RELATIVE EFFECTS OF OBSERVATIONALLY-NUDGED MODELED METEOROLOGY AND DOWN-SCALED GLOBAL CLIMATE MODEL METEOROLOGY ON BIOGENIC EMISSIONS FOR THE UNITED STATES

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1. INTRODUCTION

The United States Environmental Protection Agency (USEPA) and National Oceanic and Atmospheric Administration (NOAA) participate in a multi-agency examination of the effects of climate change through the U.S. Climate Change Science Program (CCSP, 2003). The EPA Global Change Research Program (GCRP) and NOAA Office of Global Research support the Climate Impacts on Regional Air Quality (CIRAQ) program, a program component focused on the potential effects of climate change on air quality by the year 2050. The first phase of the CIRAQ program is investigating the effect of climate change with emissions held constant at base period (2001 inventory) levels (EPA, 2006), except for meteorologically dependent emissions including biogenic and mobile source emissions. The second phase will incorporate future emission scenarios.

The CIRAQ approach uses modeled estimates of regional meteorology, emissions, in a chemical - transport model to examine air quality in a ten-year base period centered on 2000 and in a future ten-year period centered on 2050. As of this writing, base period and future period meteorology and emissions for the base period have been modeled. Preliminary future period biogenic emissions based on the future period meteorology have also been prepared, and work is near completion on a future air quality simulation proportionate to the International Panel on Climate Change A1B scenario emissions (IPCC, 2006).

The meteorology was modeled using Regional Climate Model (RCM) scenarios developed by the Department of Energy Pacific Northwest National Laboratory (PNNL) (Leung and Ghan, 1999). A regional climate model (RCM) version of the Mesoscale Meteorology Model, Version 5 (Grell et al., 1994) was used A 36 km resolution grid was used to descritize the horizontal model domain, and the RCM was used to model base and future year meteorology. Boundary conditions for the RCM were derived from the National Aeronautic and Space Administration (NASA) GISS version II' (two prime) Global Climate Model (GCM) (Rind et al., 1999). Meteorological data from MM5 were applied to the Biogenic Emission Modeling System (BEIS), version 3.13 (Pierce et al., 2002) within the Sparse Matrix Operator Kernel Emission (SMOKE) (CEP, 2006) model, version 2.2, and to the Community Multiscale Air Quality Mode (CMAQ) version 4.5.1 (Byun and Schere, 2006).

CMAQ is driven both by meteorology and emissions into the atmosphere. Because biogenic emissions are especially dependent upon meteorology, it is important to define the spatial and temporal variability of the meteorology and of the biogenic emissions as a part of modeling base year and future period air quality conditions. The variability of the base period emissions modeled with RCM received a preliminary examination (Benjey and Cooter, 2005). However, most other (non-CIRAQ) regional meteorological modeling for the base period is retrospective, and reflects Newtonian relaxation or “nudging” with meteorological observations. Because nudging provides the best representation of current meteorological conditions, it is desirable to determine how emissions based on RCM meteorology compare with emissions modeled using meteorological observations as the forcing terms. If emissions based on RCM meteorology are not similar in magnitude and in temporal and spatial variability to the base period “nudged” meteorology-based emissions, the differences might mask any signal due to climate change in future period RCM based emission values.

2. APPROACH

To determine the relative spatial and temporal variability of the emissions of biogenic compounds based on RCM and nudged meteorology, statistics for Isoprene, and Nitric Oxide (NO) emissions were prepared for regions of the modeling domain. Because nudged MM5 meteorology data for the

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domain were available for 2001 through 2003, this time frame was used for the comparison. The regions used for the analysis (Figures 1 and 2) are:

- An Eastern Domain, which typifies the east-west division historically used in air quality modeling because of topographic and atmospheric chemistry differences.
- A Western Domain.
- Five ozone regions of the eastern United States as defined by Lehman et al. (2004) based on analysis of monitoring data using principal component analysis (PCA). The regions represent areas of relative consistency based on dominant PCA modes, but overlap geographically.

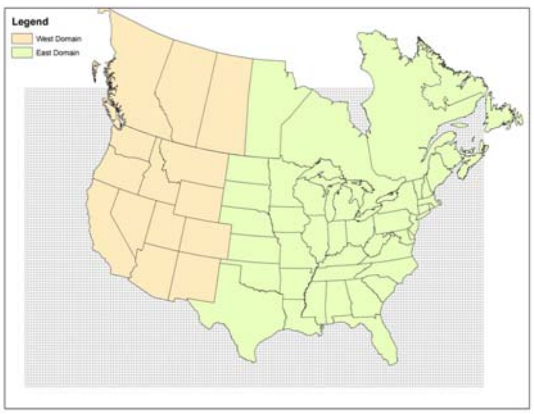

Figure 1. CIRAQ modeling domain illustrating the Eastern and Western Regions.

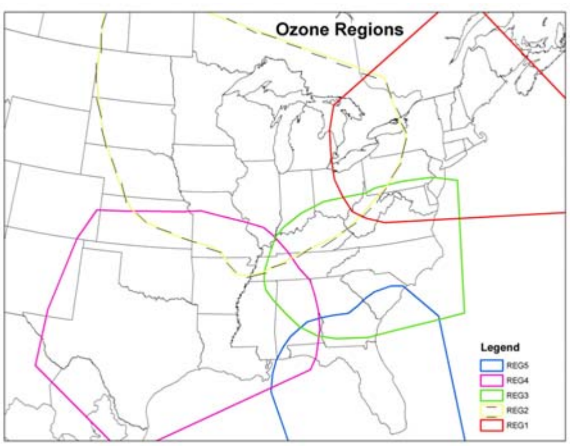

Figure 2. Five ozone regions of the eastern United States based on principal component analysis.

Because biogenic emissions are important in the chemistry of ozone formation, the main seasonal focus of this paper is on the summer, in addition to overall 3-year modeling period differences between RCM and nudged-based emissions. .

Statistics were generated for each of the emitted compounds for the three-year period, annual periods, seasons, and diurnal periods. The statistics were computed for each time period to quantify the departure from central tendency for mean hourly emission values for each season and between years. The modeled emission fluxes were normalized to emissions per second per square kilometer for each region to aid in comparison. The patterns shown by the emission statistics are compared with analyses of RCM based and nudged meteorology.

3. VARIABILITY OF BIOGENIC EMISSIONS

Tables 1 and 2 present the area normalized mean hourly emissions and variances of Isoprene and NO, respectively, for the modeling period by analysis regions. For each region, the mean-

Table 1. Overall mean hourly Isoprene emissions based on RCM and observationally nudged meteorology for 2001 - 2003**.**

Modeling Period Isoprene Emissions moles/sec/km^2			
Region	**Type**	**Emissions**	**Variance**
Eastern	RCM	3.2190E-04	4.8179E-07
	Nudged	4.0660E-04	6.5656E-07
Western	RCM	1.1950E-04	7.0091E-08
	Nudged	1.4680E-04	9.7884E-08
Region 1	RCM	1.9440E-04	2.1433E-07
	Nudged	2.5640E-04	3.6853E-07
Region 2	RCM	3.3960E-04	6.9448E-07
	Nudged	4.5200E-04	1.0778E-06
Region 3	RCM	8.9930E-04	4.1352E-06
	Nudged	1.0410E-03	4.3426E-06
Region 4	RCM	7.3090E-04	2.5635E-06
	Nudged	8.1850E-04	2.5022E-06
Region 5	RCM	2.8500E-04	2.9652E-07
	Nudged	4.0210E-04	4.7249E-07

hourly Isoprene emissions based on nudged meteorology are greater than for the emissions based on RCM/MM5 meteorology. This is evident when comparing the mean-hourly Isoprene emissions for the Eastern Region using RCM and Nudged meteorology (Figures 3 and 4). For the five eastern ozone regions, the percent differences of Isoprene emissions range from 10.7 percent for Region 4 to 29.1 percent for Region 5 **(**Florida

Table 2. Overall mean hourly Nitric Oxide emissions based on RCM and observationally nudged meteorology for 2001-2003.

Modeling Period NO Emissions moles/sec/km^2			
Region	**Type**	**Emissions**	**Variance**
Eastern	RCM	6.3100E-05	1.3784E-09
	Nudged	7.5190E-05	1.7650E-09
Western	RCM	3.2480E-05	3.7725E-10
	Nudged	3.9300E-05	5.3313E-10
Region 1	RCM	3.0400E-05	3.3690E-10
	Nudged	2.9930E-05	3.9805E-10
Region 2	RCM	1.2310E-04	7.4097E-09
	Nudged	1.6540E-04	1.4860E-08
Region 3	RCM	6.6310E-05	1.7289E-09
	Nudged	7.6760E-05	2.1413E-09
Region 4	RCM	1.6490E-04	6.0966E-09
	Nudged	1.7920E-04	7.2974E-09
Region 5	RCM	3.9490E-05	2.4598E-10
	Nudged	4.3660E-05	2.7903E-10

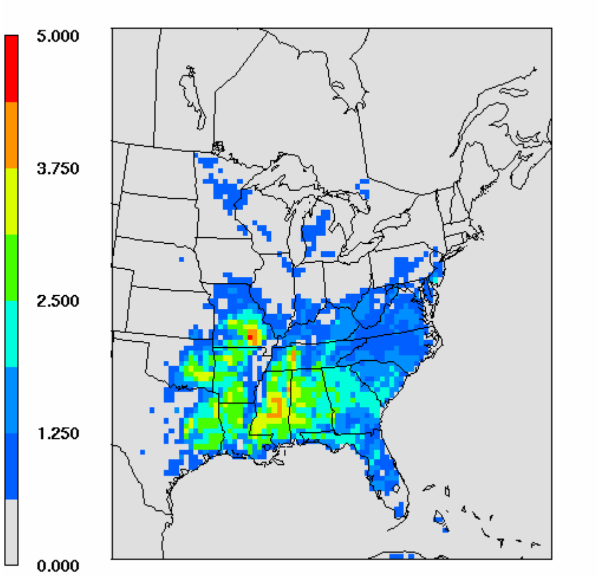

Figure 3. Mean hourly Isoprene emissions for the Eastern Region using RCM meteorology.

and Georgia). Regional variances over the modeling period are two orders of magnitude less than the mean values (0.1 to 0.2 percent of the mean values). The variance reflects the temporal changes in Isoprene emissions, which are dependent on temperature and cloud-influenced solar insolation.

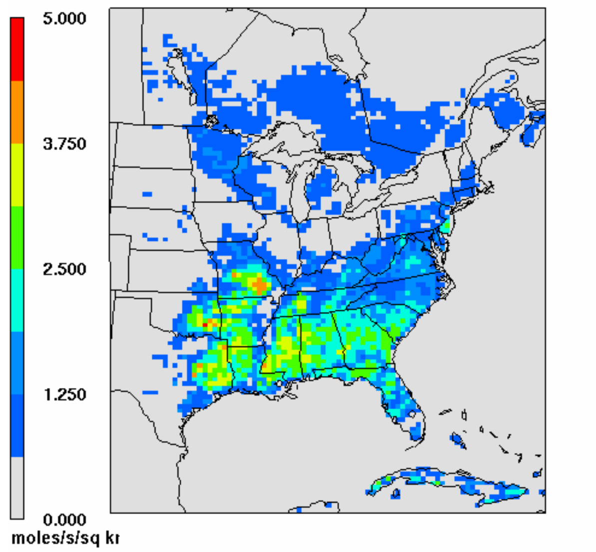

Figure 4. Mean hourly Isoprene emissions for the Eastern Region using Nudged meteorology.

Mean-modeling-period hourly NO emissions also demonstrate that emissions based on nudged meteorology are greater than those based on RCM emissions. Mean-hourly NO emissions are greater for nudged meteorology based data for all regions except Region 1, ranging from 8 percent for Region 4 (the South Central) to 25.6 percent for Region 2 (the North Central). Regional variances (about 0.2 percent) are two orders of magnitude less than the mean values. The variability of NO reflects dependency on changes in temperature and moisture in the BEIS model, rather than solar insolation.

The summer ozone season is of primary interest here. Tables 3 and 4 illustrate regional summer statistics for Isoprene and NO, respectively. The mean-hourly summer emissions for the modeling period are consistently greater for the Eastern Region than for the Western Region for Isoprene and NO, reflecting a greater concentration of emitting vegetation in the East. The differences between Nudged and RCM-based-biogenic emissions are greater in the Eastern Region. For example, summer mean-hourly Isoprene emissions based on nudged meteorology are 21.6 percent greater than RCM-based emissions in the Eastern Region, and 12.6 percent greater in the Western Region. Table 3 indicates that mean-hourly Isoprene emissions based on nudged meteorology are greater than RCM-based emissions for all regions. The greatest mean values are in Region 3 (Mid-

Atlantic). The percent differences in regional RCM and nudged-meteorology based mean-hourly Isoprene emissions (in decreasing order) is the same for both the entire modeling period and the summer seasons: Regions 1, 2, 5, 3 and 4. The differences range from 2.6 percent (Region 4) to 33.7 percent (Region 1). Most hour-to-hour variability is due to the influence of cloud cover on insolation.

Table 3. Mean hourly summer season Isoprene emissions based on RCM and observationally nudged meteorology for 2001-2003.

Summer Season Isoprene Emissions moles/sec/km^2			
Region	**Type**	**Emissions**	**Variance**
Eastern	RCM	7.1098E-04	9.3744E-07
	Nudged	9.0758E-04	1.3884E-06
Western	RCM	3.0684E-04	1.6434E-07
	Nudged	3.5092E-04	2.1886E-07
Region 1	RCM	4.1933E-04	3.6808E-07
	Nudged	6.3294E-04	8.1021E-07
Region 2	RCM	7.8827E-04	1.4153E-06
	Nudged	1.1299E-03	2.4212E-06
Region 3	RCM	1.9944E-03	8.2594E-06
	Nudged	2.2310E-03	8.7905E-06
Region 4	RCM	1.6916E-03	5.5051E-06
	Nudged	1.7374E-03	5.1104E-06
Region 5	RCM	5.3567E-04	5.3622E-07
	Nudged	6.9701E-04	8.0562E-07

Table 4. Mean hourly summer Nitric Oxide emissions based on RCM and observationally nudged meteorology for 2001-2003.

Summer Season NO Emissions moles/sec/km^2			
Region	**Type**	**Emissions**	**Variance**
Eastern	RCM	9.2395E-05	3.1017E-10
	Nudged	1.0320E-04	4.5468E-10
Western	RCM	5.2578E-05	1.2346E-10
	Nudged	6.3629E-05	2.1453E-10
Region 1	RCM	4.4145E-05	7.8445E-11
	Nudged	4.2350E-05	1.0215E-10
Region 2	RCM	1.7774E-04	1.6749E-09
	Nudged	2.3641E-04	4.2842E-09
Region 3	RCM	8.6846E-05	3.3282E-10
	Nudged	9.5016E-05	4.4412E-10
Region 4	RCM	2.2133E-04	1.5826E-09
	Nudged	2.3217E-04	1.7796E-09
Region 5	RCM	4.8205E-05	4.3740E-11
	Nudged	5.0149E-05	4.0581E-11

Summer-season mean-hourly NO emissions follow the pattern of the entire modeling period in that emissions based on nudged meteorology are greater than those based on RCM emissions in all regions except Region 1 (Table 4). Eastern Region mean-hourly emissions are an order of magnitude greater than in the Western Region The mean-hourly RCM based emission value is 4.1 percent larger than nudged meteorology based emissions in Region 1. The greatest mean value is for Region 2, only slightly greater than Region 4. The order of the percent size differences between nudged and RCM based emissions, by region, are: Regions 2, 3, 4, 1 and 5, The differences range from 24.8 percent (Region 2) to 3.9 percent (Region 3). In Region 1, Summer variance statistics are in the range of 0.1 to 0.2 percent of the mean hourly values As expected, summer variance statistics are much less for NO than for Isoprene, on the order of 0.001 % of the mean hourly emission values. This is because NO is not dependent on the daily and hourly variation of insolation, but varies with temperature and moisture.

4. DISCUSSION: SUMMER METEOROLOGICAL AND EMISSION PATTERNS

Although nudged-meteorology mean-hourly Isoprene and NO emissions are generally greater than the RCM-meteorology based emissions over the modeling period, the emission statistics show more variability between regions during the summer season. These differences reflect modeled meteorology patterns. Using the 10 year CIRAQ base period, Gilliam and Cooter (submitted) used principal component analysis to examine the differences between RCM and the observed North American Regional Reanalysis (NARR) (Mesinger et al., 2006) dataset in terms of synoptic mean pressure patterns. The NARR generally approximates the MM5 meteorology nudged with observations. Surface pressure, precipitation and 2 meter temperature data for 1800 hours GMT were extracted from the RCM data, and sea level pressure was calculated from surface pressure, elevation, and temperature.

The analyses of annual summer season synoptic differences between RCM and NARR show that general synoptic sea level pressure patterns across the United States are close, particularly in the western part of the country. However, the summer subtropical high pressure area (Bermuda High) is not replicated by the RCM. Instead, there is a relatively cool and dry high pressure area over the northeastern United States and southern Canada. In addition, the RCM places a low-pressure area off the coast of the southeastern United States.

Because of the meteorological dependencies of biogenic emissions, it is expected that the differences between NARR and RCM would be

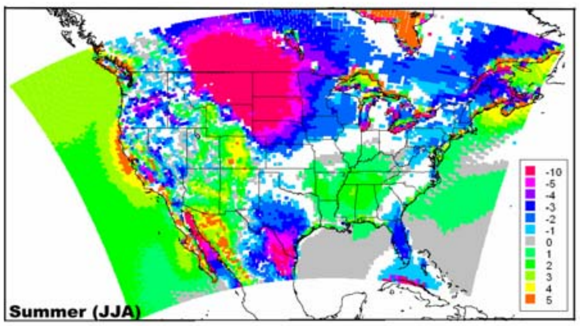

Figure 5. Summer RCM - NARR ten year mean temperature differences (^{o}K) (after Gilliam and Cooter, submitted)

reflected in modeled emissions based on observation nudging and RCM. Gilliam and Cooter (submitted) concluded that summer RCM temperatures are significantly cooler (2 to 10 degrees K) over much of the northern part of the domain east of the Rocky Mountains; and 3 to 5 degrees K cooler over Texas and Florida (Figure 5). They also found that the RCM underestimates precipitation for the eastern United States, consistent with the cooler and dryer continental high pressure produced by the RCM.

The summer biogenic emissions based on RCM and nudged meteorology are consistent with the RCM – NARR temperature and moisture differences. Isoprene emissions in the northeastern (Regions 1 and 2) portion of the domain exhibit substantially greater nudged meteorology Isoprene emissions than RCM based Isoprene emissions (Figure 6). The Nudged meteorology NO emissions are also greater in the Northeast, but the difference is not as pronounced and the spatial pattern more dispersed (Figure 7).

The RCM-to-nudged Isoprene summer emissions differences for Regions 1 and 2 are 33.7 and 30.2 percent, respectively. Nudged and RCM

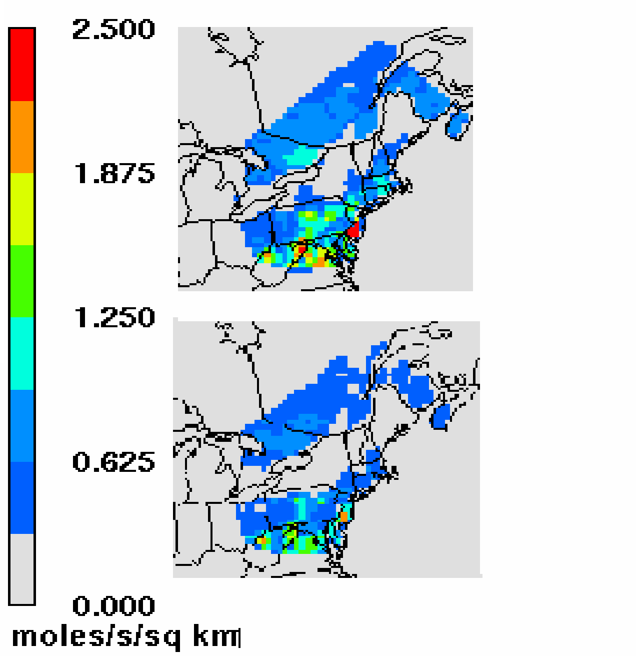

Figure 6. Summer mean hourly Isoprene emissions with Nudged (top) and RCM (bottom) meteorology.

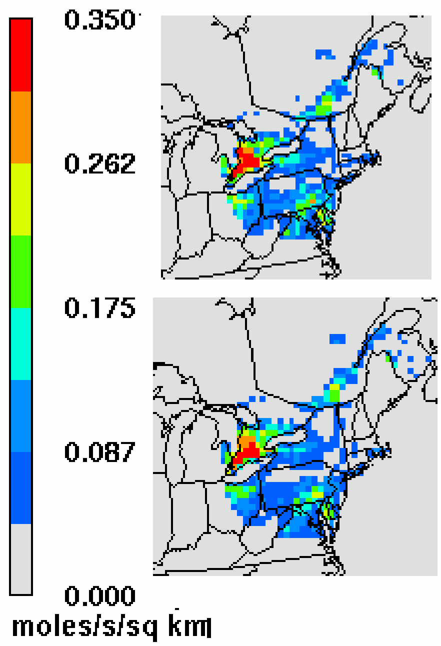

Figure 7. Summer mean hourly NO emissions with Nudged (top) and RCM (bottom) meteorology.

summer NO emissions are much closer. The differences for NO for Regions 1 and 2 are -4.1

and 24.8 percent, respectively, where the minus sign denotes that the RCM values were larger than the nudged values. A cool, dry summer continental high pressure pattern in the northern United States is conducive to reduced cloudiness, and increased insolation. This results in increased Isoprene emissions. Summer temperatures and reduced precipitation aid in increasing NO emissions, especially inland away from coastal precipitation.

This initial examination of modeled biogenic emission data indicates that RCM meteorology based emissions are generally less than emissions based on observationally nudged meteorology, particularly for Isoprene. This is consistent with analyses of synoptic meteorology patterns based on RCM and NARR meteorology. RCM-based biogenic emissions may be significantly lower for current and future model periods in the Northeastern U.S., which may lead to lower modeled ozone concentrations in some areas. More detailed analysis of the biogenic emission data and CMAQ model results will help to better quantify the degree to which reduced modeled ozone may occur.

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