REMOTE SENSING CHARACTERIZATION OF THE URBAN LANDSCAPE FOR IMPROVEMENT OF AIR QUALITY MODELING

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ABSTRACT:

The urban landscape is inherently complex and this complexity is not adequately captured in air quality models, such as the Community Multiscale Air Quality (CMAQ) model that is used to assess whether urban areas are in attainment of EPA air quality standards, primarily for ground level ozone. This inadequacy of the CMAQ model, exacerbated by coarse low resolution land cover data inputs, inhibits the model's ability to make a sufficient response to the heterogeneous nature of the urban landscape. This can impact how well the model predicts ozone pollutant levels over metropolitan areas and ultimately, whether cities exceed EPA ozone air quality standards. We are exploring the utility of high-resolution remote sensing data and urban growth projections as improved inputs to the meteorology component of the CMAQ model focusing on the Atlanta, Georgia metropolitan area as a case study. These growth projections include "business as usual" and "smart growth" scenarios to 2030. The growth projections illustrate the effects of implementing urban heat island mitigation strategies, such as increasing tree canopy and albedo across the Atlanta metro area, with the goal of moderating ground-level ozone and air temperature, compared to "business as usual" simulations in which heat island mitigation strategies are not applied. The National Land Cover Dataset at 30m resolution is being used as the land use/land cover input and aggregated to the 4km scale for the MM5 mesoscale meteorological model and the CMAQ modeling schemes. Use of these data has been found to better characterize low density/suburban development as compared with USGS 1km land use/land cover data that have traditionally been used in modeling. Air quality prediction for future scenarios to 2030 is being facilitated by land use projections using a spatial growth model. Land use projections were developed using the 2030 Regional Transportation Plan developed by the Atlanta Regional Commission. This allows the state Environmental Protection agency to evaluate how these transportation plans will affect future air quality and to determine opportunities for State Implementation Plan (SIP) credits.

1. INTRODUCTION/BACKGROUND

Urban expansion is a ubiquitous process around the world. It was estimated by the United Nations Population Fund in 2001 that by 2025, 60 percent of the global population will reside in urban areas. Additionally, there are now some 411 cities of more than one million inhabitants in the world. Cities with populations of 10 million or more, known as "megacities" are becoming predominant global population centers with 19 of them expected to be in existence by 2015. Urban areas are complex in arrangement and composition and exist as a heterogeneous "quilt" of land covers and surface types across the built landscape. Outside of the obvious impacts that urban growth has on land cover and land use change, the expansion of cities has profound impacts on a plethora of biophysical, environmental, and atmospheric processes. Exemplary of this is the deterioration in air quality over cities as a result of increased vehicular and industrial emissions. Under the more stringent air quality guidelines established by the U.S. Environmental Protection Agency (EPA) in 1997, almost 300 counties in 34 states will not meet the new standards for ground-level ozone and will be considered in "non-attainment". The non-attainment designation carries serious penalties to metropolitan urban areas, of which one of the most severe is the risk of losing new highway development funds if plans are not established and implemented to reduce ground-level ozone to an acceptable level. States that have urban areas that are in non-attainment must develop a State Implementation Plan (SIP) to illustrate what measures will be taken to bring these metropolitan areas into attainment with EPA air quality standards.

The Urban Heat Island and its Potential Impact on Ground-Level Ozone

The mitigation of what is known as the "Urban Heat Island" (UHI) effect is now being considered as a possible way to reduce ground-level ozone levels over cities and assist states in developing and implementing SIPs. The UHI results from the replacement of non-urban (i.e., "natural") land covers (e.g., trees, grass) with surface types such as pavements and buildings that are ubiquitous in the urban landscape. Urban surfaces have much different thermal properties (e.g., thermal inertia, heat capacity) than do vegetated or natural surfaces. The energy exchanges that occur between the disparate urban surfaces and the lower atmosphere are complex, with transfers of energy occurring at different times and at different rates. These multifarious energy exchanges come together to formulate thermal energy dynamics within cities that make them distinctly different from their rural counterpart. The alteration of the landscape through

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urbanization involves the transformation of the radiative, moisture, and aerodynamic characteristics that displace or modify the natural channelling of thermal energy that presides in non-urbanized environments (e.g., forests). Surfaces that are endemic to cities generally store solar energy throughout the daytime and convert this energy to sensible heat. In turn, this sensible heat energy is released into the air during the daytime and evening hours, resulting in a "dome" of elevated surface temperatures that preside over cities. The UHI is most prevalent on clear, hot summer days with intense solar radiation and calm winds that set up conditions for fostering development of the UHI.

Given that the UHI is a source of additional heat energy into the lower atmosphere, this phenomenon may be a significant contributor to the exacerbation of ground-level ozone (O_3) over cities. O_3 is formed under the presence of intense solar radiation, high surface temperatures (>26^{o}C), and calm wind conditions. In the company of these conditions, a chemical reaction occurs in conjunction with volatile organic compounds (VOC's) and nitrogen oxides (NO_x) to produce O_3. VOC's come from a variety of non-source point initiators such as paint or gasoline cans and even biogenic sources (i.e., vegetation, primarily trees). NO_x results from point source contributors such as automobile or smokestack emissions. Thus, the UHI, which may elevate air temperatures by 2-3^{o}F (4-5^{o}C) or more, may exacerbate ground-level ozone conditions. By mitigating the UHI, therefore, it is anticipated there could be reductions in ozone levels for better air quality management over cities. The most viable measures for reducing the UHI are focused on planting more trees in urban areas and increasing the reflectivity, or albedo, of urban surfaces. The increased presence of trees provides two direct benefits: 1) trees provide shade which reduces the temperatures of urban surfaces during the summertime; and 2) trees increase evapotranspiration, a process that helps cool the near-surface air. Although these mitigation methods can provide favorable conditions for reducing the overall characteristics of the UHI, the amount of tree planting that needs to take place, or the extent of urban surfaces that need to have higher reflectivity indices to show mitigation in the UHI effect, is open to speculation.

Atlanta, Georgia as a Study Area

In this study, we are assessing the impact of UHI mitigation measures on O_3 over the Atlanta, Georgia metropolitan area using high-resolution remote sensing data and air quality modeling. The objective of this study is to understand how changing land cover composition by planting more trees and by increasing the overall reflectivity of urban surfaces across the Atlanta metro area can impact ozone concentrations over the region. Atlanta has been chosen as a study area because it has consistently been out of attainment for EPA air quality standards for O_3 for many years and Georgia is now faced with difficult decisions to make in preparing a SIP plan to help bring Atlanta back into attainment. Atlanta has been one of the fastest growing metropolitan areas in the United States for many years. As a "modern era" city, Atlanta is one of the least densely populated and most sprawling cities in the US. The urbanization rate is one of the fastest in the country and has resulted in a tremendous change in land cover over the region, with over 20 acres (8 ha) of impervious surface cover being generated each day. The overall result of this dramatic change in urban land cover has been degradation in water quality and the amount of open space, a reduction in air quality, an increased usage of energy for heating/cooling and overloaded urban infrastructure. Figure 1 provides a representation from Landsat satellite data of the amount of land cover change that has occurred over the Atlanta metro area from 1973-2005. Given this dramatic change in the extent of urban growth and the subsequent increase in ground-level ozone over the area, there is much to be anticipated about the beneficial prospects of adopting UHI mitigation measures. These measures are sustainable concepts (i.e., they can be consistently maintained or sustained through time) and they are relatively easy to implement as opposed to more stringent mandates that could be ordered to reduce O_3 (e.g., mandated reduction in vehicular traffic). Additionally, there is no need for a significant "behavioral change" by the urban populace to adapt to these "Cool Community" mitigation measures, and they are cost-effective, especially when compared with other more strict measures that could be mandated, such as extensive costs to further lower power plant emissions.

Figure 1a. Atlanta urbanized land cover 1973

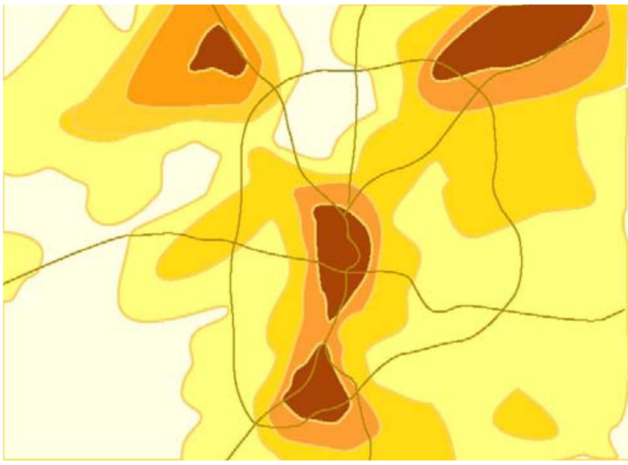

Figure 1b. Atlanta urbanized land cover 2005

Current and Projected Land Cover/Land Use

In using Atlanta as a study, the goal of our research is to understand the effects of the metropolitan region's current and future land cover composition on climate and air quality to assist local officials in developing Cool Community strategies that can be used to mitigate the UHI. High-resolution thermal infrared remote sensing aircraft data obtained from the NASA Advanced Thermal and Land Applications Sensor (ATLAS) were used to derive a profile of surface thermal responses across the study area. These ATLAS data were obtained over Atlanta at a 10m spatial resolution during May 1997 and were used to provide a measurement of temperatures from typical surfaces endemic to urban landscape as a surrogate for assessing the magnitude of Atlanta's UHI (Figure 2).

Current land cover assessments were derived from the LandPro99 GIS database that provides specific land cover types derived from aerial photography of the Atlanta region in conjunction with the National Land Cover Dataset (NLCD). The LandPro99 database was produced by the Atlanta Regional Commission (ARC), which is the regional planning agency for the 13-county metropolitan Atlanta area.

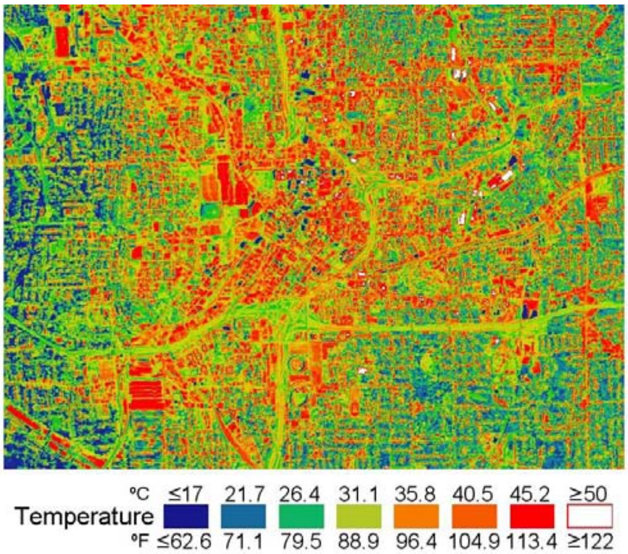

Figure 2. ATLAS surface temperatures for downtown Atlanta

In turn, the LandPro99 data and the NLCD were used as a baseline for developing land use land cover projections to 2030 for the Atlanta area, complemented by population, employment and transportation network projections provided by ARC (Figure 3). In Figure 3, developed areas are shown in the red, pink and light blue shades and rural land covers are depicted in green and yellow. Growth scenarios were developed to project the potential impact of aggressive actions and support from local governments across the Atlanta metro area for three UHI mitigation strategies: 1) use of higher reflectivity roof materials; 2) use of higher reflectivity paving materials; and 3) increasing vegetation cover through tree planting. Combinations of these strategies were also evaluated. Figure 5 provides an illustration of the assumed roofing and pavement albedo values for current year and 2030 based on Cool Communities mitigation strategies for six categories of land use. In Figure 4, it is assumed that albedo values for roofing materials within these general urban land uses can be reasonably increased from around .15 to .2 or greater within a Cool Communities scenario for 2030 across the Atlanta metropolitan area. Similarly, the albedo from pavements can reasonably be increased by 2030 from about .15 to .20, primarily due to a transition from asphalt to concrete as the predominant paving material.

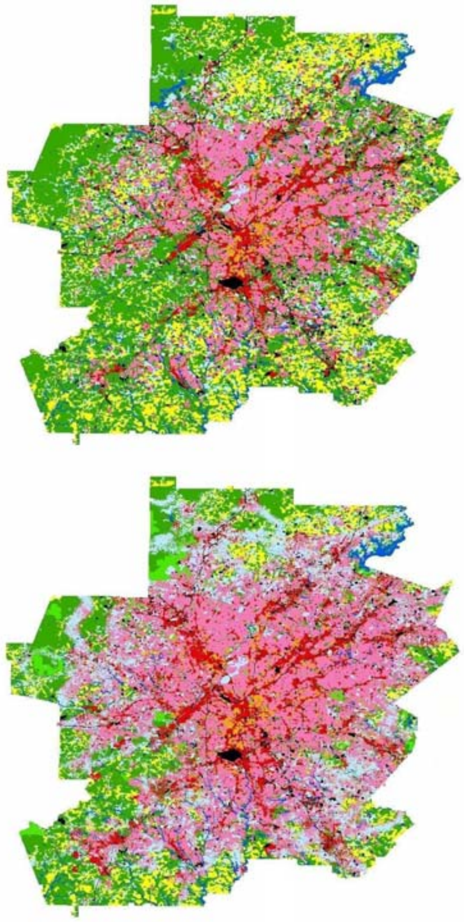

Figure 3. Current and projected (2030) land use

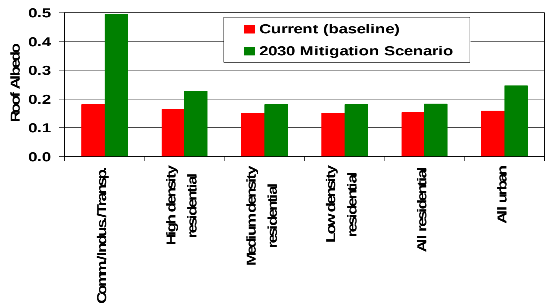

Figure 4a. Current and 2030 assumed roofing albedo values

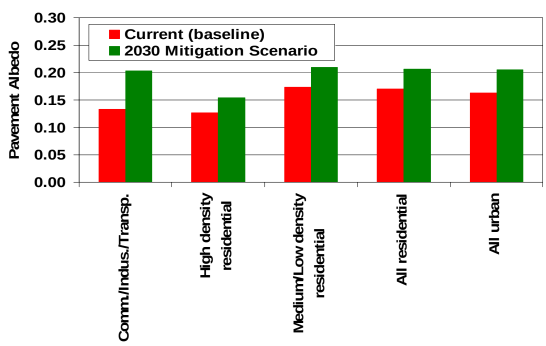

Figure 4b. Current and 2030 assumed pavement albedo values

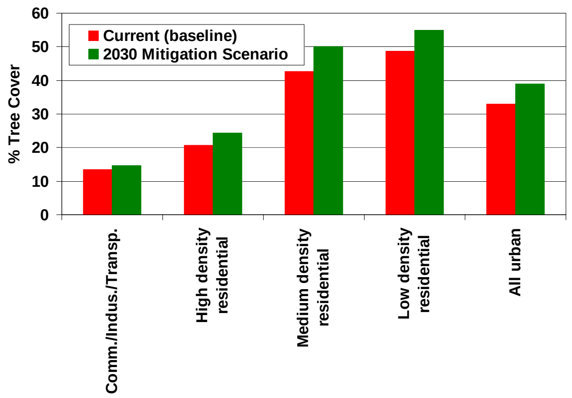

Figure 5. Current and assumed % tree cover for 2030

Figure 5 illustrates the assumed tree cover percentages for current and year 2030 mitigation scenarios. The assumption for the 2030 vegetation mitigation scenario is that tree cover can be increased across the urban landscape, but increases were concentrated within residential areas.

To provide government officials, policy-makers and the general public with an overall perspective on what these mitigation scenarios mean as far as how much effect can be achieved through Cool Communities measures, albedo and vegetation cover for "current", 2030 Business as Usual (BAU) (i.e., projected growth without mitigation), and 2030 mitigation growth strategies are shown in Table 1 for the 13-county Atlanta Metropolitan area. The table shows there could be a .014 increase in albedo over a 2030 BAU growth strategy if Cool Community measures were employed. An increase in vegetation of 2.1% by 2030 could result if mitigation measures are taken as opposed to what would occur via BAU growth projections. Note this is less overall vegetative cover than the current baseline, thus the mitigation strategies are only reducing the impact of deforestation from urbanization not increasing overall vegetative cover. The impact of current and projected growth projections along with their anticipated impacts on roofing, pavement and vegetation, as well as the combined affects on albedo and tree canopy on air temperature over the Atlanta study area, have been evaluated using the meteorological model MM5. This meteorological model is integral to the operation of the Community Multiscale Air Quality (CMAQ) model that is used by states to assess air quality as stipulated by the U.S. EPA.

	Albedo	**Veg. Cover (%)**
Current	.162	73.5
2030 BAU	.161	68.6
2030 Mitigation	.175	70.7
2030 Mitigation Effect	.014	2.1

Table 1. Current, 2030 BAU, and 2030 Mitigation scenario albedo and % vegetation cover for 13-county Atlanta metropolitan area. The 'Mitigation Effect' is the difference between the 2030 Mitigation and BAU cases.

2. EVALUATING POTENTIAL EFFECTS OF UHI MITIGATION STRATEGIES USING THE MM5 METEOROLOGICAL MODEL

MM5 has been run using a current (2000) 10-day summer episode as a baseline for assessing the impact of UHI mitigation strategies using the following model run strategies:

1. Current land use land cover
2. Future (2030) land use land cover with no mitigation scenarios (BAU)
3. Future (2030) land use land cover with high albedo (roofing and pavement) mitigation scenarios
4. Future (2030) land use land cover with increased tree canopy mitigation scenarios
5. Future (2030) land use land cover with combined (albedo and tree canopy) mitigation scenarios.

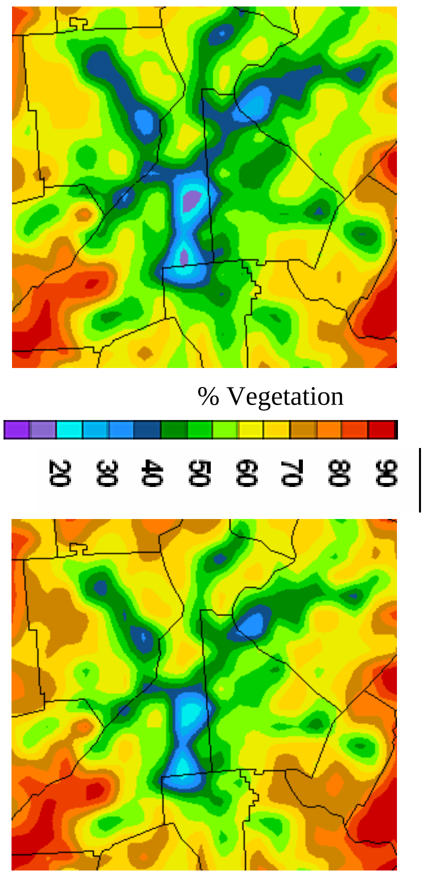

Figure 6. Vegetation Cover Distribution for 2030. 2030 BAU (top); 2030 High Vegetation Scenario (bottom)

The amount of change in vegetation that could be attained using a high vegetation UHI mitigation scenario is illustrated in Figure 6. The changes evident in the bottom figure in percentage of vegetation cover using a high scenario are subtle – but significant. Primary locations that are impacted by increased vegetation canopy are along major transportation networks leading out from the urban core, as well as in the city center itself, and in residential neighborhoods on the periphery of the central business district. Figure 7 is an albedo corollary to Figure 7, wherein BAU (top); 2030 High Vegetation Scenario (bottom) surface albedo (in %) has a considerably larger extent in the 2030 high albedo scenario (bottom) than that projected for the

BAU simulation (top). It is apparent that with the high albedo scenario, values >20% albedo can potentially be achieved by 2030, but these high values are not seen in the BAU scenario.

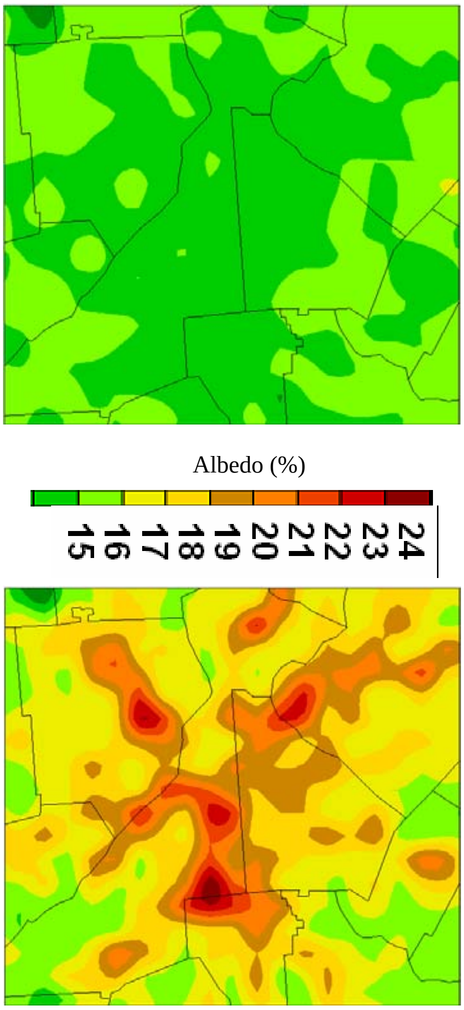

Figure 7. Albedo Distribution for 2030. BAU (top); High Albedo Scenario (bottom)

Figure 8 illustrates the impact of the urbanization of the Atlanta area between 2000 and 2030 on 2 meter air temperature. This is simply one example of the MM5-simulated air temperature difference (2030 BAU minus 2000 Baseline) over the Atlanta study area. In this example, a 1.35°F (.75°C) increase in temperature is projected to occur using a BAU scenario at 3:00 p.m. local time. Similar effects were seen at mid-afternoon on other days; the temperature impact was much less during the cooler times of day.

In Figures 9 and 10, air temperature differences as affected by combined mitigation measures (i.e., both high albedo and high vegetation) are shown for 2030. These examples are for 1:00 and 3:00 p.m. local time on day 1 of the MM5 simulations, but are typical of most days during the 10-day episode. It is evident from these figures that combining Cool Community measures can have a near surface cooling effect of in excess of 0.9°F (0.5°C) over the city center and extending out into the surrounding lesser-urbanized areas of the Atlanta metropolitan area. Figures 11 and 12 show similar cooling values for combined mitigation efforts projected for 2030 at 1:00 and 3:00 p.m. local time, respectively on day 7 of the simulations. The 1:00 p.m. case illustrates an abnormally large cooling effect in which a general pattern of cooling expands out from the city center with "islands" of significant cooling occurring to the north and northeast of the Atlanta urban core. The 3:00 p.m. air temperature differences shown in Figure 12 are similar to those exhibited in Figure 10, but the overall pattern of temperatures in the 0.2-0.5°F (0.11-.27°C) drifts more north-easterly than that shown in Figure 10.

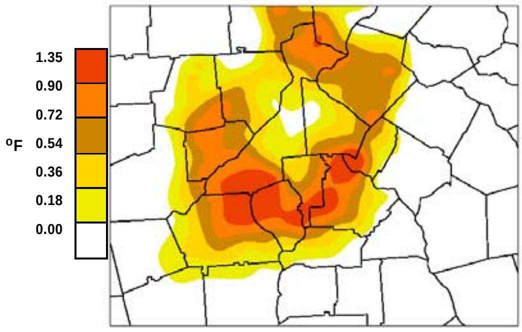

Figure 8. 2030 BAU Air Temperature Difference2000 Baseline 3:00 PM EDT Day 1 of simulation

3. SUMMARY AND CONCLUSIONS

The goal of this study has been to assess the impacts of Cool Community strategies through enhancing tree canopy cover and increasing albedo of urban surfaces, on reducing air temperatures for the Atlanta metropolitan area in a prognostic modeling scenario for land use conditions representative of the year 2030. High-resolution thermal remote sensing data obtained from the ATLAS airborne instrument have been used to derive a profile of "current" surface heating and cooling conditions as a baseline for establishing urban surface temperatures. LandPro99 and NLCD data have been used as a baseline for current land use assessment and as a foundation for simulations of land use change and use change (i.e., urban growth) to 2030. Based on these current and future land uses, the MM5 meteorological model has been run for a 10-day summer episode to evaluate the impact of UHI mitigation methods on air temperatures across the Atlanta region. For the 5-county area around the Atlanta urban core that constitutes the main urbanized area around the city, as well as for the urban core (i.e., the Atlanta central business district), the overall modeling output suggest that if combined high vegetation and high albedo Cool Community measures are implemented to 2030, as opposed to a "business as usual" growth scenario, air temperatures over the city center and a ignificant portion of the adjacent less urbanized area, could be cooled by up to 2.7°F (1.5°C) over limited areas and for short periods of time. More typical mid-afternoon cooling for the urban core is estimated to be 0.5-1.0 °F (0.3-0.6°C). It must be emphasized, however, that the model assumptions used here are for "reasonable" to even "conservative" application of Cool Community measures across the Atlanta metro area. Dependent upon how aggressive these UHI measures are embraced by political leaders, urban planners, decision-makers and the general public within the Atlanta metropolitan region, the overall effects these strategies have on air temperature may be less or greater than indicated in this study.

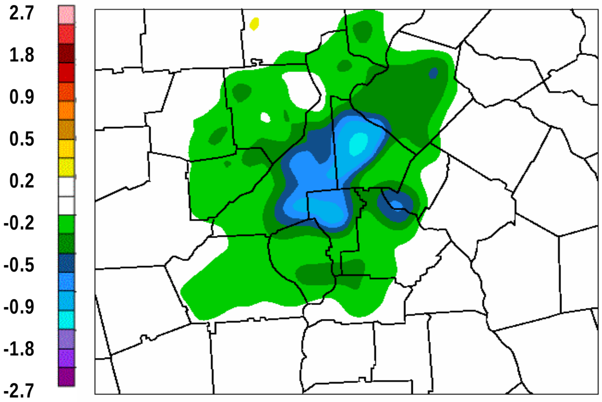

Figure 9 Air Temperature Difference – 2030 Combined Mitigation – 2030 BAU 1:00 PM EDT Day 1

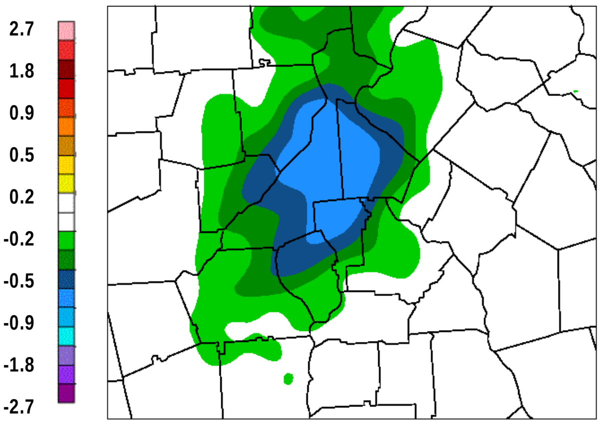

Figure 10. Air Temperature Difference – 2030 Combined Mitigation – 2030 BAU 3:00 PM EDT Day 1

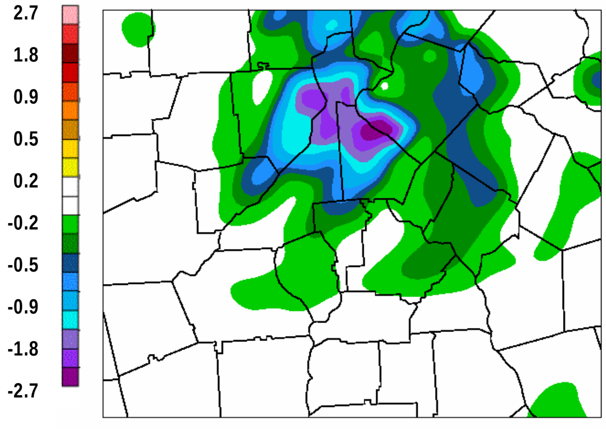

Figure 11. Air Temperature Difference - 2030 Combined Mitigation – 2030 BAU 1:00 PM Day 7

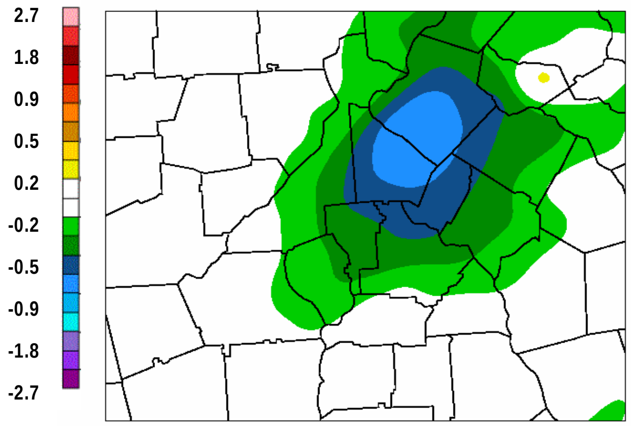

Figure 12. Air Temperature Difference - 2030 Combined Mitigation – 2030 BAU 3:00 PM Day 7