The SGM provided LULC projections at 2010, 2020, and 2030 time horizons; current conditions and the projection for 2030 are shown in figure 11.

As shown in figure 12, substantial LULC changes are projected for the Atlanta region by the year 2030. The majority of the changes result in less vegetative cover and more urban development in various classes. Low-density residential development is projected to increase by 89%, medium-density residential development by 62%, and industrial/commercial development by 54%. Conversely, forest decreases by 51%, agriculture/crops by 50%, and agriculture/orchards by 71%.

Overall the landscape in the Atlanta region is projected to change substantially in both the 13-county and core 5-county areas. The core five counties are Fulton, Cobb, DeKalb, Gwinnett, and Clayton. Table 1 provides an analysis of LULC change in both areas from 1999 to 2030. The most significant LULC changes were the conversion of forest, agricultural, and vacant land to residential uses with the extent or percent coverage being greater in the 13-county area due to the availability of undeveloped land versus the more urban 5-county area. Conversion of vegetated land to commercial uses is also continuing in both areas.

The use of higher spatial resolution LULC data provides more heterogeneity of LULC classes and an overall more accurate LULC input to meteorological models. The finer resolution also provides the basis for evaluating in more depth the linkages between land cover change and related physical processes. One such linkage is the UHI phenomenon created by the removal of vegetation in favor of urban impervious surfaces that creates a dome of warmer air over cities.

The extent to which regional climate and LULC changes may impact air quality over heavily populated areas is an important consideration in air quality planning. In this project, the SGM provided projections based on an extension of trends and business as usual (BAU) assumptions for 2010, 2020, and 2030. Utilizing the recommendations of numerous Atlanta stakeholders, several “Cool Communities” strategies to mitigate the impacts of the UHI were developed. These were subsequently used in the AQMDSS in simulations out to the year 2030 to evaluate the effectiveness of the strategies in reducing the UHI

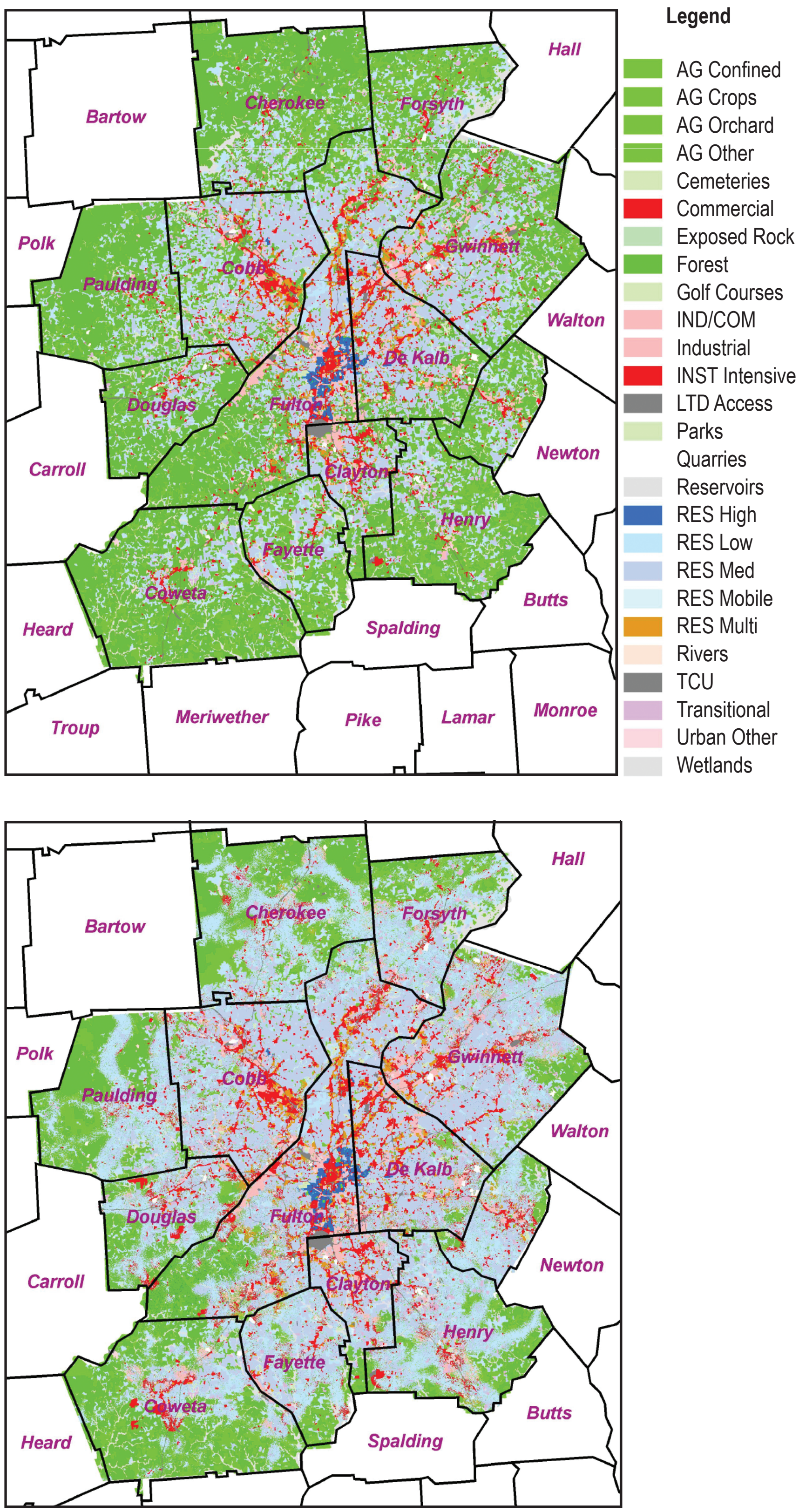

Figure 11. Year 2000 (top) and 2030 (bottom) LULC by the SGM for the 13-county metropolitan Atlanta area. (Source: Prescott College, <www.BlueLineGroup.us>, Johnson, Hoyt, 2005.)

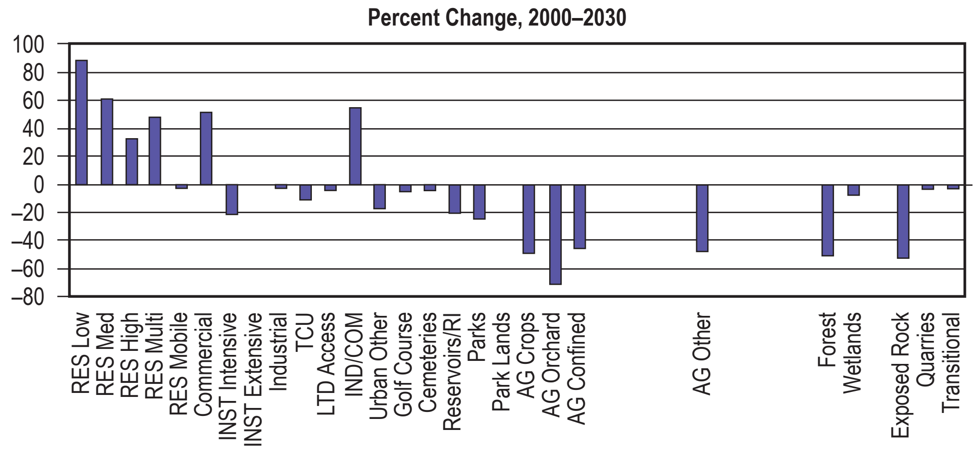

Figure 12. LULC changes from the year 2000 to 2030 for the 13-county metropolitan Atlanta area. (Source: Prescott College, <www.BlueLineGroup.us>, Johnson, Hoyt, 2005.)

Table 1. Percent coverage of each land use class for 1999 and projected for 2030 for 5-county and 13-county metropolitan Atlanta areas.*

Aggregated Land Use	1999 5-County	2030 5-County	% Change, 5-County	1999 13-County	2030 13-County	% Change, 13-County
Commercial	10.62	11.94	12.4	5.91	8.54	**44.5**
Transportation/utilities	2.02	1.98	–2.0	1.21	1.12	–7.4
Industrial/institutional	2.33	2.50	7.3	1.29	1.64	**27.1**
Transitional/extractive lands	2.64	2.59	–1.9	2.14	2.03	–5.1
Multifamily residential	3.06	3.40	11.1	1.42	2.09	**47.2**
High-density residential	1.20	1.26	5.0	0.60	0.73	21.7
Medium-density residential	33.77	39.96	18.3	20.05	32.43	**61.7**
Low-density residential	8.29	12.53	**51.1**	11.14	19.61	**76.0**
Agriculture	5.98	2.60	**–56.5**	13.49	6.72	**–50.2**
Forest/open space	27.59	19.01	**–31.1**	38.86	21.71	**–44.1**
Water/wetlands	2.49	2.23	–10.4	3.89	3.38	–13.1

*Percent changes greater than 25% are in bold.

and improving air quality. The strategies were developed by focus groups that included stakeholders representing the building industry, environmental organizations, U.S. Department of Agriculture, Forest Service, the transportation industry and local and state agencies such as GA EPD, ARC, GA Forestry Commission, and city planners. By including these targeted groups to develop strategies, we hoped to design and test in models realistic scenarios for the Atlanta region that could be implemented if model results are favorable. Cool Communities strategies focused on increasing vegetative cover through tree planting and increasing albedo with the use of more reflective roofing and lighter paving materials such as concrete instead of asphalt. For each of these areas low, medium, and high penetration strategies were developed, with the high penetration being the most aggressive in terms of increasing the vegetative cover and/or albedo. The specific strategies developed for the Atlanta region are given in detail in appendix A.

2.7 Design and Implementation of Numerical Experiments

2.7.1 Modeling Episodes

The meteorological/air quality modeling system was evaluated for two summertime episodes selected to represent quiescent, mostly clear and warm conditions with moderate to high daytime ozone concentrations. Episode 1 covers the 9.5-day period of August 12–21, 2000 and episode 2 spans 10.5 days from August 1–11, 1999. These episodes are dominated by days with meteorological regimes that are likely to cause exceedances of the 8-hr ozone standard in the Atlanta area. Examples shown in this TP are for episode 1, but results for episode 2 are similar and lead to the same conclusions regarding the benefit of the NLCD data within the AQMDSS. Air temperature measured at three sites within the Atlanta area is shown in figure 13 for episode 1. During this period, temperatures were warming each day before a cold front passed through the domain on August 19, after which temperatures dropped significantly.

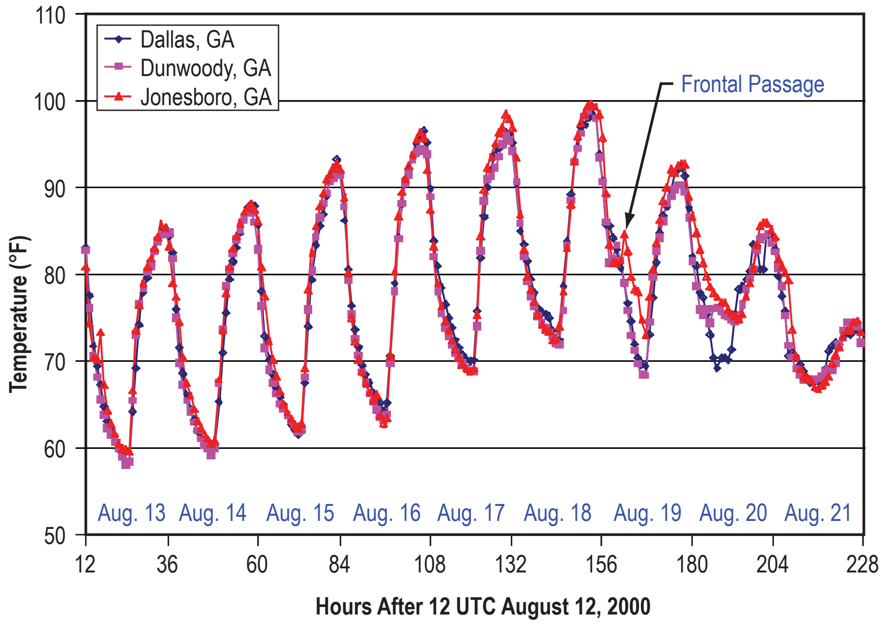

Figure 13. Near-surface air temperature measured at three Atlanta area sites for meteorological episode 1.

2.7.2 Meteorological Model Configuration

A total of four domains (three nested) were used in this study (fig. 14). A 108-km grid covered most of North America and a 36-km mesoalpha-scale grid covered the U.S. east of the Rocky Mountains. Next, a 12-km domain covered the southeastern U.S. Finally, a 4-km mesobeta-scale grid covered a region of 336 km × 432 km centered on the northern two-thirds of Georgia. The grid has a Lambert Conformal map projection with origin at 90 W and true latitudes at 30 and 60 N. All domains had 29 layers, with the lowest calculation level at 9 m. There were 12 layers below 1500 m above ground level (m AGL) to provide high resolution within the mixed layer. The top of the model was at 100 hectoPascals (hPa). All model layers were defined using a time-invariant “background” pressure field based on a standard atmospheric lapse rate. Forecast variables include the three wind components, air temperature, water vapor, cloud water and ice, and precipitation water and ice.

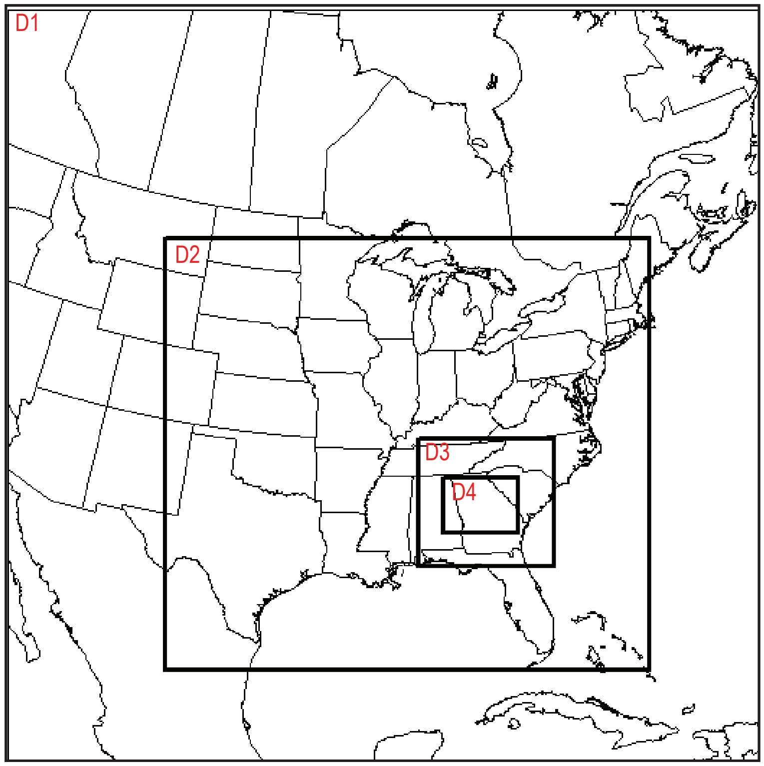

Figure 14. Nested MM5 model domains.

The MM5 has numerous options for physical parameterizations. The configuration chosen for this study is as follows. The Pleim land surface model (LSM) was used[25,26] and is composed of a surface model including soil moisture and evapotranspiration based on the Interactions between Soil, Biosphere, and Atmosphere (ISBA) model,[27] and a nonlocal closure PBL model developed by Pleim and Chang.[28] The surface model includes a two-layer soil model with a 1-cm surface layer and a 1-m root-zone layer. Ground surface temperature is computed from the surface energy balance using a force–restore algorithm for heat exchange within the soil. Shortwave radiation interacts with atmosphere, clouds, precipitation, and the land surface as described by Dudhia. The longwave atmospheric radiation is represented by the Rapid Radiative Transfer Model (RRTM) developed by Mlawer et al. 1997.[29] The simple ice microphysics[30] is used for cloud and precipitation processes and the Kain-Fritsch cumulus scheme[31] was employed on all but the 4-km domain.

The intent of this project is to determine the potential impact of land use change on the near surface meteorology under conditions of maximum solar forcing. It is recognized that small perturbations in the lower boundary condition in a highly nonlinear modeling system can cause dramatic differences in the numerical solution, especially when it comes to vertical motion and associated cloud development. Therefore, MM5 was specifically configured to exclude the effects of clouds and precipitation on the surface energy budget in order to isolate the impact of the land use changes on the near surface meteorology. The "fake dry" option was implemented in MM5 such that atmospheric moisture exists but clouds are not allowed to interact with the atmosphere. It amounts to disabling the resolvable-scale and subgrid cloud and precipitation processes. The "fake dry" configuration eliminates terms involving the phase change of water, i.e., latent heating/cooling, from the thermodynamic equation. Precipitation is allowed to occur, but the latent heating/cooling effects are turned off and the impact on the soil model is ignored, i.e., no soil wetting is considered. Most importantly, the effect of clouds on the incoming solar energy is completely eliminated.

Three-dimensional initial and lateral boundary conditions for wind, temperature, and mixing ratio were prepared at 12-hr intervals on the 108-km domain from the NCEP Eta Data Assimilation System (EDAS) analysis[32] available on the 40-km Advanced Weather Information Processing System (AWIPS) 212 grid. Fields are interpolated to the MM5 grid using standard preprocessing software. Initial conditions for the three finer domains were obtained by interpolation from the 108-km grid. The 108-km and 36-km domains were two-way interactive. The 12-km and 4-km domains, however, received boundary conditions from the next coarser grid but did not feed information back to the larger domains (one-way interactive nest interfaces).

The experiment design for the MM5 also included the FDDA system described by Stauffer and Seaman (1990, 1994).[33,34] FDDA was applied to reduce error growth at the larger scales while allowing the 12- and 4-km solutions, which are the object of the experiment, to develop solely from dynamical and physical forcing. FDDA was accomplished by relaxing the model solutions at every time step toward the synoptic-scale three-dimensional analyses of wind, temperature, and mixing ratio that were described above. These fields were blended into MM5's 108-km and 36-km solutions using a continuous-relaxation approach known as analysis nudging. No data assimilation was done on the 12- and 4-km domains in this experiment. Limiting FDDA to the outer two domains was designed to provide accurate lateral boundary conditions for the 12- and 4-km domains while allowing the model's 4-km solutions to develop without artificial forcing. By reducing the phase and amplitude errors in the synoptic-scale solution, the meso-beta-scale structures on the innermost grid were found to have skill consistent with statistics reported for typical air quality episodes simulated using FDDA-assisted models.[35–37] Furthermore, on the outer two domains, no FDDA was applied below 850 hPa. This data assimilation strategy ensured that important surface-forced features could develop in the fields used to supply boundary conditions to the 4-km domain (i.e., on the 12-km grid) without being damped by assimilation of the synoptic-scale analyses.

For each meteorological episode, the modeling system was run first using the USGS LULC data and associated specified values for surface characteristics (i.e., albedo, vegetation fraction, etc.) within the Pleim LSM on all four domains. In these preliminary runs, the cloud physics were turned on in MM5.

After the runs were made with the USGS data, simulations were performed for the two episodes using the NLCD/LandPro99 data, again with clouds turned on. It became apparent that differences in cloud fields between model simulations seriously confounded the analysis of air temperature and ozone differences between the simulations; this was observed earlier in air quality modeling analysis for Houston, Texas.[38] Therefore, we repeated the USGS and NLCD/LandPro99 simulations for both episodes in the "fake dry" mode, the results of which were used in our Verification/Validation/Benchmarking analysis. We refer to these as the 2000 Baseline simulations.

2.7.3 Emissions Inventory Development

In general, the emissions inventory for the project was developed from the 1999 National Emissions Inventory (NEI) Version 2.3, and the Fall line Air Quality Study (FAQS) emissions inventories.[39] Emissions of carbon monoxide (CO), nitrogen oxides, ammonia (NH_3), sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$, PM_{10}), and VOCs from Electricity Generating Units (EGUs), Non-Electricity Generating Units (non-EGUs), on-road mobile sources, off-road mobile sources, and biogenic sources are included. Databases used in the development of emission inventories are described in the following paragraphs. Databases and modeling tools used to generate base and future year emission inventories are summarized in tables 2 and 3.

2.7.3.1 Electricity Generating Units. Sulfur dioxide and nitrogen oxides emissions were based on CEM data available from the EPA's Clean Air Markets Division and 1999 NEI Version 2.3. Emissions of other pollutants were calculated by multiplying relevant emission factors with the heat input values obtained from the CEM database. Future year emissions were computed using unit-specific control factors and projection factors from the Economic Growth and Analysis System (EGAS) Version 4.0.

2.7.3.2 Nonelectricity Generating Units and Area Sources. The non-EGUs and Area Sources emissions inventory was developed from 1999 NEI Version 2.3 and the FAQS emissions inventories. The FAQS inventory was developed through a survey of industrial facilities in 11 counties in and around the cities of Augusta, Columbus, and Macon, GA. The emission inventory includes only those sources that have annual emissions greater than 25 tons. Future year emission inventories were developed using control factors developed by U.S. EPA and projection factors from EGAS Version 4.0.

2.7.3.3 On-Road Mobile Sources. EPA's MOBILE6 model was used to calculate on-road mobile source emission factors. Estimates of vehicle miles traveled (VMT) from GDOT and speeds from the ARC were used.

2.7.3.4 Off-Road Mobile Sources. With the exception of emissions from aircraft and locomotives, off-road mobile emissions were calculated using EPA's NONROAD model (released June 2000). Aircraft and locomotive emissions were obtained from the 1999 NEI Version 2.3.

Table 2. Data sources and modeling tools used in the development of base year (i.e., 2000) emissions inventory.

Source Category		Georgia: FAQs Area[a]	Georgia: Rest of the State	Other States
Point	EGU	CEM data[b] for August 2000 and NET99[c] emissions inventory version 2.3		
	Non-EGU	FAQS emissions inventory[d]		NET99 EI version 2.3 projected to 2000 with EGAS4.0 growth factors
Area (NH_3)	All	Cardelino, 2003[e]		NET99 EI version 2.3 projected to 2000 with EGAS4.0 growth factors
Area	Forest wildfires, slash burning and prescribed burning, agricultural burning	FAQs emissions inventory		NET99 EI version 2.3 projected to 2000 with EGAS4.0 growth factors
	Others	NET99 EI version 2.3 projected to 2000 with EGAS4.0 growth factors		
Nonroad	Aircraft, railroad, and locomotives	FAQS Emissions Inventory	NET99 EI version 2.3 projected to 2000 with EGAS4.0 growth factors	
	Others	NET99 EI version 2.3 projected to 2000 with growth factors from EPA's NONROAD model[f]		
On-road (VMT and speeds)		GDOT[g] and ARC[h], respectively		NET99 mobile source activity data[i] projected to 2000 using EGAS4.0

[a]Includes the counties of Richmond, Columbia, McDuffie, Muscogee, Chattahoochee, Harris, Bibb, Houston, Jones, Peach, and Twiggs.
[b]Emissions from EGUs in the NET99 Emissions Inventory are replaced with CEM data available at <http://cfpub.epa.gov/gdm> using the air quality emissions processor.
[c]Emissions Inventory is available at <http://www.epa.gov/ttn/chief/net/index.html#1999>.
[d]FAQS Emissions Inventory Development report available at <http://cure.eas.gatech.edu/faqs/models/index.html>.
[e]Developed by Dr. Carlos Cardelino <carlos.cardelino@eas.gatech.edu>, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia.
[f]EPA's Nonroad mobile model (June 2000) <http://www.epa.gov/ttn/chief/emch/models/index.html>.
[g]Annual average daily VMT data for 2000 available at <http://www.dot.state.ga.us/dot/plan-prog/transportation_data/400reports/index.shtml>.
[h]Speed data for the 13-county Atlanta nonattainment area is from Atlanta Regional Commission's travel demand model.

Table 3. Data sources and modeling tools used in the development of future year (i.e., 2030) emissions inventory.

Source category		Growth: Georgia	Growth: Other States	Controls: Georgia	Controls: Other States
Point	EGU	EGAS4.0	EGAS4.0	Plant specific control factors developed for Augusta EAC	NOx SIP call and plant specific control factors developed for Augusta EAC
	Non-EGU	EGAS4.0		VOC RACT controls, MACT controls, NOx SIP call control factors used in development of EPA's Emissions Inventory for HDDV Final Rulemaking documented	
Area	All	EGAS4.0		STAGE-II controls, fuel efficiency, VOC controls, etc., used in EPA's HDDV Rule modeling	
Nonroad	Aircraft, railroad, and locomotives	NET99 EI version 2.3 projected to 2030 with EGAS4.0 growth factors			
	Others	EPA's NONROAD model (June 2000)			
On-road VMT		VMT grown using linear regression	EGAS4.0	Enhanced vehicle I/M, Stage II vapor recovery, Phase 1 Ga. Gasoline	NET99 MOBILE6 input files

2.7.4 Air Quality Model Configuration

CMAQ provides several scientific options for the most important atmospheric processes, e.g., gas-phase chemistry, advection. CMAQ Version 4.4 released by EPA was used the modeling simulations described in this TP. The model configuration is shown in table 4.

Table 4. CMAQ model configuration.

Physical Process	Reference
Horizontal and vertical advection	Piecewise parabolic method (PPM)
Horizontal diffusion	Spatially varying
Vertical diffusion	Eddy diffusion formulation based on K-theory
Gas-phase chemistry and solver	SAPRC–99 chemical mechanism with Modified Euler Backward Iterative (MEBI) solver
Aqueous-phase chemistry	Reactive Acid Deposition Model (RADM)
Aerosol chemistry	Improved treatment for secondary organic aerosol (SOA) and ISORROPIA for thermodynamics
Dry deposition	RADM
Cloud dynamics	RADM

MCIP Version 2.3 was used to create meteorological input files. Most meteorological variables are passed through directly from the MM5 output fields. Others, such as dry deposition velocities, are computed by MCIP. MCIP also creates the horizontal and vertical grid structure for CMAQ by extracting data for the domain defined by the user. Since computational limitations prohibit the use of all 34 vertical layers used in the MM5 simulations, the CMAQ modeling grid consisted of only 13 vertical layers.

3. BENCHMARKING

3.1 Comparison of Air Quality Modeling Decision Support System Performance With Earlier Version

3.1.1 MM5 Evaluations—Air Temperature, Planetary Boundary Layer Heights

Evaluation of the value added by higher resolution LULC data was tested by comparing the 4-km resolution USGS LULC dataset currently being used in CMAQ runs for Georgia with the 30-m resolution NLCD/LandPro99 classes in the base case analysis. The impacts of using the high-resolution data in the AQMDSS are manifest in meteorological fields such as near-surface air temperature, humidity, winds and PBL heights, and in air quality model outputs, most importantly ground-level ozone concentrations. In order to evaluate the performance of the modeling system against meteorological observations, simulations performed with full cloud and precipitation physics were compared. Overall, the effect of using the NLCD/LandPro99 dataset is to increase near-surface air temperatures over the model domain (fig. 15). This reduces the large cool model bias by ≈1 °C based on comparisons at 10 surface measurement sites for the 3:00–8:00 p.m. local daylight time (LDT) period. However, an average bias of about 2 °C remains.

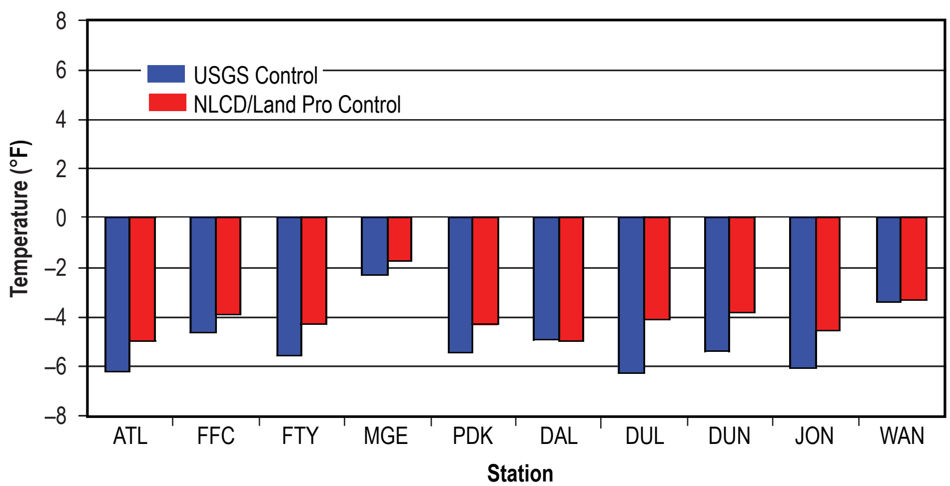

Figure 15. Temperature biases from MM5 simulations using the USGS and NLCD/LandPro99 land use inputs at 10 surface observing sites in the Atlanta area. Biases are averaged for the hours 3:00–8:00 PM LDT over episode 1.

For evaluating the effects of the LULC inputs on spatial features of the meteorological and air quality fields, it is necessary to utilize the simulations performed in “fake dry” mode. Figure 16 shows an example of the differences in near-surface air temperature between episode 1 simulations (August 2000) using the two LULC schemes, both in this mode. This is a dramatic illustration of the impact of the land use data on air temperature at a given time—5:00 p.m. LDT on day 6 of the simulation. The largest differences are positive (NLCD/LandPro99 warmer than USGS) and exist in the Atlanta suburban areas, particularly on the east side of the city. This is consistent with a change of land use from dry cropland/grassland in the USGS scheme to low-density residential and medium-density residential in the NLCD/LandPro99 classification. Smaller differences, both positive and negative, occur outside of the Atlanta metropolitan area. The temperature impact shown here is larger than for most other days of this simulation; however the pattern is representative of afternoon conditions throughout the episode. The temperature impacts during cooler times of the day are smaller. Nighttime temperature differences are erratic due to complex temperature profiles in shallow boundary layers.

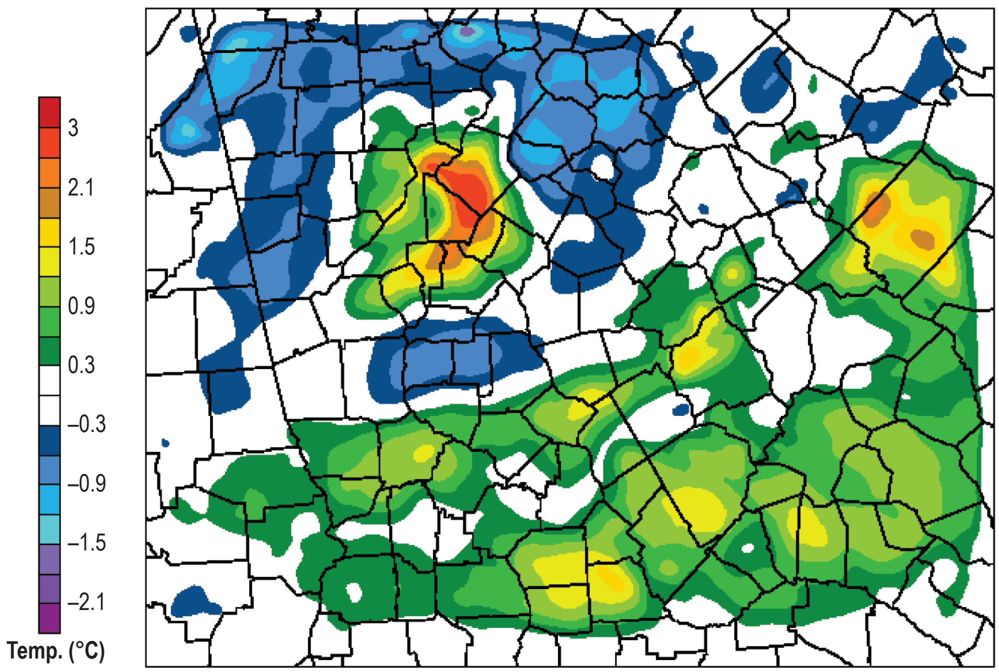

Figure 16. Difference (NLCD/LandPro99—USGS) in 2-m air temperature at 21 UTC (5:00 p.m. LDT) on day 6 of the episode 1 model simulation (August 17, 2000).

Figure 17 illustrates the effect of changing the LULC on mean daily PBL heights. Using either dataset, PBL heights for the immediate Atlanta area are higher than in the suburbs and for rural areas. PBL heights are lowest for the agricultural regions of central and southern Georgia. Use of the NLCD/LandPro99 input (right panel) results in increased PBL heights in the vicinity of Atlanta and in central and southern Georgia. This is consistent with warmer surface temperatures show in figure 16. Consistent with lower air temperatures are lower PBL heights in the areas north of Atlanta.

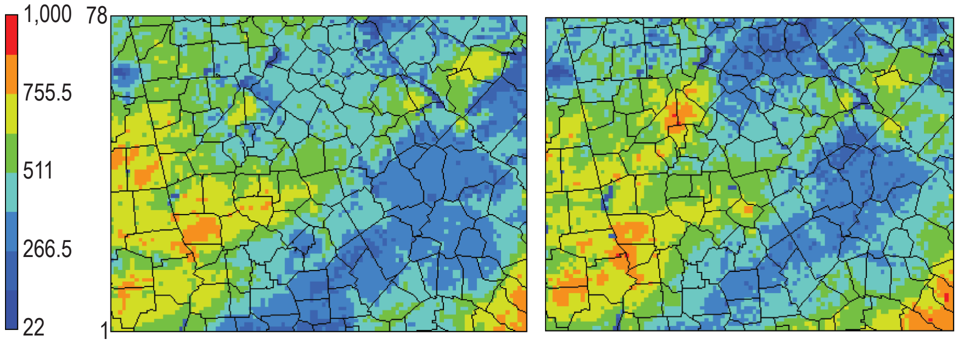

Figure 17. Mean daily PBL heights (m) for August 16, 2000 from MM5 simulations using the USGS (left) and NLCD/LandPro99 (right) land use inputs.

3.1.2 Emission Evaluations

The SMOKE emissions processor was used to create gridded, temporalized, and speciated emission files for use in CMAQ. Since biogenic, mobile, and point source emission processing requires meteorological variables, emissions were processed using meteorological fields simulated using both the USGS and NLCD/LandPro datasets. Visual examination of gridded emission fields was conducted and is summarized below.

Mobile source emissions processed using the MM5 simulation that employs NLCD/LandPro99 data are higher than emissions processed with the simulation using USGS data. Recall that the NLCD/LandPro99 simulation predicted higher near-surface temperatures and greater daytime mixing depths on almost all modeling days. Clearly, higher temperatures associated with the NLCD/LandPro99 data led to higher emissions within the 13-county region. The effects of changing the LULC on daily mobile source CO and NOx emissions are illustrated in figures 18 and 19. Differences in daily biogenic isoprene emissions are shown in figure 20. The effects of temperature on meteorology-dependent emissions (mobile and biogenic) are seen to increase emissions of all types. Mixing depth and other meteorological variables also effect the vertical distribution of point source emissions. For a number of large sources outside the five-county area, use of USGS and NLCD/LandPro99 land cover data resulted in significant differences in the vertical distribution of emissions and their subsequent transport downwind.

3.1.3 Community Multiscale Air Quality Evaluations—Ozone

The performance of the model at 12- and 4-km grid resolution has been evaluated; results for the 4-km grid are presented here. The statistical measures include the mean normalized bias (MNB) and mean normalized error (MNE) in hourly averaged O_3 concentrations predicted at the monitoring station. Formulation of these metrics is provided in table 5. Since the normalized quantities can become large when observations are small, values below 40 ppb were excluded from these computations. The hourly normalized bias and error metrics are presented in figure 21 as daily averages over all monitoring stations. This figure shows that, using either LULC dataset, the air quality model underpredicts ozone over the 4-km model domain. MNBs are greater than 10% on all eight days and greater than 20% on two days. Use of the NLCD/LandPro99 LULC data reduces the bias on half the days but increases it for the other half. MNE is reduced for six of the eight days using the NLCD/LandPro99 data.

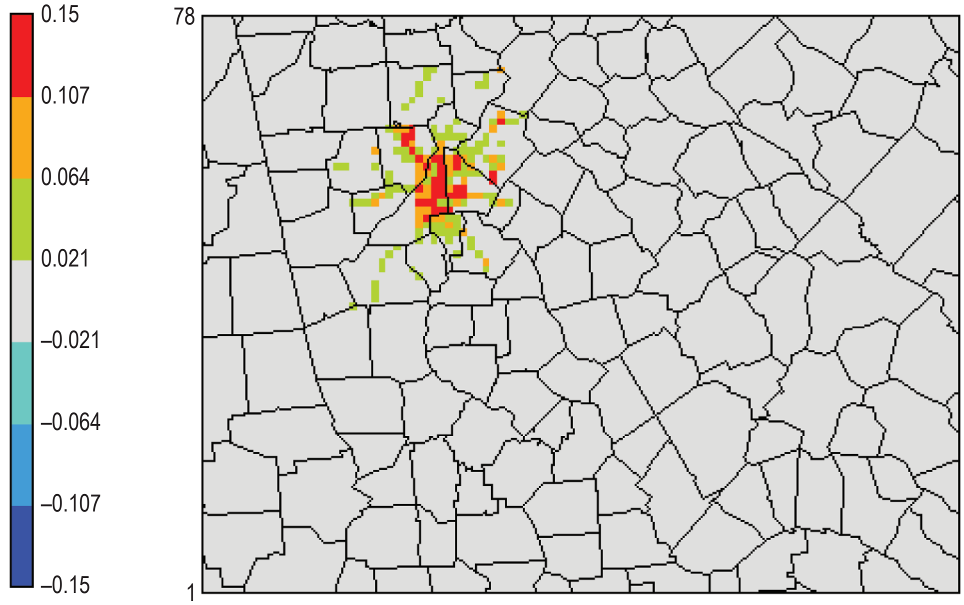

Figure 18. Difference in mean daily CO emissions (moles/s) from mobile sources for August 17, 2000 from MM5 simulations using NLCD/LandPro99 and USGS land use inputs. (Source: Georgia Environmental Protection Division, Air Quality Branch, 2004.)

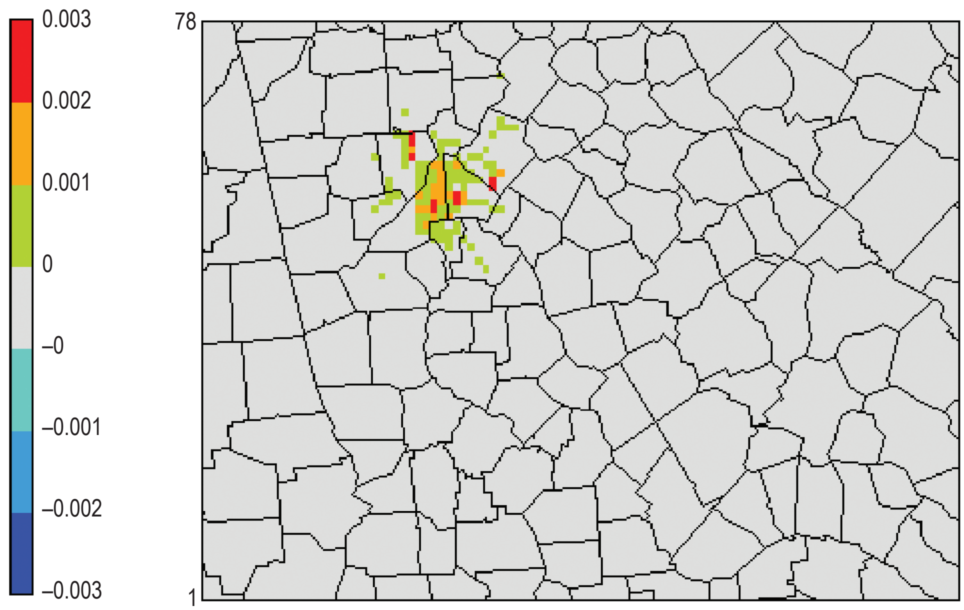

Figure 19. Difference in mean daily NO emissions (moles/s) from mobile sources for August 17, 2000 from MM5 simulations using NLCD/LandPro99 and USGS land use inputs. (Source: Georgia Environmental Protection Division, Air Quality Branch, 2004.)

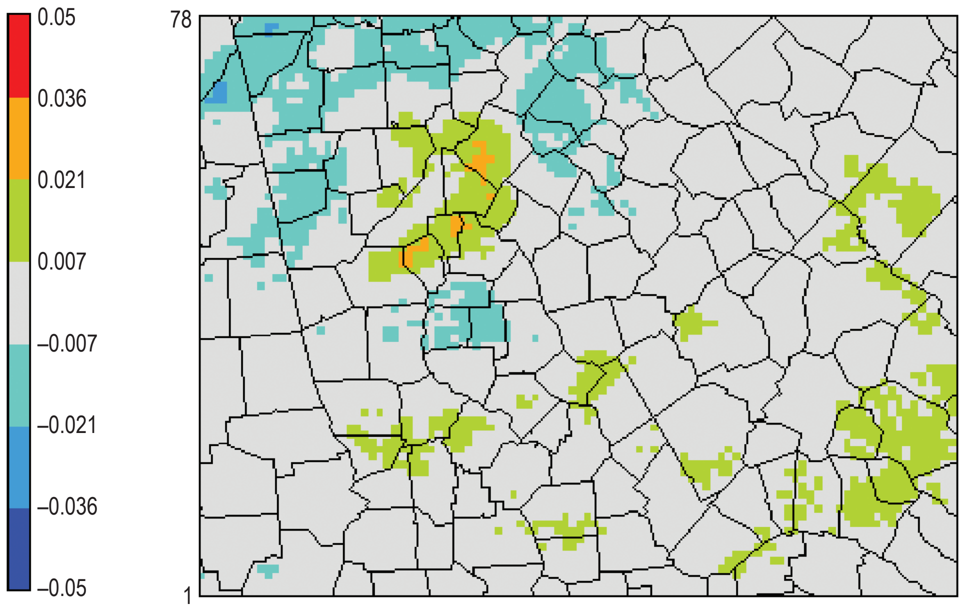

Figure 20. Difference in mean daily isoprene emissions (moles/s) from biogenic sources for August 17, 2000 from MM5 simulations using NLCD/LandPro99 and USGS land use inputs. (Source: Georgia Environmental Protection Division, Air Quality Branch, 2004.)

Table 5. Ozone performance statistics and EPA criteria.

Metrics	Formulation	EPA criteria
Mean normalized bias	$\frac{1}{N}\sum_{i=1}^{N}\frac{\left(C_i^s - C_i^o\right)}{C_i^o}\times 100\%$	Less than 15% for 1-hr and 8-hr average ozone concentration and 20% in peak 1-hr and 8-hr average ozone concentration
Mean normalized error	$\frac{1}{N}\sum_{i=1}^{N}\frac{\left\|C_i^s - C_i^o\right\|}{C_i^o}\times 100\%$	Less than 35% for 1-hr and 8-hr averaged ozone concentration

The statistical analysis was followed by visual inspection of predicted concentrations fields. This helps in identifying dynamics of pollutant plumes in the region and interpreting the performance issues related to individual monitors. For example, poor model performance at a monitoring station might be related to displacement of a plume due to error in wind direction. Finally, time series plots of predicted and observed hourly concentrations provide a stringent test of how well the model replicates the observed hourly concentration at the same time and location as the observed value. Problems with diurnal variation in predicted concentrations are readily apparent in a time series plot.

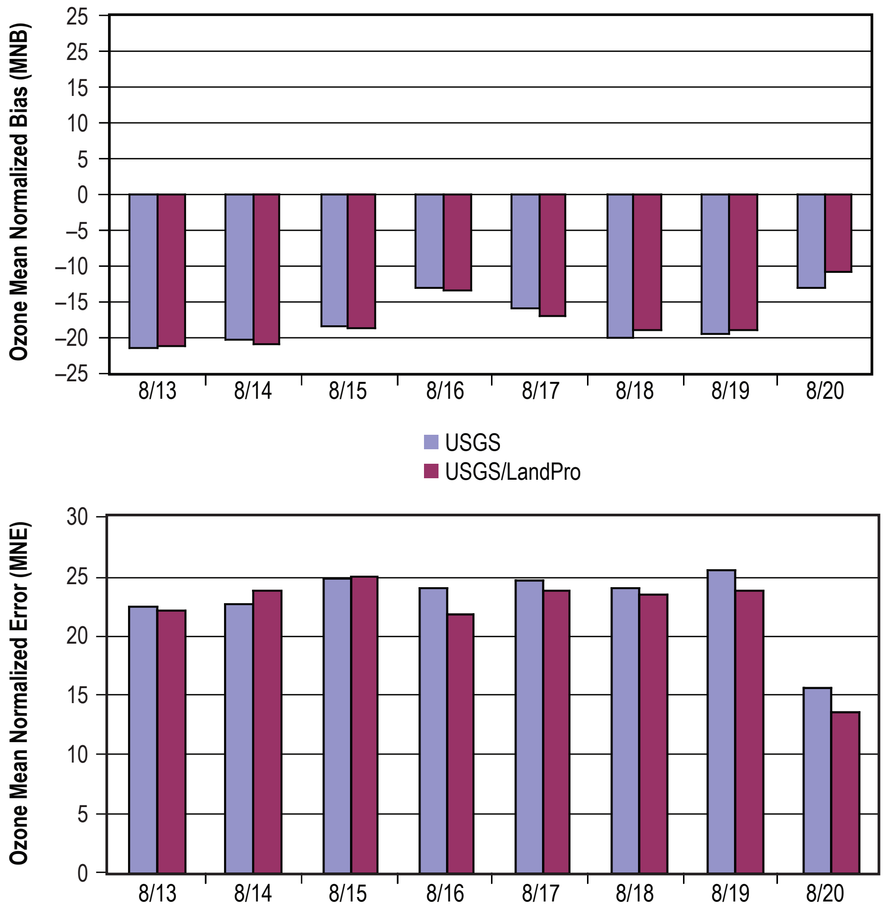

Figure 21. MNB (top) and MNE (bottom) for hourly ozone (PPB) for model simulations over the 4-km grid using USGS and LandPro99 LULC data. (Source: Georgia Environmental Protection Division, Air Quality Branch, 2004.)

Visual analysis revealed significant differences in the predicted ozone field. For example, figure 22 shows a general reduction in daily 1-hr maximum ozone concentrations for August 17, 2000 when the NLCD/LandPro99 LULC data are used. On other days, however, ozone concentrations are slightly higher with the NLCD/LandPro99 data. The inconsistent results are due to the competing effects of higher temperatures, which tend to increase ozone formation and higher PBL heights that tend to lower ground-level ozone by vertical mixing.

3.2 Impact of Urban Heat Island Mitigation Strategies on Urban Climate Change

In order to evaluate the effectiveness of the UHI mitigation strategies in reducing urban air temperatures and to test the sensitivity of the modeling system to changes in urban albedo and vegetation cover, simulations were performed for the year 2030 using various assumptions. All were run in “fake dry” mode and used the episode 1 meteorological forcing. The first simulation, 2030 BAU, used the SGM-projected LULC data with the same albedo and vegetation cover values used in the year 2000 simulations. Albedo and vegetation mitigation scenarios were also simulated in which urban albedos and tree cover fractions, as well as leaf area index (LAI) were increased for each LULC class according to the recommendations of the focus groups—see table 6 for details. A 2030 combined mitigation simulation was also performed, incorporating increases in both albedo and tree cover. The mean albedo and vegetation cover values, averaged over the 5-county and 13-county areas, are shown for the 2030 BAU and combined mitigation simulations in table 7. Because much of the area is not urbanized, particularly within the 13-county area, the mean albedo and vegetation cover changes are quite modest.

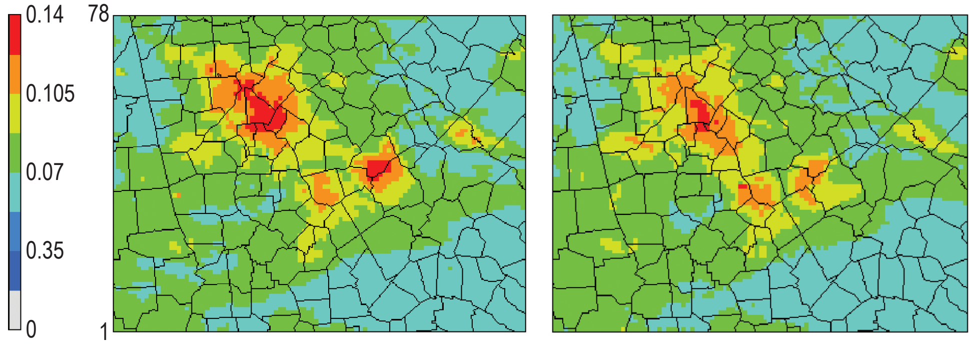

Figure 22. Daily 1-hr maximum ozone concentrations (PPM) for August 17, 2000 from MM5 simulations using the USGS (left) and NLCD/LandPro99 (right) land use inputs. (Source: Georgia Environmental Protection Division, Air Quality Branch, 2004.)

Table 6. Albedo, fractional vegetation cover, and LAI values used in the baseline and combined mitigation (high) simulations for each LULC class.

Landcover Class	Baseline Albedo	High Albedo	Baseline Fractional Vegetation	High Fractional Vegetation	Baseline LAI	High LAI
Low-density single family residential	16	16	75	84	2.50	2.80
Medium-density single family residential	16	17	70	74	2.00	2.20
High-density residential	15	17	30	37	1.00	1.20
Multifamily residential	15	17	30	37	1.00	1.20
Mobile home parks	15	17	30	37	1.00	1.20
Commercial and services	15	27	20	23	0.75	0.85
Intensive institutional	15	25	20	23	0.75	0.85
Extensive institutional	16	25	75	75	2.50	2.50
Industrial	15	25	20	23	0.75	0.85
Transportation, communication, and utilities	15	27	20	23	0.75	0.85
Limited access highways	13	27	20	23	0.75	0.85
Industrial and commercial complexes	15	26	20	23	0.75	0.85
Other urban	16	16	75	75	2.50	2.50

Table 7. Mean values of albedo and vegetation cover over the 5-county and 13-county areas for the 2030 baseline and 2030 combined mitigation simulations.

	Albedo		Vegetation Cover (%)	
	5-County	13-County	5-County	13-County
2030 BAU	0.160	0.161	63.8	68.6
2030 Combined Mitigation	0.181	0.175	66.0	70.7
Difference	0.021	0.014	2.2	2.1

The effects on temperature of changes in LULC between 2000 and 2030 are illustrated in figure 23, which represents typical midafternoon conditions during episode 1. In the urban center, there is very little change in air temperature as this area is already almost completely urban and there is very little LULC change projected by 2030. The largest warming occurs in the suburban regions where temperatures are projected to be more than 0.5 °C warmer in 2030 than in 2000. Averaged over 11:00 a.m.–6:00 p.m. LDT for all days in episode 1, the 2030 BAU simulation shows a warming of 0.34 °C.

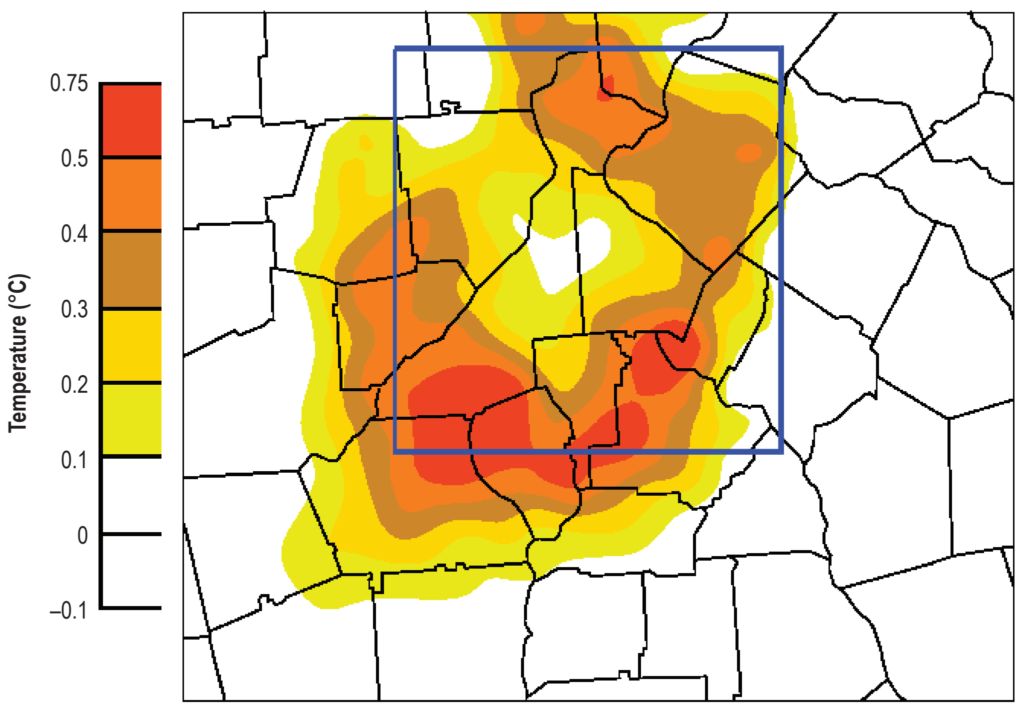

Figure 23. Difference in 2-m air temperature between 2030 BAU and 2000 dry baseline simulations at 3:00 p.m. EDT on day 1 of episode 1. The box indicates a region used in analysis as the five-county area.

The impact of the UHI mitigation strategies in 2030 is illustrated by the air temperature difference (2030 combined mitigation—2030 BAU) map shown in figure 24. At midday, the effect of higher albedos and vegetation cover in urban areas is to cool the urban core by nearly 0.5 °C. Smaller cooling extends out into the suburban areas, while rural areas show virtually the same temperature for the two simulations. This result is typical of most afternoons in episode 1. Daily mean temperature differences for the 5-county and 13-county areas are shown in figure 25 and the overall means for the 11:00 a.m.–6:00 p.m. period and at 2:00 p.m. are shown in table 8.

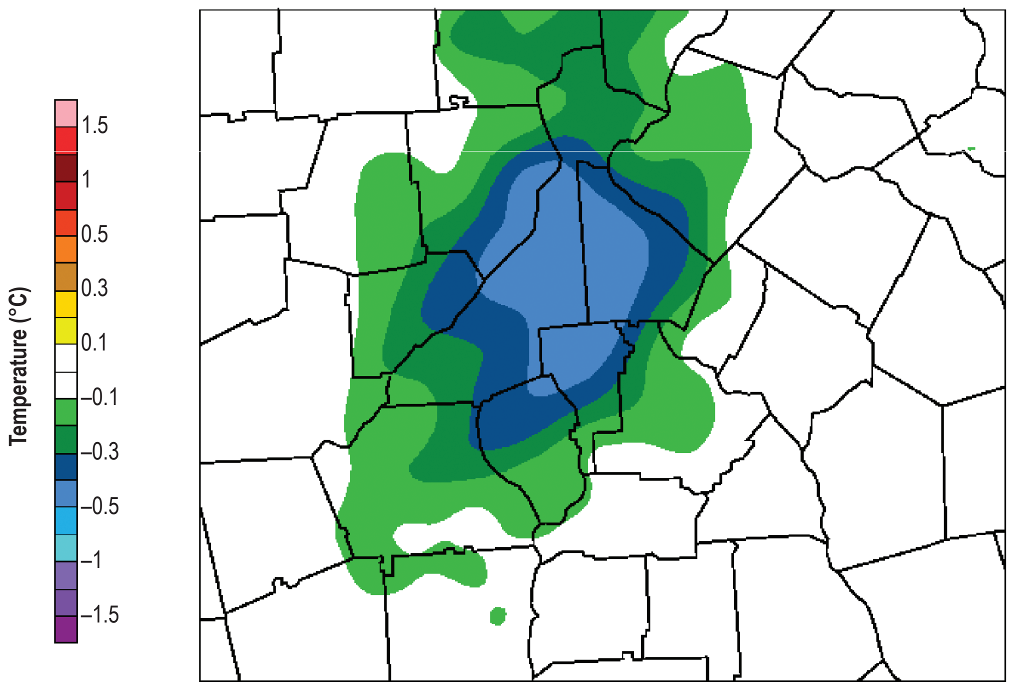

Figure 24. Difference in 2-m air temperature between 2030 combined mitigation and 2030 BAU simulations at 3:00 p.m. EDT on day 1.

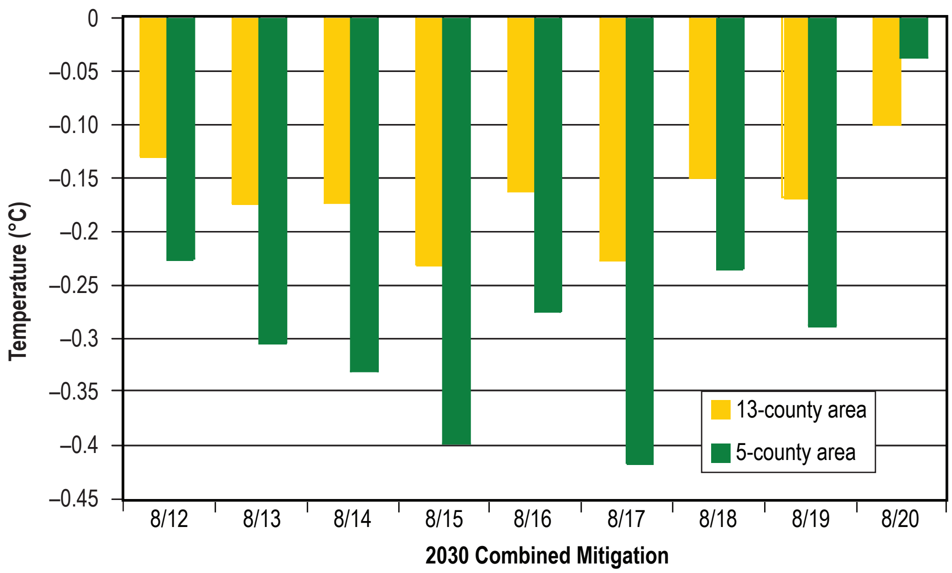

Figure 25. Daily differences in 2-m air temperature between 2030 combined mitigation and 2030 BAU simulations at 2:00 p.m. EDT, averaged over the 5-county and 13-county areas.

Table 8. Five-county and 13-county mean, 2-m air temperature differences in °C (2030 BAU—2030 combined mitigation) for two daily periods averaged over 9 days of episode 1.

Time Period	5-County Mean	13-County Mean
11:00 a.m.– 6:00 p.m.	–0.23	–0.14
2:00 p.m.	–0.28	–0.17

4. LESSONS LEARNED AND RECOMMENDATIONS

4.1 Lessons Learned

It is frequently difficult to evaluate, in a complex modeling system with many interacting components, the benefits of making specific changes in the model inputs or physics, vis-à-vis a statistical comparison of the model output and independent measurements. This is because changes made in a modeling system may act to counteract or to amplify existing model biases. For example, in this application MM5 showed a substantial cold daytime bias in air temperature compared with observations. In changing the land use data input to MM5, large areas that were classified as dry cropland/grassland were changed to medium-density residential and low-density residential land use classes. This change reduced the overall vegetation cover, consequently increasing air temperatures and PBL heights. This change certainly represents an improvement, and this is captured in the statistical evaluation. The air quality model performance for surface ozone did not show an improvement of a comparable magnitude. The increase in temperature that tends to enhance photochemistry was not large enough to offset the decrease in ozone due to enhanced mixing. The results are thus consistent with our fundamental knowledge of the atmospheric processes.

It must be recognized, however, that it is difficult to ascertain the root cause of the cold bias. It may be a combination of model physics and land surface properties, and we can not claim that the use of the improved land use dataset would lead to better validation statistics in a different geographic setting or with a different modeling system. AQMDSS is a complex modeling system. Generally, incorporation of data derived from latest techniques is able to identify deficiencies in the modeling system. Over time new techniques are developed in an attempt to remove these deficiencies. Inconsistencies in coupling of meteorological and air quality models have been documented extensively, some of which have been highlighted in this work.

NLCD, USGS, and Landpro99 data were used to characterize landscape dynamics and to generate model inputs. Both USGS and NLCD are national datasets that may be acquired by other states or regions outside the state of Georgia to perform similar studies and enhance decision-making. Other local or regional data such as the LandPro99 data for the Atlanta region would need to be acquired from local sources if available. While more detailed local landscape data such as LandPro99 may be useful in future studies, it will likely not be essential. Thus, although the focus of this study has been on the Atlanta metropolitan region, the general construct and flow processes of the AQMDSS utilized here can be adapted and modified to accommodate different landscape attributes, climate regimes, and air quality characteristics endemic to other urbanized areas across the U.S.

4.2 Recommendations

The following are five recommendations:

1. Evaluate the differences in future year modeling results using the SGM-projected LULC classes versus existing LULC classes. Currently, changes in LULC are not accounted for in future year simulations.

2. Investigate the air quality model performance for other pollutants such as $PM_{2.5}$, NO, CO, nitric acid (HNO_3), nitrous acid (HONO) and VOC.

3. Examine the elevated concentrations of other modeled pollutants.

4. Use Process Analysis or similar techniques to evaluate the contribution of individual atmospheric processes, focusing on grid cells whose land cover classification is significantly different.

5. Evaluate UHI development and growth for other cities in different geographic regions of the U.S. to obtain a more complete understanding of the relationship of the UHI to urban morphology and LULCC for improved air quality modeling.

5. SUMMARY

Introduction of an improved, higher-resolution dataset to specify LULC in the meteorological and air quality model components has enhanced an AQMDSS. Use of this dataset reduced a major deficiency of the land use data used previously in the DSS, specifically the poor representation of land use in urban and suburban areas. As a result, performance of the meteorological model improved substantially, with the overall daytime cold bias reduced by over 30%. However, the air quality model performance for ozone did not show an improvement of a comparable magnitude, with air quality modeling simulations conducted using either LULC dataset underpredicting ozone concentrations within the five-county area. It appears that the ozone forecasts were insensitive to the air temperature changes because of increased PBL mixing in the warmer MM5 NLCD/LandPro99 simulations, which negates the effects of warmer air temperatures near the surface. The net effect on ozone is near zero, with increases on some days and decreases for others.

The use of the new LULC dataset has also enabled testing of UHI mitigation strategies. These strategies were developed in conjunction with Atlanta stakeholders to determine the affects of increased albedo and vegetation cover on urban temperatures and air quality. The strategies formed the basis for a suite of simulations by the AQMDSS for current conditions and the year 2030. Results show that, without UHI mitigation, urban temperatures will increase of the next 30 yr based on changes in land use that result in larger impervious surface area. UHI mitigation strategies offset much of this predicted warming. However, because of the opposing forces of decreasing temperatures and lower PBL heights, the impact on air quality, specifically ozone concentration, was less pronounced, increasing in some instances and decreasing in others.

APPENDIX—FOCUS GROUP RECOMMENDATIONS FOR COOL COMMUNITY STRATEGIES

Tables 9-11 reflect the focus group recommendations for cool community strategies.

Table 9. Reflective Roofing Focus Group's recommendations for Cool Community strategies.

Reflective Roofing Focus Group				
Current Baseline				
Representative albedo for category -->	0.15	0.35	0.70	
	Percent of roof space in 2003 characterized by:			
Land Use Class	**Low Albedo (<0.20)**	**Medium Albedo (0.20-0.60)**	**High Albedo (>0.60)**	**Mean Albedo**
Comm./Ind./Trans.	86%	13%	1%	0.182
High density residential	95%	4%	1%	0.164
Medium density residential	99%	1%	0%	0.152
Low density residential	99%	1%	0%	0.152
All residential	98.8%	1.2%	0.1%	0.153
All urban	96.2%	3.6%	0.3%	0.159
Projections: 2030	**Percent of roof space in 2030 characterized by:**			
High Penetration	**Low Albedo (<0.20)**	**Medium Albedo (0.20-0.60)**	**High Albedo (>0.60)**	**Mean Albedo**
Comm./Ind./Trans.	15%	35%	50%	0.495
High density residential	70%	25%	5%	0.228
Medium density residential	90%	7%	3%	0.181
Low density residential	90%	7%	3%	0.181
All residential	88.8%	8.1%	3.1%	0.183
Projections: 2020	**Percent of roof space in 2020 characterized by:**			
High Penetration	**Low Albedo (<0.20)**	**Medium Albedo (0.20-0.60)**	**High Albedo (>0.60)**	**Mean Albedo**
Comm./Ind./Trans.	30%	35%	35%	0.413
High density residential	85%	11%	4%	0.194
Medium density residential	95%	5%	0%	0.160
Low density residential	95%	5%	0%	0.160
All residential	94.4%	5.4%	0.2%	0.162
Projections: 2030	**Percent of roof space in 2030 characterized by:**			
Medium Penetration	**Low Albedo (<0.20)**	**Medium Albedo (0.20-0.60)**	**High Albedo (>0.60)**	**Mean Albedo**
Comm./Ind./Trans.	40%	40%	20%	0.340
High density residential	85%	12%	3%	0.191
Medium density residential	95%	5%	0%	0.160
Low density residential	95%	5%	0%	0.160
All residential	94.4%	5.4%	0.2%	0.162
Projections: 2020	**Percent of roof space in 2020 characterized by:**			
Medium Penetration	**Low Albedo (<0.20)**	**Medium Albedo (0.20-0.60)**	**High Albedo (>0.60)**	**Mean Albedo**
Comm./Ind./Trans.	60%	30%	10%	0.265
High density residential	90%	7%	3%	0.181
Medium density residential	97%	3%	0%	0.156
Low density residential	97%	3%	0%	0.156
All residential	96.6%	3.2%	0.2%	0.157

Table 10. Paving Focus Group's recommendations for Cool Community strategies.

Paving Focus Group				
Representative albedo for category -->	0.08	0.15	0.30	
Current Baseline	**Percent of pavement in 2003 characterized by:**			
Land Use Class	**Low Albedo (<0.10)**	**Medium Albedo (0.10 -0.20)**	**High Albedo (>0.20)**	**Mean Albedo**
Comm./Ind./Trans.	30%	67%	3%	0.134
High density residential	35%	64%	1%	0.127
Medium density residential	20%	55%	25%	0.174
All residential	21%	56%	24%	0.171
All urban	22.7%	57.9%	19.4%	0.163
Projections: 2030	**Percent of pavement in 2030 characterized by:**			
High Penetration	**Low Albedo (<0.10)**	**Medium Albedo (0.10 -0.20)**	**High Albedo (>0.20)**	**Mean Albedo**
Comm./Ind./Trans.	10%	50%	40%	0.203
High density residential	15%	75%	10%	0.155
Medium density residential	1%	59%	40%	0.209
All residential	2%	60%	38%	0.206
Projections: 2020	**Percent of pavement in 2020 characterized by:**			
High Penetration	**Low Albedo (<0.10)**	**Medium Albedo (0.10 -0.20)**	**High Albedo (>0.20)**	**Mean Albedo**
Comm./Ind./Trans.	20%	60%	20%	0.166
High density residential	20%	75%	5%	0.144
Medium density residential	1%	69%	30%	0.194
All residential	2%	69%	28%	0.191
Projections: 2030	**Percent of pavement in 2030 characterized by:**			
Medium Penetration	**Low Albedo (<0.10)**	**Medium Albedo (0.10 -0.20)**	**High Albedo (>0.20)**	**Mean Albedo**
Comm./Ind./Trans.	20%	55%	25%	0.173
High density residential	20%	72%	8%	0.148
Medium density residential	7%	60%	33%	0.195
All residential	8%	61%	31%	0.192
Projections: 2020	**Percent of pavement in 2020 characterized by:**			
Medium Penetration	**Low Albedo (<0.10)**	**Medium Albedo (0.10 -0.20)**	**High Albedo (>0.20)**	**Mean Albedo**
Comm./Ind./Trans.	25%	65%	10%	0.148
High density residential	27%	70%	3%	0.136
Medium density residential	15%	57%	28%	0.182
All residential	15.7%	57.8%	26.5%	0.179

Table 11. Vegetation Focus Group's recommendations for Cool Community strategies.

Vegetation Focus Group						
Current Baseline						
Land Use Class	**% Vegetation cover (trees, grass, shrubs)**	**% Tree Canopy**	**Trees Per Acre**	**Total # Trees**		
Comm./Ind./Trans.	22.2	13.3	11	2,382,588		
High density residential	35.0	21.0	17	876,710		
Medium density residential	70.0	42.0	35	18,140,156		
Low density residential	80.4	48.2	40	11,448,798		
All urban	**54.5**	**32.7**	**27**	**32,848,251**		
Projections: 2030 High Penetration	**% Vegetation Cover (trees, grass, shrubs)**	**% Tree Canopy**	**Trees Per Acre**	**Total # Trees**	# New Trees	# New Trees/yr
Comm./Ind./Trans.	23.0	15.0	12	2,599,186	216,599	8,022
High density residential	37.0	25.0	20	1,031,423	154,713	5,730
Medium density residential	74.0	50.0	41	21,249,897	3,109,741	115,176
Low density residential	83.8	55.0	45	12,879,897	1,431,100	53,004
All urban	57.5	38.7	32	**37,760,404**	**4,912,153**	**181,932**
Projections: 2020 High Penetration						
Comm./Ind./Trans.	22.5	14.0	12	2,599,186	216,599	12,741
High density residential	35.5	22.0	18	928,281	51,571	3,034
Medium density residential	72.0	46.0	38	19,695,026	1,554,870	91,463
Low density residential	82.3	52.0	43	12,307,457	858,660	50,509
All urban	**55.9**	**35.6**	**29**	**35,529,951**	**2,681,700**	**157,747**
Projections: 2030 Medium Penetration						
Comm./Ind./Trans.	25.0	15.0	12	2,599,186	216,599	8,022
High density residential	36.7	22.0	18	928,281	51,571	1,910
Medium density residential	76.7	46.0	38	19,695,026	1,554,870	57,588
Low density residential	86.7	52.0	43	12,307,457	858,660	31,802
All urban	**56.1**	**35.9**	**29**	**35,529,951**	**2,681,700**	**99,322**
Projections: 2020 Medium Penetration						
Comm./Ind./Trans.	23.3	14.0	12	2,599,186	216,599	12,741
High density residential	35.0	21.0	17	876,710	0	0
Medium density residential	73.3	44.0	36	18,658,446	518,290	30,488
Low density residential	83.3	50.0	41	11,735,018	286,220	16,836
All urban	**55.2**	**34.2**	**28**	**33,869,360**	**1,021,109**	**60,065**

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13. ABSTRACT *(Maximum 200 words)* Local and state agencies are responsible for developing state implementation plans to meet National Ambient Air Quality Standards. Numerical models used for this purpose simulate the transport and transformation of criteria pollutants and their precursors. The specification of land use/land cover (LULC) plays an important role in controlling modeled surface meteorology and emissions. NASA researchers have worked with partners and Atlanta stakeholders to incorporate an improved high-resolution LULC dataset for the Atlanta area within their modeling system and to assess meteorological and air quality impacts of Urban Heat Island (UHI) mitigation strategies. The new LULC dataset provides a more accurate representation of land use, has the potential to improve model accuracy, and facilitates prediction of LULC changes. Use of the new LULC dataset for two summertime episodes improved meteorological forecasts, with an existing daytime cold bias of ≈3 °C reduced by 30%. Model performance for ozone prediction did not show improvement. In addition, LULC changes due to Atlanta area urbanization were predicted through 2030, for which model simulations predict higher urban air temperatures. The incorporation of UHI mitigation strategies partially offset this warming trend. The data and modeling methods used are generally applicable to other U.S. cities.			
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