1950−2000. These results are supported, and expanded upon, by more recent work from this group, e.g., see Leibensperger et al. (2008), who found that the frequency of mid-latitudes cyclones tracking across eastern North America in the southern climatological storm track was a strong predictor of the frequency of summertime pollution episodes in the eastern United States for the period 1980−2006. In addition, they found a decreasing trend over this period in the number of cyclones in this storm track that they attributed to greenhouse warming, consistent with a number of other observational and modeling studies. However, as will be discussed in more detail below, other groups, including those participating in this assessment, do not necessarily find the same decrease in future mid-latitude cyclones when analyzing similar GCM outputs, or even the same GCM outputs downscaled using an RCM (e.g., see Leung and Gustafson, 2005).

Subsequent to the initial modeling effort described in Mickley et al. (2004), the Harvard group applied the GEOS-Chem GCTM, driven by the GISS III GCM (Wu et al., 2007), to the direct simulation of 2050s O_3 air quality over the United States (Wu et al., 2008a) and global tropospheric O_3 and the policy-relevant background O_3 over the United States (Wu et al., 2008b). For one set of simulations with this modeling system designed to isolate the impacts of climate change alone on air quality, anthropogenic emissions of precursor pollutants were held constant at present-day levels, while climate changed in response to greenhouse gas increases under the IPCC A1b scenario (Wu et al., 2008a). Climate-sensitive natural emissions, e.g., of biogenic VOCs, were allowed to vary in response to the change in climate. In these simulations, they found that at global scales, future O_3 averaged throughout the depth of the troposphere increases, primarily due to increases in lightning (leading to additional NO_x production), but near the surface increases in water vapor generally caused O_3 decreases, except over polluted continental regions. Focusing in more detail on the United States, they found that the response of O_3 to climate change varies by region. Their results show increases in mean summertime O_3 concentrations of 2−5 ppb in the Northeast and Midwest, with little change in the Southeast. The Harvard group also found that peak O_3 pollution episodes are far more affected by climate change than mean values, with effects exceeding 10 ppb in the Midwest and Northeast.

In contrast to this regional pattern of future U.S. O_3 change, the Carnegie Mellon work (described next) found a relatively smaller response in the Northeast and Midwest but a strong increase in the Southeast, using some similar models and assumptions as the Harvard project (although with a different IPCC greenhouse gas scenario and some key differences in the ocean surface boundary condition). As will be discussed in greater detail below, the explanations for these differences appear to reside in (1) differences in how the chemical mechanisms regulating the reactions and transformation of biogenic VOC emissions are represented in the two modeling systems and (2) possible differences in future simulated mid-latitude storm track changes.

In addition to these findings, this group used historically measured relationships between temperature and the probability of O_3 concentrations above the air quality standard (e.g., see Lin et al., 2001), together with statistically downscaled climate projections for the Northeast United States from an ensemble of IPCC AR4 GCMs and scenarios, to project future O_3 exceedances in the region (Lin et al., 2007). They found a doubling of the frequency of exceedances in the climate of the 2050s if anthropogenic emissions were to remain constant. As will be discussed further below, statistical relationships between observed O_3 and temperature reflect both the direct impact of temperature on O_3 chemistry and the often strong correlation between temperature and other factors conducive to high O_3 concentrations, such as clear skies, stagnant air, and increased biogenic emissions. As such, they tend to be regionally and seasonally dependent. Work exploring the use of these types of statistical approaches to project O_3 NAAQS exceedances (and PM concentrations) is ongoing.

As a final part of this project, the Harvard group has developed, and is in the process of testing, a linked global-to-regional system of models (including a GCM, GCTM, RCM, and RAQM). This system will be applied to investigations of the effects of climate change, as well as future changes in pollutant emissions and long-range transport, on regional-scale O_3 and PM concentrations and mercury (Hg) deposition.

Additional information on the Harvard research effort can be found in Appendix D and at

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6157/report/0
- http://www.as.harvard.edu/chemistry/trop/gcap/

3.2.1.2 *Impacts of Climate Change and Global Emissions on U.S. Air Quality: Development of an Integrated Modeling Framework and Sensitivity Assessment: Carnegie Mellon University*

The Carnegie Mellon group performed global-scale simulations of atmospheric chemistry under present and future (2050s) climate conditions using a "unified model," i.e., the GISS II′ model modified to incorporate tropospheric gas phase chemistry and aerosols. Ten years of both present and future climate were simulated, following the A2 IPCC greenhouse gas emissions scenario, with anthropogenic air pollution emissions held at present-day levels to isolate the effects of climate change. As in the Harvard project described above, the effects of changes in certain climate-sensitive natural emissions were also included as part of the "climate" changes simulated.

They found that a majority of the atmosphere near the Earth's surface experiences a decrease in average O_3 concentrations under future climate with air pollution emissions held constant, mainly due to the increase in humidity, which lowers O_3 lifetimes (Racherla and

Adams, 2006). Further analysis of these results on a seasonal and regional basis found that, while global near-surface O_3 decreases, a more complex response occurs in polluted regions. Specifically, summertime O_3 increases over Europe and North America, with larger increases for the latter. A second key finding is that the frequency of extreme O_3 events increases in the simulated future climate: over the eastern half of the United States, where the largest simulated future O_3 changes occurred, the greatest increases were at the high end of the O_3 distribution, and there was increased episode frequency that was statistically significant with respect to interannual variability (Racherla and Adams, 2008). They further suggested that it is necessary to simulate a minimum of five present-day and future years to separate a climate change response from this interannual variability. These general results are broadly consistent with the Harvard experiments described above. However, as also mentioned, there are important regional differences in response between the two groups. These can largely be attributed to differences in the modeled chemical mechanism for isoprene oxidation in the southeastern United States, as well as possibly differences in the future simulation of the summertime storm track across the northern part of the country. These issues will be discussed in more detail in the synthesis to follow these summaries.

The Carnegie Mellon team is also pursuing two complementary approaches in conjunction with their global modeling efforts. First, they are investigating the sensitivity of O_3, PM, acid deposition, and visibility to individual meteorological parameters by performing a set of sensitivity experiments using the PM Comprehensive Air Quality Model with Extensions (PMCAMx) (e.g., see Dawson et al., 2007a, b). One key finding from this work is that O_3 concentrations increased nearly linearly with temperature in the study region/period, and that a 2.5ºC increase in temperature led to a 30% increase in the area exceeding the EPA 8-hour standard. Second, they have now developed and tested a global-to-regional modeling system to carry out higher-resolution investigations of the impacts of climate and anthropogenic emissions changes on air quality (Dawson et al., 2008).

Additional information on this research effort can be found in Appendix D and at

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6240/report/0
- http://www.ce.cmu.edu/~adams/index.html
- http://www.cheme.cmu.edu/who/faculty/pandis.html

3.2.2 Linked Global-Regional-Focused Modeling Work

3.2.2.1 *The Climate Impacts on Regional Air Quality (CIRAQ) Project: EPA*

In addition to the extramural projects described in this section, an intramural modeling study, the CIRAQ project, is being conducted at EPA NERL, as introduced in Section 2. Under this project, the NERL team built a coupled global-to-regional climate and chemistry modeling system covering the continental United States. They used the output from a global climate simulation with the GISS II′ model (including a tropospheric O_3 chemistry model) for 1950−2055, following the A1b IPCC SRES greenhouse gas emissions scenario for the future simulation years (i.e., the same simulation described in Mickley et al., 2004) as climate and chemical boundary conditions for the regional climate and air quality simulations. The Penn State/NCAR Mesoscale Model Version 5 (MM5) was used at DOE's Pacific Northwest National Laboratory (PNNL) to create downscaled fields from this GCM simulation for the periods 1996−2005 and 2045−2055 (Leung and Gustafson, 2005). The NERL group used this regionally downscaled meteorology to simulate air quality for 5-year-long subsets of these present and future time periods with the CMAQ model. Multiple years were simulated, in spite of the considerable computational expense, to examine the role of interannual variability in the results.

A key element of this project was extensive evaluations of the simulated meteorological variables, not just for long-term climate statistics (e.g., monthly and seasonal means), but of synoptic-scale patterns that can be linked more directly to air quality episodes (Cooter et al., 2005; Gilliam et al., 2006; Gustafson and Leung, 2007). One important finding was that the subtropical Bermuda High pressure system off the southeastern United States coast, a critical component of eastern United States warm season weather patterns, was not well simulated in the downscaled model runs, a result that is likely attributable to biases in the GCM, as will be discussed further below. Another key finding was that, as mentioned above in the summary of the Harvard project, the reduction in cyclones tracking across the northern United States found in Mickley et al. (2004) was not as clearly present when this global model output was downscaled using MM5 (Leung and Gustafson, 2005).

The NERL team also evaluated the CMAQ results against historical O_3 observations, finding high biases in summertime O_3 related to the choice of chemical mechanism in CMAQ between the Carbon Bond-IV (CB-IV) vs. the Statewide Air Pollution Research Center (SAPRC) representations. In addition, they found O_3 biases related to biases in MM5-downscaled meteorology. For example, the model under-predicted precipitation and over-predicted temperature in the areas of the Midwest and Southeast where O_3 was most over predicted, highlighting the strong control that meteorology can exert on O_3.

In a set of future simulations with this global-to-regional climate and air quality modeling system, for which anthropogenic emissions of precursor pollutants were held constant while

climate changed, the NERL group found increases in future summertime maximum daily 8-hour (MDA8) O_3 concentrations of roughly 2−5 ppb in some areas (e.g., Northeast, Mid-Atlantic, and Gulf Coast) compared to the present-day, though with strong regional variability and even decreases in some regions (Nolte et al., 2008). This regional variability in future O_3 concentration changes was associated primarily with changes in temperature, the amount of solar radiation reaching the surface, and, to a lesser extent, climate-induced changes in biogenic emissions. The increases in peak O_3 concentrations tended to be greater and cover larger areas than those in mean MDA8 O_3. These results will be discussed in more detail in the synthesis below. The NERL team also found significant O_3 increases in September and October over large portions of the country, suggesting a possible extension of the O_3 season into the fall in the future.

Additional information on the NERL effort can be found in Appendix E and at http://www.epa.gov/asmdnerl/Climate/index.html.

3.2.2.2 *Modeling Heat and Air Quality Impacts of Changing Urban Land Uses and Climate: Columbia University*

The Columbia group built a linked air quality modeling system based on the GISS Atmosphere-Ocean (AO) GCM (Russell et al., 1995) and the MM5 RCM and carried out simulations using two SRES greenhouse gas scenarios (A2 and B2) for 5 summers each during the 1990s, 2020s, 2050s, and 2080s, focusing on the eastern half of the continental United States. Additional simulations using higher resolution were carried out for the New York City metro area for particular meteorological/air quality episodes. One important feature of the Columbia effort is that the team carried the air quality modeling results through to an assessment of human health endpoints.

A key aspect of the Columbia team's work was the evaluation of the performance of this coupled modeling system. They found that (1) dynamical downscaling with MM5 reduces biases present in the GCM simulation, most strongly for temperature and less so for precipitation and (2) there is a strong sensitivity of climate to the choice of RCM parameterizations, e.g., the cumulus convection scheme (e.g., see Lynn et al., 2004). In addition, the downscaled results were often quite different from those of the driving GCM, including, for example, warmer summers. For O_3, they found that their modeling system was able to simulate synoptic and interannual variability reasonably well, including the frequency and duration of extreme O_3 events, but underestimated variability on shorter time scales (Hogrefe et al., 2004a).

In future climate change simulations (with anthropogenic emissions of air pollutants held constant at present-day levels), the Columbia group found summertime O_3 increases of 2−8 ppb across broad swathes of the Midwest and Mid-Atlantic (Hogrefe et al., 2004b). Significant

effects were already seen by the 2020s, with greater increases by the 2050s and 2080s. One exception was certain geographic areas that experienced increases in mixed layer depths and convective activity in the 2080s, changes that actually ended up decreasing O_3, illustrating the complexity of the climate-meteorology-O_3 relationship. In general, the spatial correlation of O_3 increases with any one meteorological variable was not particularly strong in their results. Again the largest future increases in O_3 were for the highest-concentration O_3 episodes, leading to large increases in hypothetical exceedances concentrated in the Ohio Valley and the Mid-Atlantic coast. They also found an increase in the duration of high-O_3 events. The effect of climate change in 50 eastern U.S. cities, without considering future changes in air pollution emissions, was to increase the number of days exceeding the 8-hour O_3 standard by 68% (Bell et al., 2007).

These model results also showed future increases in biogenic VOC emissions in most places as a result of climate change, with the largest absolute increases in the southern and southeastern parts of the United States. While biogenic emissions changes were responsible for up to half of the total climate effect on O_3 concentrations in some parts of the Ohio Valley and Mid-Atlantic further to the north, they did not produce significant O_3 changes in these more southern areas that experienced the largest changes in these emissions. The impact of how biogenic emissions chemistry is represented in air quality modeling systems on simulated O_3 is discussed in more detail in the synthesis below.

Finally, an analysis of the effects of land-use change on O_3 (and heat waves) in the smaller New York City metro region suggests that such changes could also have local impacts of comparable magnitude to the climatic, emissions, and boundary conditions factors considered (Civerolo et al., 2007).

For more information on the Columbia team's efforts, see Appendix D and

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/812/report/0
- http://www.mailman.hs.columbia.edu/ehs/research.html
- http://www.geography.hunter.cuny.edu/luca/
- http://www.cmascenter.org/2003_workshop/session2/hogrefe_abstract.pdf

3.2.2.3 *Impacts of Global Climate and Emission Changes on U.S. Air Quality: University of Illinois*

The University of Illinois group focused on exploring and evaluating, as comprehensively as possible, the capabilities and sensitivities of the tools and techniques underlying the full, global-to-regional model-based approach to the problem. They concentrated on building a system that accounts for global chemistry and climate, and regional meteorology and air quality, capable of simulating effects of climate changes, emissions changes, and long-range transport

changes on regional air quality for the continental United States (Huang et al., 2007; 2008). To capture a wider range of sensitivities, they built different versions of this system, which combines multiple GCMs (PCM and the Hadley Centre Model, HadCM3), SRES scenarios (A1Fi, A2, B1, B2), and convective parameterizations (the Grell and Kain-Fritsch schemes) with the Model for OZone And Related chemical Tracers (MOZART) GCTM, a modified version of the MM5 RCM (referred to as CMM5), and the SARMAP[11] Air Quality Model (SAQM). They also made considerable efforts to evaluate both climate and air quality variables with respect to historical observations and to understand the implications of these evaluations for simulations of future changes.

Several important findings emerge from this group's model evaluation efforts. First, they demonstrated that any individual GCM will likely have significant biases in temperature, precipitation, and circulation patterns, as a result of both parameterizations and internal model variability, so multi-model ensemble means will tend to be more accurate than individual models (Kunkel and Liang, 2005). With proper attention, RCM downscaling can improve on these GCM biases in climate variables over different temporal scales (e.g., diurnal, seasonal, interannual), due to higher resolution and more comprehensive physics, and that furthermore the RCM can produce future simulations of temperature and precipitation patterns that differ significantly from those of the driving GCM (e.g., Liang et al., 2006). They found that the improvements in present-day climate generally led directly to improvements in simulated air quality endpoints, though they also found that the performance of their modeling system tended to be better for monthly and seasonal average O_3 concentrations than for multi-day high-O_3 episodes, reflecting the primary use for which the driving climate models have been designed (Huang et al., 2007). In addition, they found a high sensitivity of downscaled climate (and downscaling skill) to the convective scheme chosen, with different parameterizations working better in different regions/regimes (Liang et al., 2007). This sensitivity strongly affects simulated air quality, for example by altering meteorology and hence also biogenic emissions (Tao et al., 2008). All of these findings are consistent with, and expand considerably upon, the results from the Columbia project described above.

Notably, the Illinois team also found that the different patterns of GCM biases with respect to present-day observations in different simulations, as well as the way the RCM downscaling altered these biases, were consistently reflected in the future GCM and GCM-RCM differences as well. This suggests a strong link between the ability of a GCM or GCM-RCM downscaling system to accurately reproduce present-day climate and the type of future climate it simulates (Liang et al., 2008).

[11] SARMAP stands for the San Joaquin Valley Air Quality Study (SJVAQS)/Atmospheric Utility Signatures, Predictions, and Experiments (AUSPEX) Regional Model Adaptation Project.

In future simulations with their coupled global-to-regional modeling system completed to date, based on PCM GCM simulations following both the A1Fi and B1 SRES greenhouse gas scenarios, the Illinois group found changes in O_3 due to climate change alone (i.e., with anthropogenic pollutant emissions held constant at present-day levels) that were of comparable magnitude to those seen by the NERL and Columbia groups, though with differences in regional spatial patterns (Tao et al., 2007). These similarities and differences will be described in greater detail in the synthesis below. The larger greenhouse gas concentrations, and hence greater simulated climate change, associated with the A1Fi scenario generally resulted in larger future O_3 increases than for the climate change simulation driven by the B1 scenario.

For more information on the Illinois group's efforts, see Appendix D and

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6160/report/0
- http://www.sws.uiuc.edu/atmos/modeling/caqims/

3.2.2.4 *Impact of Climate Change on U.S. Air Quality Using Multi-Scale Modeling with the MM5/SMOKE/CMAQ System: Washington State University*

Similar to the NERL, Columbia, and Illinois groups, the Washington State team developed a combined global and regional climate and air quality modeling system to investigate changes in O_3 (and PM) (Chen et al., 2009; Avise et al., 2009). They used the PCM, MM5, and CMAQ models, and they focused on the IPCC A2 scenario for future greenhouse gases. With this system, the Washington State group investigated climate and air quality changes for the continental United States as a whole, and in addition focused in more detail on two specific regions: the Pacific Northwest and the northern Midwest. A key distinguishing feature of their effort is the attention to biogenic emissions and the consideration of land cover changes (both vegetation cover and urban distributions), as well as changes in the frequency of wildfires in their simulations. Evaluations of their coupled system against observations indicated reasonable agreement with observed climatology and O_3 concentrations in their two focus regions. They also examined wet and dry deposition rates and found qualitatively similar results between modeled and measured rates in the Pacific Northwest.

In five years of simulated summertime O_3 under both present-day and future climate conditions (with constant anthropogenic precursor pollutants), the Washington State group found future O_3 increases in certain regions, most notably in the Northeast and Southwest, with smaller increases or slight decreases in other regions (Avise et al., 2009). These climate change effects were most pronounced when considering the extreme high end of the O_3 concentration distribution. The magnitude of the O_3 increases found by the Washington State group (i.e., a few to several ppb) were roughly comparable to those found by the other regional modeling groups

already discussed, though again with differences in the specific regional spatial patterns of the future changes, linked to differences in the spatial patterns of key O_3 drivers, discussed in more detail in the synthesis below.

In addition, by accounting for plausible future changes in land-use distribution, they simulated both net decreases and increases in biogenic emission capacity, depending on region: i.e., they found that reductions in forested area in the Southeast and West due to increases in development more than offset potential increased biogenic emissions due to climate change, leading to reduction in MDA8 O_3 levels, while enhanced use of poplar plantations for carbon sequestration significantly increased isoprene emissions in the Midwest and eastern United States, leading to O_3 increases. Finally, they found that warmer and drier conditions in their future simulations yielded increased occurrences of fire in the western states.

Additional information on this group's effort can be found in Appendix D and at

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6229
- http://www.nwairquest.wsu.edu

3.2.2.5 *Guiding Future Air Quality Management in California: Sensitivity to Changing Climate—University of California, Berkeley*

Distinct from that of the other groups described above, the Berkeley group's research focused in detail on central California, using a combination of model and observation-based analyses to determine the effects on air quality of changes in temperature, humidity, atmospheric mixing, and biogenic and anthropogenic emissions changes.

Specifically, the Berkeley group used CMAQ at very high resolution (4 km horizontal grid spacing), driven by MM5, to investigate the effects of perturbations in these drivers on O_3 concentrations during a 5-day O_3 episode in the state (Steiner et al., 2006). They derived plausible, spatially resolved future changes in summertime temperatures from two simulations with the Community Climate Model version 3 (CCM3) GCM downscaled to a 40 km grid spacing for the western United States: one with a "pre-industrial" CO_2 concentration of 280 parts per million (ppm) and one representing a hypothetical 2050 climate with a doubled CO_2 concentration of 560 ppm (Snyder et al., 2002). The average August temperature difference between these two downscaled simulations at each point in the domain was added to the MM5 meteorological output used to drive CMAQ. This temperature perturbation was applied in an uncoupled manner so as not to affect other meteorological quantities such as wind speed and boundary layer height, to isolate the impact of temperature changes on chemical reaction kinetics. This imposed temperature increase was also used to derive perturbations of humidity and biogenic VOC emissions for additional, separate sensitivity experiments. In addition to

these climate-based changes, the Berkeley group carried out simulations to investigate the sensitivity of O_3 to changes in anthropogenic NO_x and VOC emissions, as well as to the inflow of pollutants from outside the state.

They found that higher temperatures increased O_3 concentrations in this simulated pollution episode both directly (through increased reaction rates) and indirectly (through increases in biogenic emissions). Across all the different effects explored, they found that O_3 sensitivity varied depending on proximity to the Pacific Coast (e.g., where impacts of increased pollution at the inflow boundary are greatest), and on preexisting NO_x or VOC levels (e.g., NO_x-saturated regions in central California appear to be most sensitive to climate-related changes).

The Berkeley team also conducted an observationally based study of the temperature sensitivity of anthropogenic VOC emissions: the role of temperature in increasing fuel evaporation was highlighted in this analysis (Rubin et al., 2006). Increased evaporation was apparent in observed correlations between speciated VOCs and temperatures as they varied by time of day and from day to day, with implications for the climate sensitivity of these emissions.

Additional information about the Berkeley project can be found in Appendix D and at http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6231/report/0.

3.2.2.6 *Sensitivity and Uncertainty Assessment of Global Climate Change Impacts on Ozone and Particulate Matter: Examination of Direct and Indirect, Emission-Induced Effects: GIT-NESCAUM-MIT*

Similar to the NERL, Columbia, Washington State, and Illinois groups discussed above, the GIT-NESCAUM-MIT group constructed a linked global-to-regional climate and air quality modeling system to investigate the impacts of global change on regional U.S. O_3 and PM concentrations (Tagaris et al., 2007; Liao et al., 2007). Specifically, they used CMAQ, driven by present-day and future climate simulations with the GISS II′ GCM downscaled using MM5 (the same MM5-downscaled GISS II′ GCM simulations developed for the NERL project described above). However, compared to these other groups, they had a unique focus on understanding the climate sensitivity of regional air quality in the context of expected future pollutant emissions under the implementation of current and future control strategies. This effort not only investigated O_3, but also PM and its speciated components of sulfates, nitrates, ammonium, and organics, in detail. A strong, built-in link between the academic and regional air quality management communities is achieved via the inclusion of NESCAUM in the partnership.

Their work to date attempts to determine if climate change will have significant impacts on the efficacy of O_3 and PM emissions control strategies currently being considered in the

United States by focusing on (1) comparing the sensitivity of future regional U.S. air quality to changes in emissions around present-day and projected future climate and emissions baselines and (2) accounting for the effects of uncertainties in future climate on simulated future air quality to evaluate the robustness of these results (see Liao et al., 2009).

To address these issues, the GIT-NESCAUM-MIT team developed a detailed, spatially resolved U.S. future air pollutant emissions inventory to understand the relative impacts of climate change on future air quality in different emissions and control strategy regimes. To accomplish this, they used the latest projection data available for the near future (to about 2020), such as the EPA CAIR Inventory, and they extended point source emissions to 2050 using the IMAGE[12] model combined with the IPCC A1b emissions scenario (the same scenario used in the GISS II′ future climate simulations) and mobile source emissions from Mobile Source Emission Factor Model version 6 (MOBILE6), projecting reductions of more than 50% in NO_x and SO_2 emissions (Woo et al., 2007).

A key finding from the GIT-NESCAUM-MIT work is that, overall, existing control strategies should continue to be effective in an altered future climate, though with regional variations in relative benefit (Tagaris et al., 2007). The magnitude of the "climate change penalty" for controlling O_3 (as defined by the Harvard group) is found to be consistent with the work of Wu et al. (2008a). The spatial distribution and annual variation in the contribution of precursors to O_3 and PM formation under the combined future scenario of climate change and emission controls remain similar to the baseline case, implying the continued effectiveness of current control strategies. The findings further suggest, however, that compliance with air quality standards in areas at or near the NAAQS in the future would be sensitive to the amount of future climate change. Finally, an analysis of potential health impacts of these simulated future air quality changes, using the environmental Benefits Mapping and Analysis Program (BenMAP),[13] is ongoing.

Additional information on the GIT-NESCAUM-MIT project can be found in Appendix D and at

- http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/6238/report/0
- http://www.ce.gatech.edu/~trussell/lamda/

3.3 SYNTHESIS OF RESULTS ACROSS GROUPS

This sub-section synthesizes findings across the global and regional modeling results from the groups that have just been introduced, focusing on nationwide changes in summertime

[12] A Netherlands Environmental Assessment Agency modeling tool.
[13] See http://www.epa.gov/ttn/ecas/benmodels.html for more information.

O_3 concentrations due to simulated climate change a few decades into the future. Other pollutants are not addressed here. As already mentioned, the major focus is the particular subset of results completed to date which are largely common across groups, to facilitate a synthesis. Nevertheless, even limiting discussion to this subset allows us to effectively illustrate a number of key points to carry forward.

Specifically, then, the focus is on inter-group comparisons of future decade (~2050s) and present-day simulations of summertime O_3 under scenarios of climate change. The emphasis on summer reflects that of the participating research groups, i.e., on the primary season for O_3 episodes and exceedances. All of the future simulations discussed in this sub-section held anthropogenic emissions of precursor pollutants constant at present-day levels, but allowed climate-sensitive natural emissions (e.g., of biogenic VOCs) to vary in response to the simulated changes in climate.[14] The organization is as follows: first, the O_3 results from the fully downscaled, high-resolution regional model simulations are presented and compared; then, comparisons of differences in key meteorological variables (and biogenic emissions) from these same simulations are provided to begin explaining these O_3 results and to highlight the sometimes complex interactions between O_3 and its drivers; and finally, some results from the global-model-only runs are presented to complement the regional model findings and to illuminate more clearly certain important issues.

Most of the groups whose results make up this synthesis of the impacts of climate change on O_3 have also carried out additional, in most cases highly preliminary, simulations designed to investigate, to first-order, the effects of changes in climate relative to changes in worldwide and/or U.S. anthropogenic emissions of precursor pollutants. The results from these simulations are not included in the synthesis below to maintain the focus on first exploring climate change impacts alone. However, these sensitivity studies provide useful insights that will help inform the more detailed treatments of future emissions planned for Phase II, highlighting key assumptions and uncertainties that will need to be addressed. Therefore, Section 4 contains a brief summary of these analyses and findings.

Similarly, some of the groups have also completed simulations of potential future changes in PM (and its component chemical species), but these results are not discussed here. This is because the research effort and the level of scientific understanding are much more mature at this time for climate and O_3 than for climate and PM—there are far more O_3 results from these projects to date to draw from, along with a greater knowledge base for interpreting them. In addition, it is anticipated that many of the modeling-related issues revealed in the examination of the O_3 results will likely apply to PM as well, though PM also poses unique

[14] Differences in IPCC SRES scenarios between the different simulations thus refer only to greenhouse gas concentrations, and not precursor pollutants.

challenges for coupled climate-air quality modeling. Some discussion of progress toward understanding climate change impacts on PM is also included in Section 4, and a future report focusing on PM is anticipated.

3.3.1 Regional Modeling Results

3.3.1.1 *Modeling System Configurations, Simulations, and Evaluation*

Table 3-1 lists the regional climate and O_3 modeling results discussed in this section. These simulations were carried out with linked systems consisting of a GCM/GCTM, dynamical downscaling with an RCM, and regional-scale air quality calculations with an RAQM. In aggregate, they cover a range of models, IPCC SRES scenarios of future greenhouse gas emissions, climate and meteorological model physical parameterizations, and chemical mechanisms.

The principal comparison in this section is across the regional modeling experiments listed in Table 3-1 that have regional simulation domains covering the entire continental United States. These are the NERL, University of Illinois (Illinois 1 and Illinois 2), Washington State (WSU), and Georgia Tech-NESCAUM-MIT (GNM) sets of simulations. Results from the Berkeley and Columbia simulations, conducted for subsets of the country, are referred to in the course of the text to reinforce particular findings. Note that the NERL and GNM sets both relied on the same MM5-downscaled GISS III climate simulations, though GNM is for three summers versus five for NERL. They also differed in their development of their emissions inventories. Note also that Illinois 1 and Illinois 2 are identical except for the greenhouse gas emissions scenario used in the GCM simulation of future global climate, with Illinois 1 using the IPCC SRES A1Fi and Illinois 2 using B1. The many additional details of each of these sets of numerical experiments can be found in the references cited in Table 3-1 (and further references therein).

It is important to reiterate that the differences in IPCC SRES scenarios for the simulations listed in Table 3-1 refer *only* to greenhouse gas concentrations, and not precursor pollutants. As emphasized previously in this report, all of the results shown here are from simulations that held anthropogenic emissions of precursor pollutants, as well as other relevant chemical species (e.g., CH_4) constant at present-day levels. Climate-sensitive natural emissions, such as biogenic VOCs, evaporative emissions, and lightning NO_x (depending on the modeling system used), were allowed to change in response to the simulated climate change, with the biogenic VOCs being the dominant impact. Land use and land cover also remained constant. Finally, potential impacts of changes in O_3 concentrations on plant productivity and carbon uptake were not included (e.g., see Sitch et al., 2007).

Table 3-1. The regional modeling systems whose results are discussed in Sections 3.3.1 and 3.3.2. The regional resolution listed for each group represents the horizontal grid spacing of the regional air quality simulation (also corresponding to the innermost nested grid of the RCM). The Illinois AQM runs use 30 km grid spacing over four sub-regions of the country and 90 km everywhere else (their CMM5 runs use 30 km everywhere). Therefore, for the O_3 results shown below, these 30 km values in the sub-regions are overlaid on the background map of 90 km values, introducing some minor contouring discrepancies at the boundaries of the sub-regions.

	Berkeley[a]	**Columbia**[b]	**NERL**[c]	**Illinois 1**[d]	**Illinois 2**[d]	**WSU**[e]	**GNM**[f]
Domain	Cent. CA	East. U.S.	Cont. U.S.	Cont. U.S.	Cont. U.S.	Cont. U.S.	Cont. U.S.
Simulation Period	1 August	5 JJAs	5 JJAs	1 JJA	1 JJA	5 Julys	3 JJAs
GCM	CCM3	GISS AO	GISS III	PCM	PCM	PCM	GISS III
Global Resolution	2.8° × 2.8°	4° × 5°	4° × 5°	2.8° × 2.8°	2.8° × 2.8°	2.8° × 2.8°	4° × 5°
GHG Scenario	2 × CO_2	A2	A1b	A1Fi	B1	A2	A1b
RCM	MM5	MM5	MM5	CMM5[g]	CMM5[g]	MM5	MM5
Regional Resolution	4 km	36 km	36 km	90/30 km	90/30 km	36 km	36 km
Convection Scheme	N/A	Betts-Miller	Grell	Grell	Grell	Kain-Fritsch	Grell
RAQM	CMAQ	CMAQ	CMAQ	AQM[h]	AQM[h]	CMAQ	CMAQ
Chemical Mechanism[i]	SAPRC99[j]	CB-IV[k]	SAPRC99	RADM2[l]	RADM2	SAPRC99	SAPRC99
Climate Sensitive Emissions	BVOCs	BVOCs; Evaporative[m]	BVOCs; Evaporative[m]	BVOCs; Evaporative[m]	BVOCs; Evaporative[m]	BVOCs; Evaporative[m]	BVOCs; Evaporative[m]

[a]For more details, see Steiner et al. (2006).
[b]For more details, see Hogrefe et al. (2004a,b)—the GISS AO model refers to the model of Russell et al. (1995).

[c]For more details, see Leung and Gustafson (2005); Nolte et al. (2008).
[d]For more details, see Liang et al. (2006); Huang et al. (2007; 2008); Tao et al. (2007).
[e]For more details, see Chen et al. (2009); Avise et al. (2009).
[f]For more details, see Tagaris et al. (2007); Liao et al. (2007); Woo et al. (2007).
[g]CMM5 is based on the standard MM5, but with modifications to the buffer zone, ocean interface, and cloud-radiation interactions.
[h]AQM has been adapted from the SARMAP model, incorporating a faster, more accurate numerical solver for gas-phase chemistry.
[i]Note that the SAPRC99 and RADM2 chemical mechanisms recycle isoprene nitrate, while the CB-IV mechanism does not.
[j]For more details, see Carter (2000).
[k]For more details, see Gery et al. (1989).
[l]For more details, see Stockwell et al. (1990).
[m]Through the SMOKE emissions modeling system, e.g., see Houyoux et al. (2000).

Cent. = Central; East. = Eastern; Cont. = Continental; U.S. = United States.

All of these modeling systems have been evaluated to some degree with respect to historical observations of both climate and chemistry. Each of the individual modeling components making up the coupled system is well established in their respective research communities, and has undergone extensive testing and evaluation, though not necessarily for the particular variables, and statistics, most appropriate for coupled climate and air quality research. For example, the CMAQ model has been extensively evaluated against observations for operational air quality forecasting evaluations (e.g., see Eder and Yu, 2006; Eder et al., 2006), as well as for the purposes of examining issues such as the sensitivity of simulated O_3 concentration to nudging of meteorological fields and subsequent impact on O_3 biases (e.g., see Otte, 2008). Similar claims may be made for the other global and regional climate and chemistry modeling components.

Evaluation of the coupled modeling systems, built out of these individual components, is at an early stage. Each of the modeling teams has performed a number of evaluations of their coupled climate and air quality systems using station observations of meteorological variables and ozone concentrations (e.g., from EPA's Air Quality System database[15]) for various historical time periods. Details of these evaluations can be found in the references cited above, and additional references therein for the individual modeling components. For example, the NERL group compared their combined GCM-RCM-RAQM MDA8 O_3 distributions with AQS observations nationally, finding reasonable agreement comparable to that found for uncoupled CMAQ simulations. In general, they found the smallest biases in the northeastearn United States, and at the high end of the O_3 distribution. They attributed these biases to both meteorological and chemical mechanism factors.

Beyond providing insight into the performance and biases of the modeling systems, these evaluation studies also provide a number of important insights that complement the simulations of climate change impacts on O_3 that will be discussed shortly, e.g., on the role of meteorological drivers or alternative chemical mechanisms in O_3 variability. For example, Nolte et al. (2008) attribute a portion of the O_3 biases over the eastern United States that they observe in their coupled system to the biases in temperature and precipitation present in the MM5 regional climate used to drive their ozone simulation (see also Leung and Gustafson, 2005). They also found, in sensitivity studies, differences in simulated O_3 using the SAPRC vs. the CB-IV chemical mechanism in CMAQ (see also Faraji et al., 2008). Similarly, Huang et al. (2007) showed how low or high biases in simulated temperature over the Northeast and Midwest lead to O_3 concentration biases in the same directions.

[15] http://www.epa.gov/ttn/airs/airsaqs/.

3.3.1.2 *Changes in O_3*

Figure 3-1 shows summertime mean MDA8 O_3 concentration differences between simulated future and present-day climates for the regional modeling experiments listed in Table 3-1 that have model domains covering the entire continental United States. These are the NERL, Illinois 1, Illinois 2, WSU, and GNM simulations. Results from the Berkeley and Columbia simulations, conducted for subsets of the country, are referred to in the course of the text to reinforce particular findings. MDA8 O_3 is selected because of its direct relevance to U.S. air quality standards. All plots discussed here show future minus present differences. All O_3 values are in ppb.

Key similarities between the results from the different groups emerge:

- For all the present/future simulation pairs, some substantial regions of the country show future increases in O_3 concentrations of roughly 2−8 ppb under a future climate.
- Other regions show little change in O_3 concentrations, or even decreases, though the decreases tend to be less pronounced than the increases.
- These patterns of O_3 differences are accentuated in the 95th percentile MDA8 O_3 (shown in Figure 3-2 for the NERL experiment, as one example of this result) compared to the mean MDA8 O_3.

The basic result of larger climate sensitivity of O_3 concentrations for high-O_3 conditions (e.g., 95th percentile MDA8 O_3) is one of the most robust findings of this synthesis—it holds across all the modeling groups and appears in many different analyses carried out by these groups. These more detailed results can be found in the papers cited in Table 3-1. This is significant, because these high-O_3 episodes are of particular concern for air quality managers.

Some pronounced differences in the broad spatial patterns of change across experiments emerge as well. For example, the NERL and GNM simulations show increases in O_3 concentration in the Mid-Atlantic and parts of the Northeast, Gulf Coast, and parts of the West. They also show decreases in the upper Midwest and Northwest and little change elsewhere, including the Southeast. By contrast, the Illinois 1 experiment shows the strongest increases in the Southeast, the Northwest, and the Mississippi Valley (as well as the Gulf Coast, in agreement with NERL), with weaker increases in the upper Midwest. In addition, these changes tend to be larger than those from the NERL experiment. The WSU experiment shows the largest increases

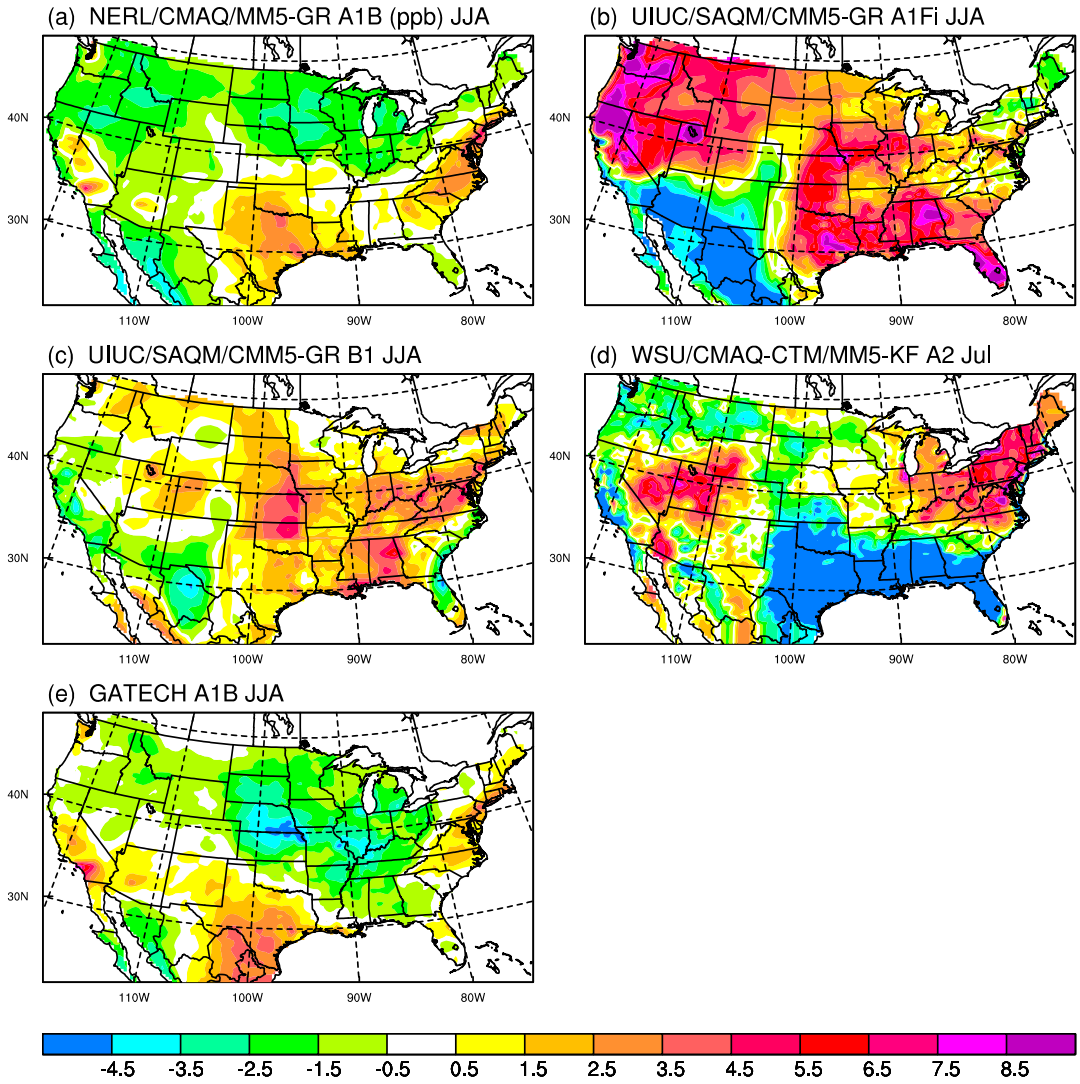


Figure 3-1. 2050s-minus-present differences in simulated summer mean MDA8 O_3 concentrations (in ppb) for the (a) NERL; (b) Illinois 1; (c) Illinois 2; (d) WSU; and (e) GNM experiments (see Table 3-1).

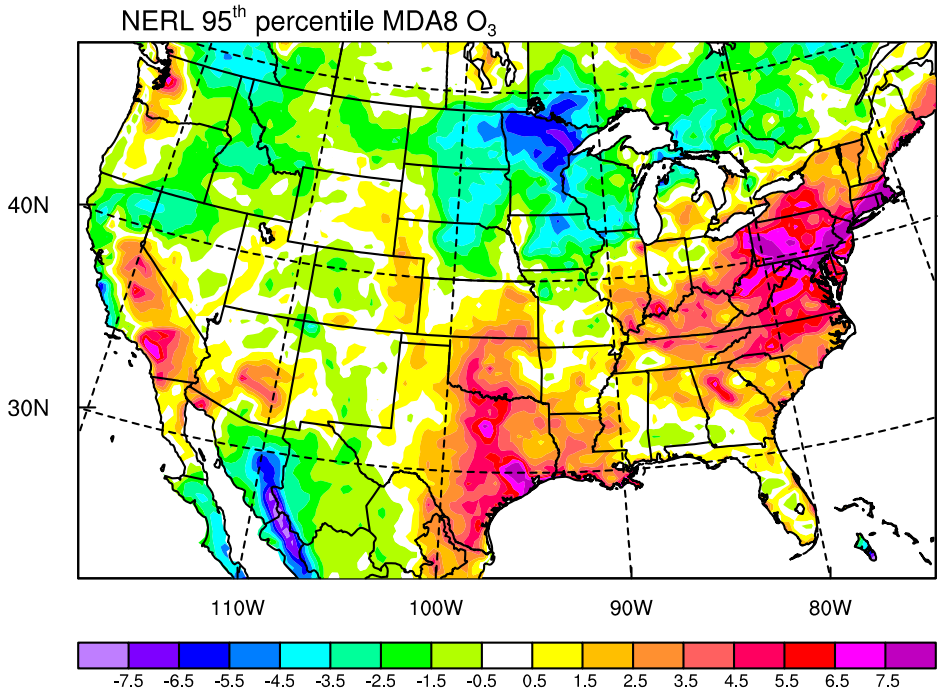


Figure 3-2. 95th percentile MDA8 O_3 concentration differences for the NERL experiment.

in the Northeast, parts of the Midwest, and desert Southwest, with decreases in some parts of the West, the Southeast, the Northwest, the Plains states, and the Gulf Coast. As is to be expected, the NERL and GNM patterns are quite similar, with differences primarily reflecting the averaging over five vs. three summers, respectively. This highlights the potential importance of interannual variability in driving differences between modeling groups, as will be discussed further below.

Certain regions show greater agreement across experiments than others. Figure 3-1 illustrates that a loosely bounded area, encompassing parts of the Mid-Atlantic, Northeast, and lower Midwest, tends to show at least some O_3 increase across all the simulations. By contrast, the West and the Southeast/Gulf Coast are areas of greater disagreement, hinting at some of the complexities underlying the interactions between climate and O_3. Even for these regions, however, at least some of the models (here and in Section 3.3.2) show substantial climate-induced O_3 increases. Changes in drivers that help explain these agreements and disagreements, and help illustrate these complexities, will be presented and discussed shortly.

All of these findings are generally consistent with results from the earlier Columbia study (see Hogrefe et al., 2004b). Figure 3-3 shows future-minus-present climate summertime mean

MDA8 O_3 concentration difference for their modeling domain, covering the eastern half of the United States.

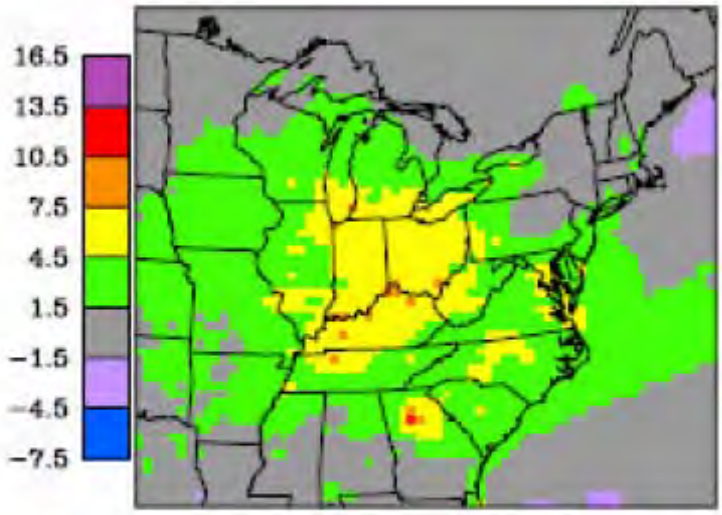


Figure 3-3. 2050s-minus-present differences in simulated summer mean MDA8 O_3 concentrations (in ppb); reproduced from Figure 2 in Hogrefe et al. (2004b).

Note from Table 3-1 that there are differences in the number of years of simulation completed by the different groups so far. As introduced in Section 1, and discussed further below, it is well recognized that interannual meteorological variability drives large year-to-year changes in O_3 (e.g., see White et al., 2007; Leibensperger et al., 2008; Jacob and Winner, 2009). All of the modeling groups eventually aim to analyze interannual variability in their simulations. In this context, Figure 3-4 (reproduced from Nolte et al., 2008) illustrates two points. First, for some regions, the average change in O_3 from the present to the 2050s as a result of climate change is just as large as (and on top of) the year-to-year O_3 variability that is of concern today. In other words, climate change has the potential to push O_3 concentrations in extreme years beyond the envelope of natural interannual variability. Second, it highlights the need for simulating multiple years to increase the robustness of findings about present-to-future changes. These results are consistent with those presented in Racherla and Adams (2008) (based on their GCTM runs), who found that the magnitude of simulated future changes in O_3 concentrations over the eastern United States tended to be greater than the magnitude of present-day interannual

O_3 variability, and that at least 5 years of simulation were needed to fully separate the effects of climate change and interannual variability.

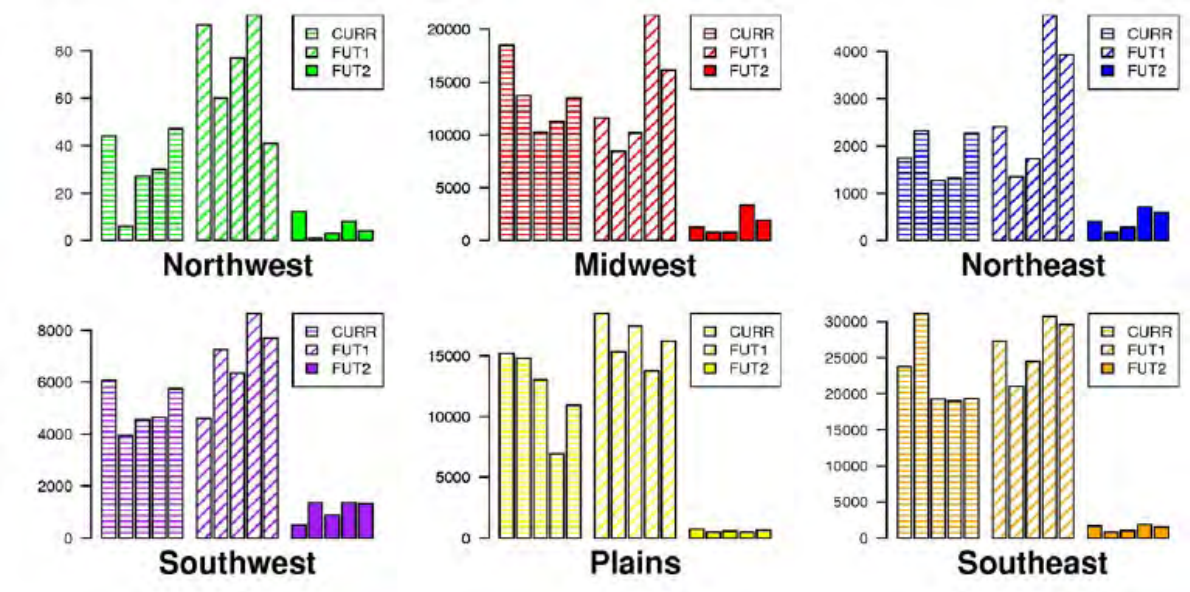


Figure 3-4. Frequency of simulated summer mean MDA8 O_3 values exceeding 80 ppb in different regions from the NERL experiment; reproduced from Figure 11 in Nolte et al. (2008). Each bar represents 1 year. The leftmost group of bars corresponds to present-day climate, the center group to 2050s climate with anthropogenic emissions held constant at present-day values, and the rightmost group represents 2050s climate and decreases in anthropogenic O_3 precursor emissions.

Finally, while this analysis focuses on summertime results, a few of the groups also found strong increases in O_3 concentrations in their future compared to present climate simulations over certain regions of the country (e.g., Nolte et al., 2008; Avise et al., 2009; Racherla and Adams, 2008). Figure 3-5 (reproduced from Nolte et al., 2008) illustrates this point, showing September-October O_3 increases in a band stretching from the Southwest, across the Plains states, and into the Upper Midwest. These results suggest a possible extension of the O_3 season for some regions of the United States under future climate change.

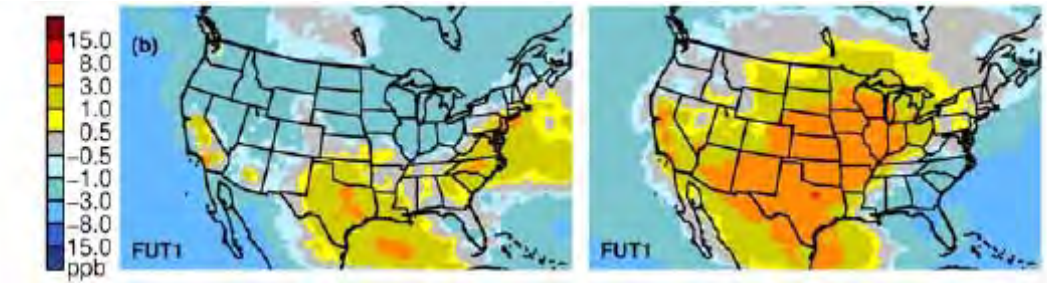


Figure 3-5. 2050s-minus-present September-October compared to June-August differences in simulated mean MDA8 O_3 concentrations (in ppb); reproduced from Figure 6 in Nolte et al. (2008).

3.3.1.3 *Changes in Drivers*

There is already a great deal of regional variability in near-surface O_3 under current climate conditions. For example, as introduced in Section 1, a large body of observational and empirical work has helped us understand that concentrations tend to be especially great where the emissions of precursor chemical species like VOCs and NO_x are also large, and that, furthermore, these pollutants tend to drive up O_3 even more during the times when meteorological conditions most favor strong net photochemical production—persistent high pressure, stagnant air, lack of convection, clear skies, and warm temperatures—and vice versa. It is for these reasons that the O_3 NAAQS are most often exceeded during summertime hot spells in places with large natural or anthropogenic precursor emissions (e.g., cities). To the extent that climate change may alter weather patterns, and, hence, the frequency, duration, and intensity of these episodes, for example, O_3 concentrations could be significantly affected.

However, the causal chain linking (a) long-term global climate change, (b) changes in the aspects of (often) short-term meteorological variability that most directly drive near-surface O_3 concentration changes of concern to air quality managers, and (c) any O_3 changes that ultimately result from the interaction of these meteorological changes with the pollutants present in the environment (which may themselves be sensitive to meteorology and climate) may not be straightforward. Changes in the O_3 distribution of a given region due to climate change will reflect a balance among competing changes in multiple factors.

For example, a number of meteorological variables have been identified as potentially important, including

- Near-surface temperature
- Near-surface humidity

- Precipitation
- Cloud cover
- Planetary Boundary Layer (PBL) height
- Near-surface wind speed and direction
- Ventilation and mixing due to convective events
- Ventilation and mixing due to synoptic-scale cyclones
- Ventilation and mixing due to coastal onshore flow.

These variables are not, in general, independent of each other. Instead, they vary, together or separately in different combinations, at different locations over different timescales, in ways that may favor either increases or decreases in O_3. For example, all other factors being equal, increases in temperature at a given time and place might lead to increases in O_3 concentration, but if these temperature increases are accompanied by increases in cloudiness, the net result might be a decrease in O_3 concentration. Box 3-1 provides a discussion of how one's perception of the relationship between O_3 and its meteorological drivers can vary depending on the timescale considered, using the temperature-O_3 relationship as an example. This provides some additional context for interpreting these next modeling results to be presented. This issue is revisited in Section 3.4 below, where the implications for interpreting long-term mean climate change-air quality modeling results are discussed.

The advantage of the type of model-based approach that is the focus of this section, i.e., the strategy of linking climate, meteorology, and air quality models, is that such integrated modeling systems are capable of capturing these complexities by representing the reinforcing and competing interactions between variables in an internally self-consistent way. As such, they help illuminate potentially non-obvious impacts of climate change on O_3 that result from synergistic interactions between the changes in key drivers.

Figures 3-6 and 3-7 display the average future-minus-present differences in near-surface air temperature and surface incoming solar radiation (typically referred to as "insolation"), which are two of the most critical meteorological drivers of ground-level O_3. The insolation changes largely reflect changes in cloud cover. Other variables besides the two shown in Figures 3-6 and 3-7 were also examined, including average daily maximum temperature, precipitation, number of rainy days, and PBL height. However, none of these additional comparisons are shown here because, at least at this level of analysis, they do not seem to add a great deal to the explanatory power of temperature and surface insolation (and, as will be discussed below, biogenic VOC emissions). This is likely due to the strong correlations among these variables already been discussed.

Box 3-1. The Temperature-O_3 Relationship
As seen through the lenses of different meteorological/climatic timescales

Episode: The severity of a particular O_3 episode lasting one or a few days can depend strongly on temperature. For example, Aw and Kleeman (2003) found that, by increasing temperature (but without modifying the other meteorological variables) in an air quality model simulation of a southern California O_3 episode, they significantly increased daily peak O_3 concentrations. Temperature affects the kinetics of the O_3-forming and destroying chemical reactions. For example, in polluted environments, increasing temperature will tend to lead to more NO_x, and hence more O_3, via a decrease in peroxyacetylnitrate (PAN) production. The new results from the Berkeley and Carnegie Mellon groups described in Section 3.2 have yielded similar insights. Steiner et al. (2006), in their very high-resolution simulations of a 5-day O_3 episode over California, found that temperature perturbations consistent with plausible 2050s climate change led to increases in afternoon O_3 concentrations of 1-5 ppb across the state. Dawson et al. (2007b) found similar effects of temperature modification when using the PMCAMx model to simulate O_3 concentrations during a week-long period over the eastern U.S.

Season: From the perspective of an entire season, however, mean O_3 concentration and the number of O_3 exceedances will likely depend at least as much on how many of these meteorological episodes that promote O_3 formation occur, and how long they last, as on how hot it is during them. In other words, how often in a given summer that cool, cloudy, rainy, and windy conditions give way to spells of hot, clear, dry, and stagnant conditions will play a large role in determining whether it was a "high-O_3" or "low-O_3" summer. At this timescale, temperature and O_3 will also be positively correlated, but here the "temperature-O_3" relationship exists at least partly because temperature itself is highly correlated with these other meteorological conditions, like more sunlight and less ventilation, that also favor increased O_3 concentrations.

Long-Term Climate Change: On the multi-decadal timescales of global climate change, however, the relationship between temperature and these other meteorological drivers may or may not play out in the same way that is characteristic of seasonal timescales. In some regions, climate change may indeed have the effect of producing long-term average associations between higher temperatures, less cloudiness, and weaker mixing that in aggregate would be likely to lead to O_3 concentration increases. This would be true, for example, in the regions most at risk for increases in the frequency, duration, and intensity of summertime heat waves (e.g., see Meehl and Tebaldi, 2004; IPCC, 2007). In other regions, however, climate change may lead to changes in these other variables that do not favor increases in O_3 concentrations. For example, a warmer world is likely, on average, to be a wetter world. Both the Harvard and Carnegie Mellon GCTM results summarized earlier showed how increases in humidity in their future simulations led to decreases in near-surface O_3 in less-polluted regions (Wu et al., 2008a; Racherla and Adams, 2006). Similarly, regions that experience increases in cloudiness (and hence decreases in sunlight and O_3 photo-production) in an altered future climate might have net O_3 concentration decreases, in spite of increased temperatures.

Combined with the O_3 results shown above in Figure 3-1, Figures 3-6, and 3-7 reveal some key similarities in the relationships between O_3 and meteorological drivers among the different model studies:

- First, in many regions the O_3 concentration changes (Figure 3-1) seem to correspond relatively well with combined changes in mean temperature (Figure 3-6) and mean surface insolation (Figure 3-7). For example, the NERL results show the O_3 increases corresponding with temperature and insolation increases in the Mid-Atlantic and Gulf Coast and O_3 decreases associated with the insolation decreases and the local minimum in temperature increases in the upper Midwest and the northern Plains.

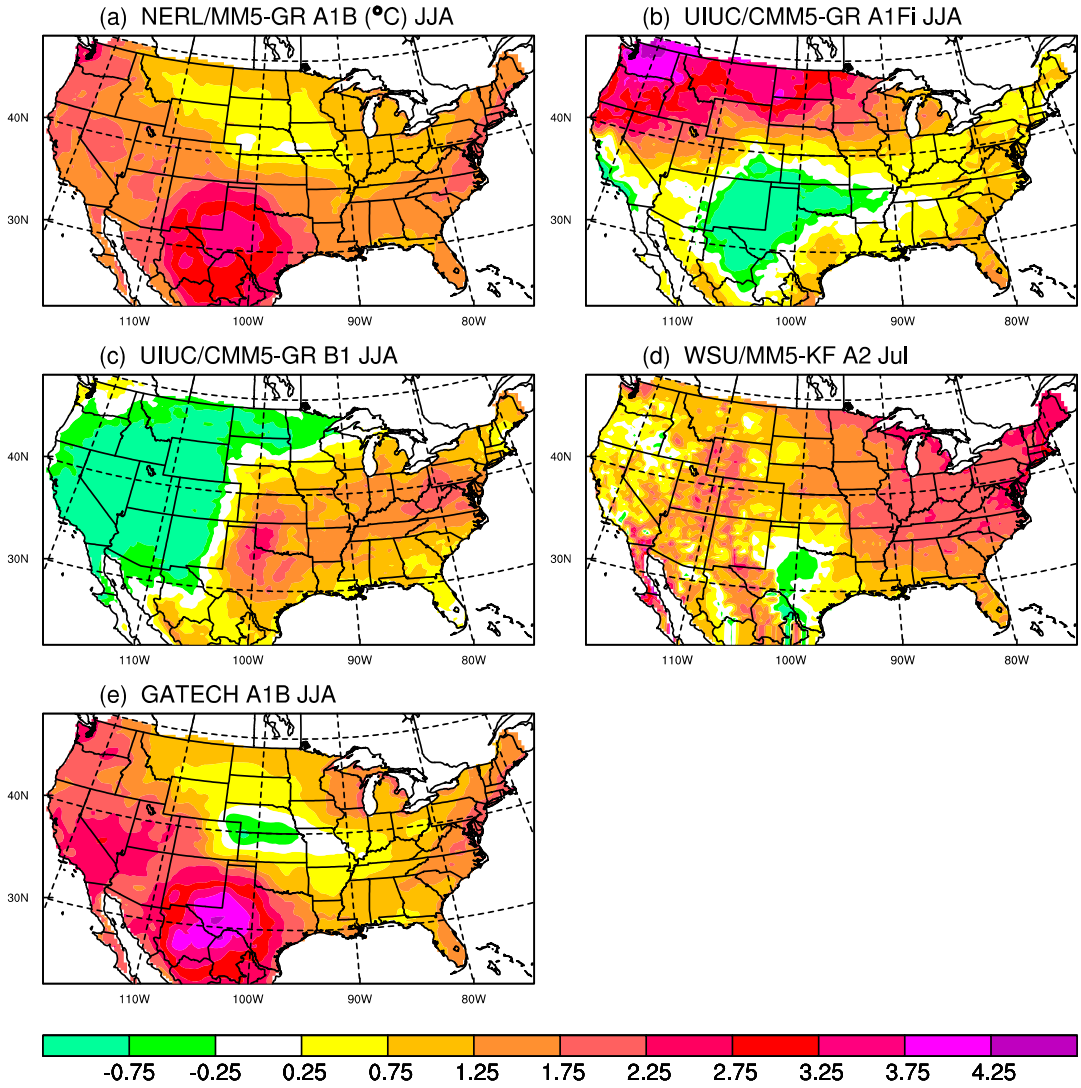


Figure 3-6. 2050s-minus-present differences in simulated summer mean near-surface air T (ºC) for the (a) NERL; (b) Illinois 1; (c) Illinois 2; (d) WSU; and (e) GNM experiments.

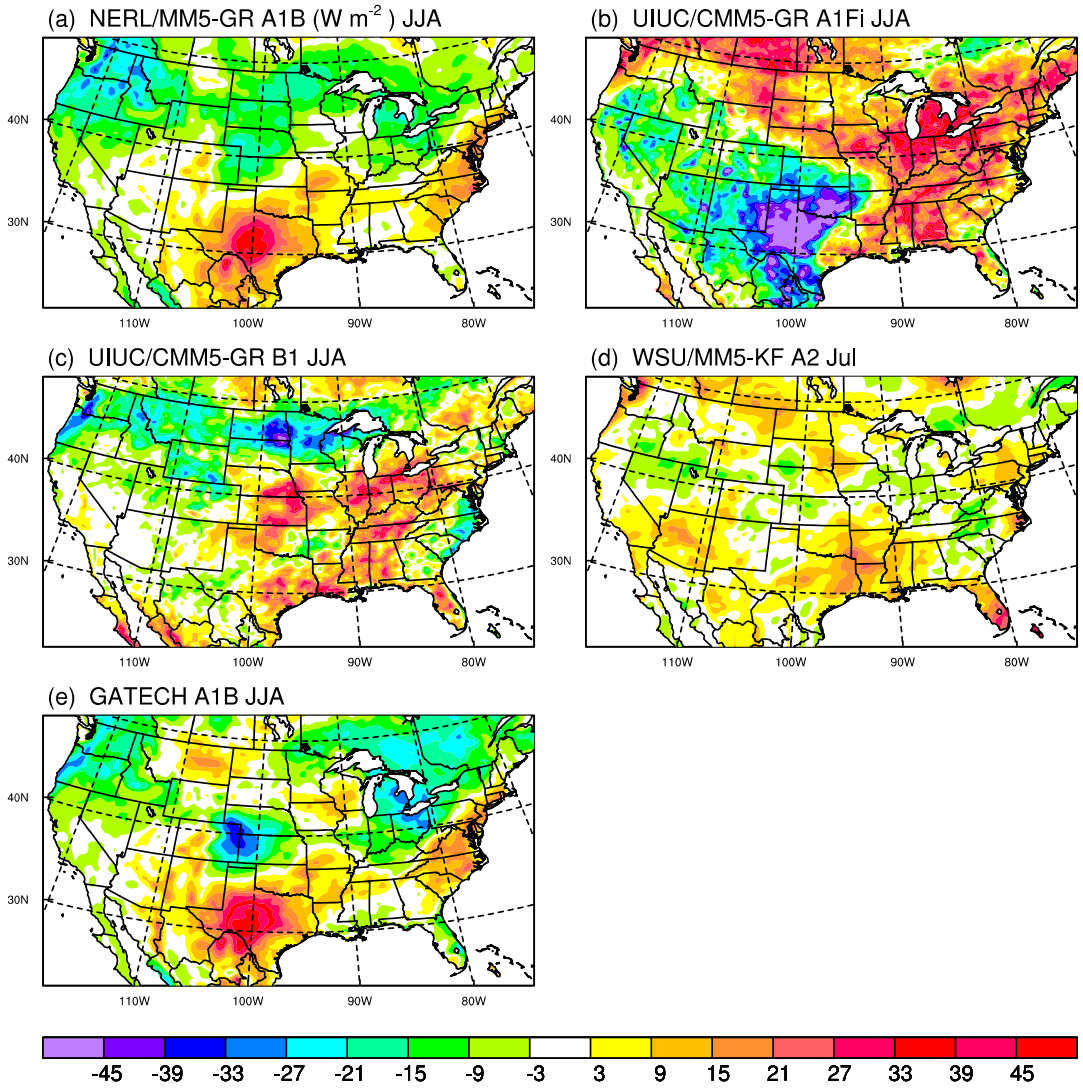


Figure 3-7. 2050s-minus-present differences in simulated summer mean surface insolation (W m^{-2}) for the (a) NERL; (b) Illinois 1; (c) Illinois 2; (d) WSU; and (e) GNM experiments.

- In other regions, temperature and insolation vary in opposite directions, with mixed impacts on O_3 concentrations. For example, in the Illinois 1 simulations, in spite of insolation decreases over much of the Northwest, the large increase in temperature there seems to drive O_3 increases.

In a small number of regions across the simulations, there is no strong correspondence between O_3 concentrations and either insolation or temperature (e.g., the areas around Oklahoma

in the Illinois 1 experiment and Nevada/Utah/Idaho in the Illinois 2 experiment), suggesting that other forcing factors may be important, and/or that a correspondence might exist, but only for different averaging periods and statistics of these variables.

The differences between the NERL and GNM results are consistent with this last bullet. For example, in the Plains states, GNM shows greater O_3 decreases, consistent with the difference in temperature and insolation trends resulting from the difference in the number of summers simulated.

Again, as discussed above and in Box 3-1, when interpreting these monthly- or seasonal-mean results it is important to recognize they encompass not just changes in the meteorological conditions most related to O_3 episodes, but the whole spectrum of changes in regional climatology arising from global climate change.

Considering the results from the Columbia group, Hogrefe et al. (2004b) do not report any single clear relationship across their study region between the spatial patterns of future-minus-present O_3 concentrations and a number of meteorological variables (e.g., temperature, wind speed, and mixed layer height), as mentioned in the summary in Section 3.2. This is consistent with the potential for different competing effects in different regions illustrated by the results shown here. They do note a strong sensitivity of future O_3 changes to changes in convective activity in certain areas, which may reflect the dependence on insolation found by the other groups.

Figure 3-8 shows the patterns of changes in mean biogenic VOC emissions across the simulations. As documented in earlier work (e.g., Chameides et al., 1988; Roselle et al., 1991; Guenther et al., 1994; Pierce et al., 1998; Fuentes et al., 2000; Purves et al., 2004; among others), the emissions of these important natural O_3 precursors are themselves sensitive to meteorology, including sunlight and temperature. Therefore, in conjunction with the direct forcing exerted on O_3 processes by changes in meteorology, climate-induced changes in biogenic emissions levels can lead to changes in O_3 concentrations as well (see also Zhang et al., 2008). As will be discussed again below, in the context of the global modeling results, this impact depends in part on the relative amounts of NO_x and VOCs in the environment. For example, Steiner et al. (2006) found significant O_3 concentration increases in the high-NO_x San Francisco Bay area due to increases in biogenic VOC emissions, whereas even larger increases in biogenic emissions over the Sierras actually produced slight O_3 decreases.

The climate-induced biogenic emissions changes shown in Figure 3-8 seem to contribute to the O_3 concentration changes, but only in some regions, and not wholly consistently across model studies. For example, temperature-driven increases in biogenic emissions may contribute to the above-mentioned O_3 increases in the Northwest in the Illinois 1 experiment, the Mid-Atlantic in the NERL and GNM experiments, the Northeast in the Illinois 2 experiment, and

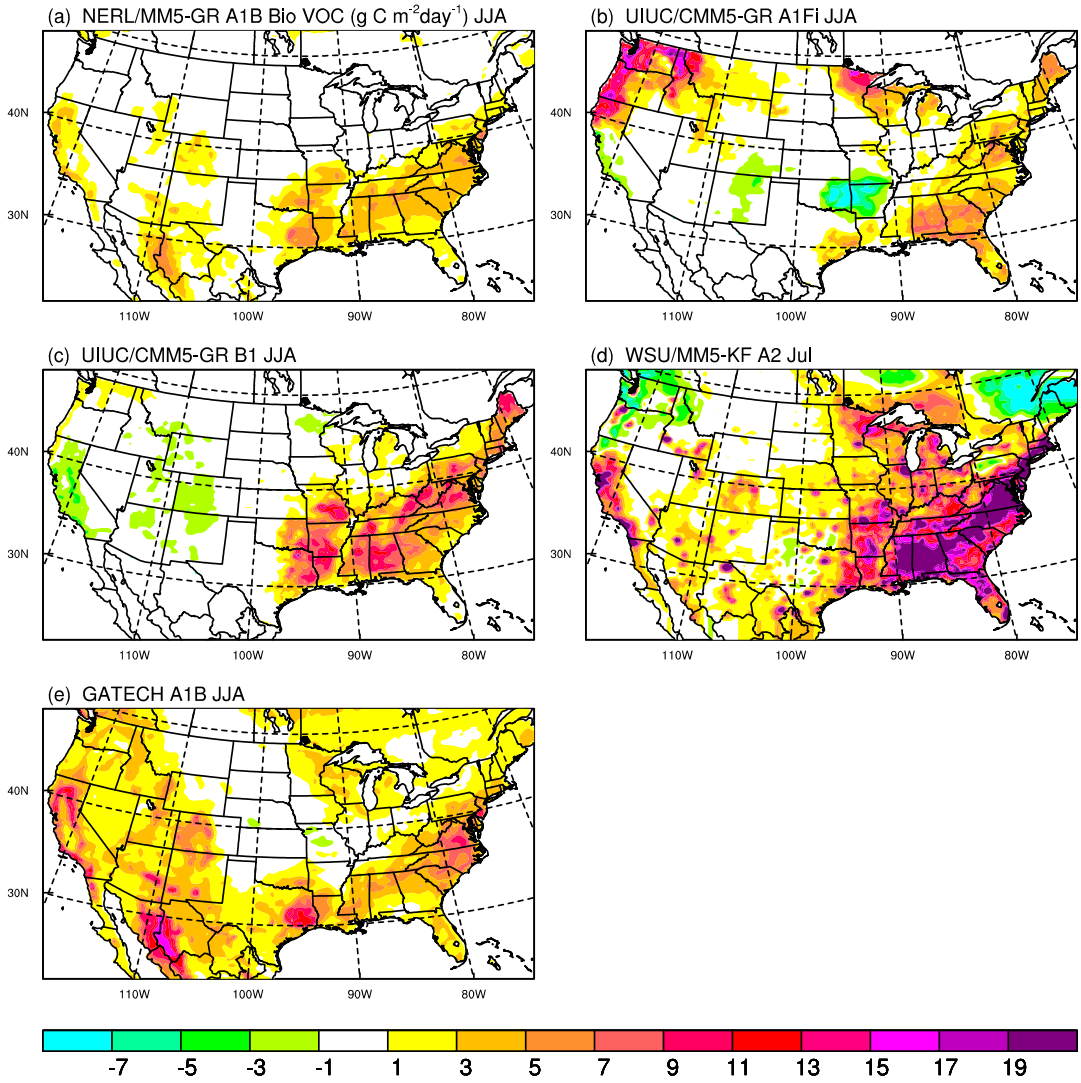


Figure 3-8. 2050s-minus-present differences in simulated summer mean biogenic VOC emissions (g Carbon m^{-2} day^{-1}) for the (a) NERL; (b) Illinois 1; (c) Illinois 2; (d) WSU; and (e) GNM experiments.

the Southeast in the Illinois 1 experiment. Contrastingly, in parts of the Southeast and Mountain West in the NERL and GNM experiments, emissions increase significantly but O_3 concentrations do not change. Notably, the WSU simulation shows large decreases in O_3 in some of the parts of the Southeast and Gulf Coast where increases in VOC emissions are the strongest, a result that is partially attributed to increases in precipitation, and hence reduced photo-production. Where there are strong correlations between biogenic emissions changes and O_3 concentration changes, often there are similarly strong changes in insolation and/or temperature, so separating the different effects is not always straightforward. The earlier work by Hogrefe et al. (2004b) found

the strongest increases in emissions in the Southeast, similar to the results from the NERL and Illinois 1 and 2 experiments, but found that the largest O_3 concentration changes that could be attributed to biogenic emissions changes occurred instead in parts of the Ohio Valley and coastal Mid-Atlantic.

Discerning the precise chemical pathways whereby O_3 responds to changes in biogenic emissions, and how they vary as a function of region and climatic conditions, is an area of ongoing scientific inquiry. Different air quality models employ different representations of these pathways in their code. As such, differences between the simulated O_3 response to changes in simulated biogenic emissions from different modeling systems is at this time a key source of uncertainty in climate change impacts on future air quality, particularly in certain regions where the effect of increasing VOC concentrations is highly dependent on NO_x levels. This issue will be highlighted further in Section 3.3.2 below, in the intercomparison of the results from the global modeling experiments.

One way to summarize the aggregate results presented in Figures 3-1 and 3-6 to 3-8 is to say that O_3 responds to the meteorological/emissions drivers in a qualitatively consistent manner across the simulations, but the regional patterns of relative changes in these drivers is highly variable across these same simulations.

In other words, there are important differences in the simulated future regional climate changes across groups that seem to drive the differences in the regional patterns of O_3 increases (and decreases). The differences in modeling systems among the groups, as documented in Table 3-1, provide some indication of a number of possible contributing factors that might be responsible for these differences in simulated future regional climate patterns, including

- Differences in the driving GCM
- Differences in the SRES greenhouse gas scenario
- Differences in the RCM (and/or model physical parameterizations) used to simulate regional meteorology
- Differences in the RAQM (and/or chemical mechanisms)
- Differences in the amount of interannual variability captured

These issues of inter-group differences, and the sensitivity of simulation results to modeling methodology, are discussed in greater detail in Section 3.4 below, to provide additional guidance on interpreting the findings and evaluating their robustness in the context of the existing scientific uncertainties.

The findings presented here, in Sections 3.3.1.2 and 3.3.1.3, are generally consistent with the limited number of regional climate and air quality modeling experiments recently carried out for Europe. For example, Forkel and Knoche (2006) simulated changes in near-surface O_3 concentrations between the 1990s and the 2030s over Southern Germany under climate change but no change in anthropogenic emissions. They found a 10 percent increase in average daily maximum O_3 during summer (approximately 2−6 ppb, depending on location in the model domain). Langner et al. (2005), in a set of regional modeling experiments, found climate change-induced increases in April-September O_3 concentrations during the mid-21st century compared to the present over Southern and Central Europe, with decreases over Northern Europe, and that these changes were significant with respect to interannual variability. Meleux et al. (2007) found higher summertime O_3 concentrations under future climate conditions over Europe, due primarily to increased temperatures, decreased cloudiness and precipitation, and increases in biogenic VOC emissions. They also found large regional variability in these O_3 changes. Finally, Szopa and Hauglustaine (2007) found worsening O_3 conditions over Europe as a result of anticipated climate change in 2030, though this was sensitive to the choice of global and regional emissions change scenarios.

3.3.2 Global Modeling Results

Table 3-2 lists the groups that have results from GCTM simulations available at the time of developing this report.

Table 3-2. GCTM-only model simulations whose results are discussed in Section 3.3.2. CMU stands for Carnegie Mellon University. The two Harvard runs use different GCMs with the same SRES greenhouse gas scenario. The two Illinois runs have identical setups but are driven with different SRES scenarios. As with the regional modeling system results discussed above, anthropogenic emissions of precursor pollutants were held constant across present-day and future simulations, while natural climate-sensitive emissions were allowed to change.

	Harvard 1[a]	Harvard 2[b]	CMU[c]	Illinois 1[d]	Illinois 2[d]
Simulation Period	5 summer/falls	5 summers	10 summers/falls	5 summers	5 summers
GCM	GISS III	GISS II′	GISS II′	PCM	PCM
Resolution	4° × 5°	4° × 5°	4° × 5°	2.8° × 2.8°	2.8° × 2.8°
GHG Scenario	A1b	A1b	A2	A1Fi	B1
GCTM	GEOS-Chem	GISS II′ [e]	GISS II′ [e]	MOZART v.4	MOZART v.4

Chemical Mechanism	GEOS-Chem[f]	Harvard Trop Chem Model[g]	Harvard Trop Chem Model	MOZART v.4[h]	MOZART v.4
Climate Sensitive Emissions	BVOCs; Lightning and soil NO_x	BVOCs; Lightning and soil NO_x	BVOCs; Lightning and soil NO_x	BVOCs; Lightning and soil NO_x	BVOCs; Lightning and soil NO_x

[a]For more details, see Wu et al. (2007); Wu et al. (2008a; 2008b)
[b]For more details, see Mickley et al. (2004)
[c]For more details, see Racherla and Adams (2006; 2008)
[d]For more details, see Tao et al. (2007); Lin et al. (2008); Huang et al. (2008)
[e]The GISS II′ model was coupled to the Harvard tropospheric O_3-NO_x-hydrocarbon chemical model (Mickley et al., 1999)
[f]For more details, see http://homepages.see.leeds.ac.uk/~lecmje/GEOS-CHEM/GEOS-CHEM_Chemistry.htm.
[g]For more details, see Mickley et al. (1999)
[h]For more details, see Horowitz et al. (2003) and http://gctm.acd.ucar.edu/mozart/models/m4/index.shtml.

All of these GCM/GCTM simulations are also associated with regional downscaling and air quality modeling efforts. The Illinois GCM/GCTM runs are the same ones used to provide climatic and chemical boundary conditions for the Illinois 1 and 2 regional simulations listed in Table 3-1 and described above (see also Lin et al., 2008), and the Harvard 2 run is the same one used to drive the NERL regional simulations (see also Mickley et al., 2004). The Harvard 1 and CMU simulations will similarly eventually be used to drive RCM and RAQM models—these groups have developed and tested full global-to-regional systems, with results expected in the near future. Here, a somewhat more limited inter-group comparison than for the regional modeling results is presented, with the goal of illustrating a few specific points.

In a global context, the results from these simulations are generally consistent with other GCTM climate change experiments (e.g., see Murazaki and Hess, 2006; Stevenson et al., 2006; Zeng et al., 2008): e.g., decreases in background O_3 concentrations in clean environments (e.g., the oceans), due to increased water vapor concentrations, and increases regionally over the polluted continents.

A comparison of results across all of these simulations for the United States in particular (not shown) supports the most general conclusions from the regional modeling studies: i.e., large regions of the country show future O_3 concentration increases of a few to several ppb, and there can be significant differences in the spatial patterns of these changes between different modeling experiments. The purpose of this sub-section is to highlight a comparison between two of these simulation sets—Harvard 1 (see also Wu et al., 2008a) and CMU (see also Racherla and Adams, 2006)—because these results illustrate particularly well two critical insights: the potential importance for simulated future O_3 of large-scale circulation changes, and the potential importance of how isoprene chemistry is represented in the modeling systems.

Figure 3-9 shows the mean MDA8 O_3 changes from the Harvard 1 experiment, along with accompanying changes in temperature, insolation, and biogenic emissions. In these results, the largest O_3 increases are mostly in a sweeping pattern from the central United States, across the Plains states and the Midwest, and extending into the Northeast. In contrast to the regional model results shown above, there is not as obvious a spatial correlation between the changes in O_3 and those of any one of the driver variables. The insolation increase in the Midwest matches, to some degree, the pattern of O_3 increase there, but the largest temperature, insolation, and biogenic emissions increases occur in the southern part of the country, where there are much smaller changes in O_3. This weak relationship also holds for a number of other variables considered but not shown (e.g., precipitation, PBL height, etc.).

In Figure 3-10, which shows the same quantities for the CMU experiment, a different regional pattern of change emerges. Here, the major increases in future O_3 concentrations are instead centered on the Gulf Coast and eastern seaboard, with minimal O_3 changes in the upper Midwest and northern Plains states.

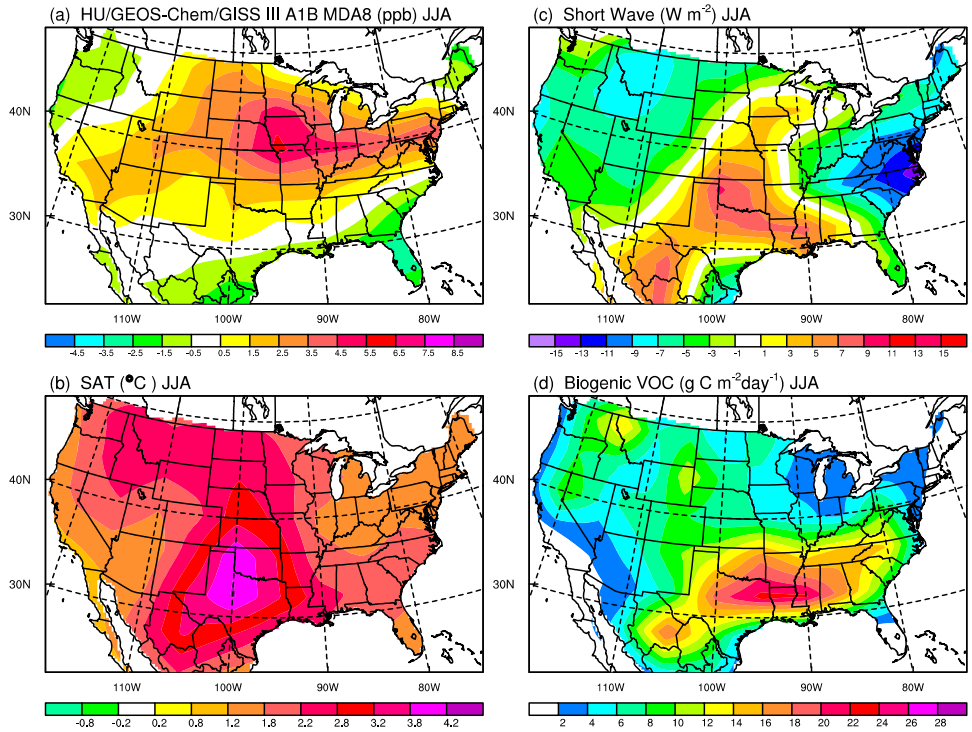


Figure 3-9. 2050s-minus-present differences in simulated summer (JJA) mean (a) MDA8 O_3 concentration (ppb); (b) near-surface air temperature (°C); (c) surface insolation (W m^{-2}); and (d) biogenic isoprene emissions (g Carbon m^{-2} day^{-1}) for the Harvard global modeling experiment (see Table 3-2).

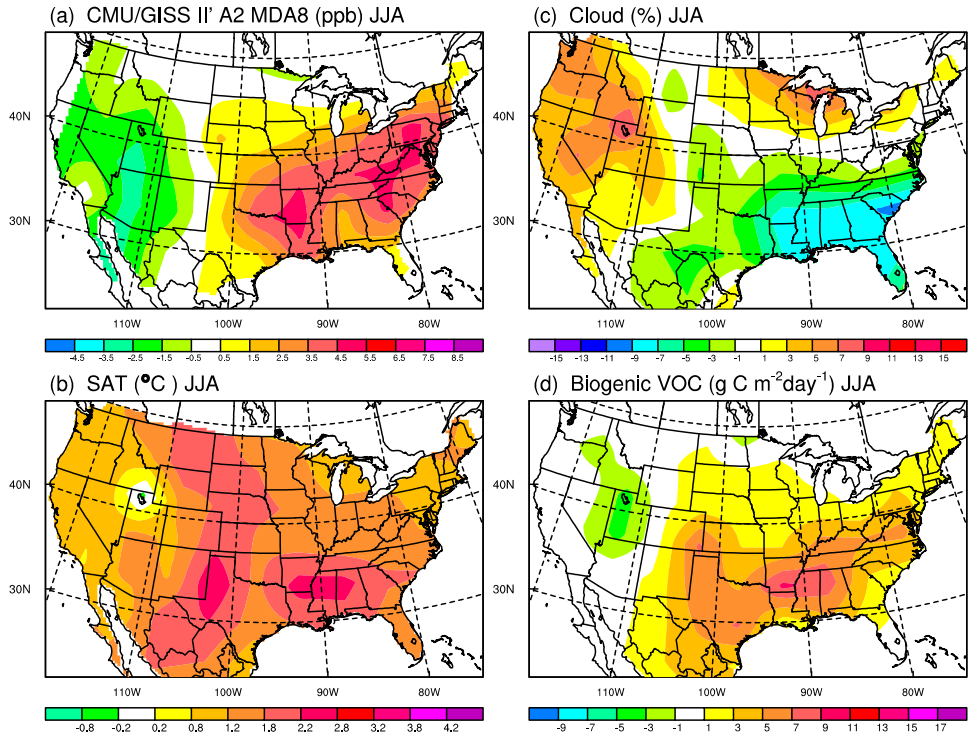


Figure 3-10. Same as Figure 3-9 but for the CMU global modeling experiment.

The differences between these two sets of results can seemingly mostly be explained by two factors: (1) differences in the future simulation of the summertime storm track across the northern part of the country and (2) differences in the response of O_3 to changes in biogenic VOC emissions in the southeastern United States.

As explained in Wu et al. (2008a), there are two distinct dynamical shifts from the present to the future climate in the Harvard 1 experiment: a decrease in summertime cyclones tracking across the upper part of the United States, resulting in a decrease in cloudiness and precipitation over the upper Midwest (as reflected in the insolation changes shown in Figure 3-9), and a northward shift of the Bermuda High, resulting in a decrease in convective activity over the Gulf Coast and the southern Great Plains. All other factors being equal, both shifts might be expected to contribute to O_3 concentration increases in their respective regions.

In this context, the spatial pattern of O_3 concentration increases in Figure 3-9a is certainly consistent with the decrease in cyclones in the north in the Harvard 1 experiment, as suggested in Wu et al. (2008a) and originally posited in Mickley et al. (2004), i.e., that the decrease in cold surges in the simulated future climate leads to a decrease in the clearing of pollutants from the

boundary layer (see also Murazaki and Hess, 2006). Racherla and Adams (2008), on the other hand, examined the distribution of sea-level pressure anomalies in the present-day and future CMU simulations and found only relatively small changes in these regions. These results suggest that storm track activity does not decrease in the future in this CMU model simulation, but a more detailed analysis of the storm tracks in this model may be needed (Leibensperger et al., 2008).

Acknowledging this qualification, it seems plausible that differences in simulated future large-scale circulation patterns explain the differences in future O_3 changes simulated by the two groups for the northern part of the country. What is the explanation for the even larger difference in simulated future O_3 changes in the southern half?

The difference in simulated future O_3 changes in the southern half of the country likely arises because of differences in how O_3 responds to the climate-induced changes in biogenic VOC emissions in modeling systems used in the Harvard 1 and CMU experiments. The spatial patterns of future-minus-present changes in isoprene emissions shown in Figures 3-9d and 3-10d are qualitatively similar, with the largest increases centered on the Southeast and Gulf Coast regions for both groups. Examining the CMU results in Figure 3-10, it appears that increases in temperature and decreases in cloud cover (and hence increases in insolation) have combined to lead to increases in both isoprene emissions and O_3 concentrations in this region. An additional CMU simulation with future meteorology but scaled-back isoprene emissions has confirmed that the enhanced O_3 chemical production resulting from these enhanced emissions are largely responsible for the simulated future O_3 increases (Racherla and Adams, 2008).

Contrast this with the Harvard 1 results, which show only weak changes in O_3 concentrations over the Southeast and Gulf Coast, in spite of the large increase in future biogenic VOC emissions. Even the especially large increases in temperature and insolation that accompany these biogenic emissions changes in the Gulf Coast region do not seem to increase appreciably future O_3 concentrations.

One factor to which this striking difference between the two sets of results might be traced is the modeled isoprene nitrate chemistry. While increased emissions of biogenic VOCs are often associated with increases in O_3 concentrations, these increased emissions can also lead to decreases in O_3 concentrations via different pathways. For example, high concentrations of isoprene can reduce O_3 amounts through direct ozonolysis and can also suppress O_3 production in NOx-limited regimes (e.g., rural areas) by sequestering NO_x in isoprene nitrates (e.g., see Fiore et al., 2005). In the modeling system used for the Harvard 1 simulations, it is plausible that increasing isoprene emissions results in little change, or even decreases in O_3 amounts, largely because the model chemistry represents these isoprene nitrates as a “terminal” sink for NO_x. In the absence of additional NO_x, the small change in O_3 concentrations in the Gulf Coast, in spite

of the strongly favorable climate changes there, could be explained by this suppressing effect of isoprene. By contrast, in the CMU modeling system, the isoprene nitrates are assumed to react rapidly with OH and O_3 and "recycle" NO_x back to the atmosphere with 100% efficiency. This NO_x then becomes available to help create O_3 again, tending to favor greater O_3 concentrations in regions of greater biogenic VOC emissions, and dominating the impact of climate change on O_3 in the CMU results.

This comparison strongly illustrates the importance of understanding the underlying details of the chemical mechanism of O_3 formation. Constraining the precise pathways whereby isoprene, NO_x, and O_3 are linked is the subject of ongoing research (e.g., see Horowitz et al., 2007), and as such remains an important source of uncertainty in the modeling systems. However, there are a number of other important uncertainties associated with the choice of chemical mechanisms, as will be discussed further in Section 3.4.

Finally, in the Harvard 1 simulations, enhanced ventilation and mixing also plays a role in partially offsetting expected climate-induced O_3 concentration increases in some near-coastal regions. This results from the combination of the humidity-driven decreases in O_3 over the oceans reported in Wu et al. (2008b) (and also Racherla and Adams, 2006), and perhaps also stronger onshore flow due to an increase in the summertime land-ocean heating contrast. Lin et al. (2008) report similar effects in their simulations of future O_3 over United States and China.

Before concluding with a summary of the synthesis points that have emerged, the following sub-section provides some additional discussion of outstanding issues related to modeling the linked climate-air quality system and the complexities and scientific uncertainties inherent therein.

3.4 CHALLENGES AND LIMITATIONS OF THE MODEL-BASED APPROACH

All of the results shown in this section are model-based. This emphasis on model studies has been built, from the beginning, into the framework and implementation of the assessment. This sub-section spends some time outlining the challenges, limitations, and areas of uncertainty associated with this model-based approach to provide context for a meaningful interpretation of this synthesis. This discussion helps delineate areas of needed future research to build on our understanding of the climate change-air quality problem, and it aims to convey how the findings presented above might be sensitive to the various modeling uncertainties.

The central concern of this section is the use of linked systems of global and regional climate and air quality models to investigate potential future changes in O_3 that may occur due to climate change. These complex modeling systems are extremely valuable scientific tools, as they allow for the exploration of nonlinearities, feedbacks, threshold effects, and in general surprising behaviors that only emerge when the various components are linked together. They

also, to a degree, encapsulate current scientific understanding of how a wide range of chemical, physical, and dynamical processes interact with each other; i.e., they provide a useful snapshot of the state of the science.

Because of the complexity of the system they mean to mirror, however, at any moment they necessarily embody only an incomplete representation. This results from technical challenges, such as limitations on computing power, as well as from a fundamental lack of understanding of certain processes.

Furthermore, different versions of these modeling systems, for example as developed by different groups, will sample different parts of the space of possible representations. The current assessment effort shows the distribution of results across multiple groups and linked modeling system. Therefore, it is possible to consider different combinations over a range of models, scenarios, and parameterizations, as summarized in Tables 3-1 and 3-2. It is also important to emphasize, however, that, because of the enormous computational burden of these modeling systems as applied to this problem, at this point it is only a very small subset of the available range that has been sampled here (e.g., a few GCMs and SRES scenarios, essentially one RCM, three regional model convection schemes, etc.). Expanding the scope to include additional models, scenarios, and parameterizations, along with multiple combinations of each, might further broaden the distribution of projected regional O_3 changes. Alternatively, such new results might reinforce previous findings.

Therefore, any synthesis conclusions are subject to revisions pending results from future investigations. However, this preliminary synthesis makes it possible to identify some of the key modeling-related sensitivities that are likely to determine our ability to accurately simulate climate change-driven O_3 changes, as summarized in the following questions:

- What kinds of differences do different GCMs (under different greenhouse gas emissions scenarios) simulate in the climate, and especially in the weather patterns that matter most for air quality?
- How do RCMs translate these climate and meteorological changes down to the regional scales that are desired?
- How are important chemical mechanisms represented in the climate-air quality modeling systems?

3.4.1 Inter-Model Variability and Model Evaluation

The IPCC AR4 (IPCC, 2007) summarizes current understanding of variations in future global climate simulations. The spread across models, groups, and scenarios is the result of differences in exogenous forcings, like natural volcanic or solar changes or changes in

anthropogenic emissions of greenhouse gases and aerosols. This spread also results from internal model variability and nonlinear behavior that reflect the inherently chaotic nature of the atmospheric and oceanic circulations. Finally, it arises from model configuration differences due to different choices for dealing with resolution constraints, numerical approximations, and lack of perfect understanding of processes or perfect observations of key parameters. The impact of these factors is reflected in the range of average climates, and regional spatial distributions of climate characteristics, simulated by the different GCMs that are featured here.

The significance of these inter-model/scenario differences varies depending on the lens provided by the particular problem of interest. For air quality in general, and O_3 specifically, a critical question is "What kind of changes do models simulate in the weather patterns that matter most for air quality?" The results shown in Figures 3-9 and 3-10 illustrate some of the uncertainties associated with this question. Physical and dynamical arguments suggest that future decreases in the equator-to-pole temperature gradient should drive poleward shifts in the mid-latitude storm tracks, and that this may lead to decreases in the frequency of cyclone ventilation of pollutants in the Northeast and Midwest. The results from the Harvard 1 experiment show this clearly, while those from the CMU experiment do not seem to. Taking a broader perspective across many models and groups, the IPCC AR4 states

> Central and northern regions of North America are under the influence of mid-latitude cyclones. Projections by AOGCMs [Atmosphere-Ocean Global Circulation Models] generally indicate a slight poleward shift in storm tracks, an increase in the number of strong cyclones but a reduction in medium-strength cyclones over Canada and poleward of 70°N (IPCC, 2007).

However, the agreement across groups is by no means absolute. Furthermore, the IPCC report states

> Results from a systematic analysis of AMIP-2 simulations (Hodges, 2004; Stratton and Pope, 2004) indicate that models run with observed SSTs are capable of producing storm tracks located in about the right locations, but nearly all show some deficiency in the distribution and level of cyclone activity (IPCC, 2007).

Recent increases in model resolution and other improvements have led to improvements in simulations of present-day storm tracks, and may eventually lead to a stronger consensus on the likely magnitude and direction of future climate-induced changes over the United States. At this time, however, current levels of uncertainty probably do not allow us to say much more than (1) the number and intensity of summertime cyclones passing over the northern United States is

a key factor in determining air quality there and (2) the occurrence of fewer and weaker cyclones is a plausible consequence of global climate change.

This discussion about cyclones suggests a broader question: how should the scientific community evaluate the performance of these modeling systems for the task at hand? It is not possible to answer this question comprehensively here, but it is possible to place some general issues with which the climate modeling community continuously struggles in the context of the specific problem of climate change impacts on air quality.

First, all groups carry out evaluations of their modeling systems compared to historical observations. The key is to conduct these evaluations for the variables, and statistics of those variables, that are most relevant for the problem of interest. As discussed in various places in this report, "air quality," from a health, environmental, and regulatory perspective in the United States, has been largely determined by episodes that occur during specific, sporadic weather events. Therefore, what is most important to know is how well available modeling tools simulate these events and how well they can predict future changes. At present, however, the focus of the climate modeling community is still largely on long-term mean values of variables like temperature, precipitation, and cloud cover. These quantities can be important in situ drivers of air quality on short timescales, but more effort is needed to understand how changes in atmospheric flow patterns are reflected in the changes in these long-term means. There is a need to address questions like "Did a simulated temperature change in a given region result from an across-the-board change in baseline temperature during all weather regimes, or instead from a change in the frequency of occurrence of one particular weather pattern (e.g., the afternoon sea breeze, synoptic-scale anticyclones, or mesoscale convective systems)?" Climatological averages of variables like temperature will only have explanatory power for air quality to the extent that they reflect the changes in the most relevant circulation patterns, as opposed to being obscured by "noise" that is less related to air quality (e.g., increases in nighttime average temperature).

The current situation reflects the relatively youthful state of coupled climate and air quality science. The application of climate models to air quality represents a significant challenge for the climate modeling community. One path forward is to make it standard practice to conduct in-depth evaluations of global and regional climate models for additional variables and metrics more relevant for air quality. As Gustafson and Leung (2007) state,

> Our ability to address these questions relies critically on the ability of climate models in simulating the meteorological conditions needed to realistically simulate air quality. Because of the nonlinear nature of atmospheric chemistry and its dependence on difficult to model variables, such as precipitation and the planetary boundary layer (PBL) height, biases in variables considered acceptable

> for other downscaling applications may not be appropriate for this new application. An additional challenge in air quality assessment is the required knowledge of the three dimensional structures of the atmosphere, which are not needed for most other assessments.

New efforts carried out under the auspices of this assessment, as summarized in Leung and Gustafson (2005), Gilliam et al. (2006), and Gustafson and Leung (2007) represent significant advances in this area and provide useful insights moving forward.

Second, it is important to remember that, for the problem under consideration here, accurately reproducing present-day conditions is not interesting in and of itself, but is interesting for what it might imply for simulating and understanding future changes. The connection between the two is not necessarily straightforward. Again from the IPCC AR4: "What does the accuracy of a climate model's simulation of past or contemporary climate say about the accuracy of its projections of climate change? This question is just beginning to be addressed…" (IPCC, 2007: Ch. 8).

Given a particular variable, and statistic of that variable, to be evaluated, there are two sources of error in any future-minus-present comparison: the bias in the present-day simulation, and some (hypothetical) bias in simulating the future conditions. The modeling community typically makes two implicit assumptions about these sources, but these assumptions are potentially contradictory. First, there is the assumption that these two errors are correlated, i.e., the better the modeling system is at reproducing present-day observations, the better it will be at reproducing future climate shifts. This could lead logically to the conclusion that a model system that does a poor job of simulating the present will likely be even worse at getting the "correct" future-minus-present changes. However, it is often simultaneously asserted that looking at differences between simulated future and present results will yield accurate insights, i.e., that the biases should be similar in the present and future simulations and thus will cancel. Barring improbable coincidences, these two assumptions can only be reconciled if a third assumption also holds: namely, that most of the biases in the present-day simulation come from error sources that will not impact the model's ability to capture the future changes, i.e., the present-day biases will simply be carried along to the future. The validity of this assumption for a highly nonlinear system like climate must be tested. Again, research carried out for this assessment is contributing to this need. For example, Liang et al. (2008) showed how GCM (and downscaled RCM) biases with respect to historical observations are consistently propagated into future simulations, empirically linking the ability of a modeling system to accurately reproduce present-day climate to the types of future climate changes it predicts.

3.4.2 The Role of Downscaling

As described in Section 2, this assessment has been built, in part, around dynamical downscaling, i.e., the use of an RCM to derive higher-resolution meteorology from a GCM simulation for a particular sub-region of the globe. This is in recognition of the dual need to be regionally explicit, so as to connect more closely with the priorities of policy makers, while at the same time capturing the inherently global scale of the climate drivers. As noted, this is really the first systematic attempt to apply these techniques to air quality impacts work, and valuable lessons are being learned.

The fundamental task of dynamical downscaling is to maximize the "value retained" from the GCM and the "value added" by the RCM. In other words, successful downscaling will take advantage of the things the RCM does well in simulating weather and climate, by virtue of its high resolution, without sacrificing too much of what the GCM does well, by virtue of its global extent. From the results presented above, it is clear that changes in both large-scale circulation patterns and local-scale forcings are crucial drivers of O_3 changes. A given modeling system will be able to accurately simulate changes in O_3 only to the extent that it can accurately capture both.

Because of its higher resolution, the RCM develops small-scale features that the GCM cannot. These features develop for three primary reasons (see, e.g., Denis et al., 2002):

- finer-scale representations of surface characteristics, like topography, water bodies, vegetation, soil moisture, and land use, that lead to local-scale circulation systems like sea and lake breezes and mountain-valley flows;
- nonlinearities in the fluid dynamics equations that lead to the development of fronts and other mesoscale features;
- hydrodynamic instabilities arising from shear or buoyancy forcing that create turbulent eddies and convection and are more accurately represented with higher resolution.

RCMs therefore add the most value by more accurately simulating near-surface meteorological fields, as well as extreme conditions (e.g., cyclone low pressure, intense precipitation, high winds). These advantages make it possible to significantly improve on regional biases in temperature and precipitation present in GCM simulations (e.g., see Liang et al., 2006), and these improvements can lead directly to improved simulations of O_3.

RCM performance is highly sensitive, however, to the physical parameterizations used, as already summarized above. For example, Liang et al. (2006; 2004a,b) and Lynn et al. (2004; 2007) found strong sensitivities of temperature and precipitation to the convection scheme chosen. These meteorological sensitivities drive corresponding sensitivities in simulated air

quality (e.g., Kunkel et al., 2007; Tao et al., 2008). In addition, sensitivities of air quality to PBL, radiation, microphysics, and land-surface schemes may also be important, but these have yet to be examined as systematically in this assessment.

Along with the physical parameterizations, the other major sensitivity of the RCM is the application of the large-scale boundary conditions from the GCM, i.e., the actual "implementation" of the dynamical downscaling that links the GCM with the RCM. By itself, an RCM cannot simulate the large-scale circulation of the atmosphere because the drivers are planetary in scale (e.g., the difference in net radiation between equator and poles), necessitating a global domain. So, for example, an RCM cannot generate dynamical systems like the mid-latitude storm tracks, which instead must be supplied by a GCM. It is in the context of this GCM-provided large-scale circulation that the smaller-scale features described above evolve. This leads to the basic question of dynamical downscaling: how best to close the system? In other words, what is the optimal method for importing information from the GCM into the RCM so as to preserve any desired features of the large-scale circulation patterns without compromising the ability of the RCM to develop realistic smaller scales?

The most common practice has been to assimilate the GCM fields into a narrow strip at the lateral boundaries of the RCM domain. This technique is commonly referred to as "lateral nudging," and follows Davies (1976). Everywhere else in the domain, the RCM develops its own solution, which it is hoped will evolve consistently within the envelope defined by the GCM flow at the boundaries. This approach is widely used and has yielded valuable results in a number of different applications across the field of regional climate modeling. It is the approach that is used in all the downscaling work contributing to this report. The major perceived advantage of this approach is that it allows for the possibility of the RCM correcting biases not only in the relatively fine-scale, near-surface temperature, and precipitation features, but also in continental-scale circulation patterns. For example, Gustafson and Leung (2007) illustrate how a better representation of the Rockies leads to improvements in the overall flow patterns over the United States when MM5 is used to downscale the GISS II′ GCM simulation.

Recent work (see Rockel et al., 2008; Miguez-Macho et al., 2004, 2005; Castro et al., 2005; von Storch et al., 2000), however, suggests that this lateral nudging approach can be problematic and introduce additional biases of its own. Specifically, if the RCM captures the energy of the large-scale flow only through assimilation at its lateral boundaries, two problems can arise. First, the energy of the large-scale circulation can be progressively lost as a result of several factors as it makes its way into the domain from the RCM boundaries. This lost energy cannot be re-supplied by the RCM, since, as already noted, the drivers are planetary in scale. A potential consequence, then, is weaker large-scale circulation features in the RCM compared to the GCM. Second, the large-scale flow field can be modified significantly as it makes its way

across the RCM domain. This can cause problems at the RCM boundaries that, in turn, can introduce artificial flow features back in the main body of the model domain. For example, the jet stream entering the western boundary of the RCM domain will encounter the steeper (because higher-resolution) Rockies and be deflected, so that by the time it reaches the eastern boundary, it will not be consistent with the GCM boundary condition there. Both of these problems are more pronounced with larger RCM domains and coarser RCM resolution.[16]

One method for handling these problems is so-called "spectral nudging," i.e., nudging applied not at the lateral boundaries at all spatial scales, but instead applied at all locations in the RCM domain (above the PBL at least) but only for the longest waves that are resolved in the GCM (see Miguez-Macho et al., 2004 and von Storch et al., 2000 for descriptions of the technique). At this time, whether lateral nudging or spectral nudging is preferable is just becoming an active research question: does one take the large-scale flow field of the GCM as "truth" and force the RCM to conform to it as closely as possible, or does one instead allow the RCM to evolve a more independent circulation? Therefore, the implications for simulating air quality are as yet unclear, since the downscaled simulations carried out to date for this assessment have all used the lateral nudging approach.

Given what we do know at this time about dynamical downscaling, however, the following should be considerations when interpreting the regional air quality results presented in this section:

- The RCM may not faithfully capture important features of the large-scale circulation patterns present in the driving GCM. In particular, the large-scale flow might be too weak in the RCM, leading to a proportionally too-strong influence of more local-scale forcing, like convection. Alternatively, there might be artificial flow features introduced by discrepancies between the RCM and GCM at the boundaries.
- Even if the RCM reproduces the GCM's large-scale circulation very closely, it may still simulate different air quality patterns because of differences in the way it simulates convective clouds and rainfall, or other fine-scale processes, embedded within this large-scale flow.

Either or both of these considerations may help explain why, as mentioned previously, the influence of a shift in the storm track present in the Mickley et al. (2004) GCM experiment does not show up as clearly when this same GCM simulation is downscaled using MM5 (Nolte et al., 2008; Leung and Gustafson, 2005). Precisely attributing these differences between the downscaled results and the driving global simulation remains a key task in the furthering of our

[16] To date, these two potential pitfalls of lateral nudging have mostly been investigated for RCM simulations driven by global reanalysis data and not GCM output, and there may be differences between the two in the impact on the downscaled fields.

understanding of the impacts of global climate change on regional air quality, and it remains the subject of ongoing investigation.

In any case, the strong influence of the GCM-simulated climate on the downscaled results is inescapable, regardless of the methodological details. Gustafson and Leung (2007) emphasize that the GCM chosen will strongly impact any downstream regional air quality findings. Nolte et al. (2008) show clearly that a large portion of the bias in the NERL group's regional simulations for the eastern United States can be traced directly to an incorrect northeastward displacement of the Bermuda High in the driving GISS II′ GCM simulation. This and similar results, then, underscore again the discussion from above: quantifying the biases and characteristics of the individual global model simulations being relied upon for representing future climate change is of critical importance for the problem of global change impacts on air quality.

3.4.3 Uncertainties in Chemical Mechanisms

The differences in simulated O_3 as a function of isoprene chemistry, as discussed in Section 3.3.2, highlight the importance of the choice of regional air pollution modeling mechanisms in investigating the potential for climate-induced changes in air quality. Differences in simulated O_3 concentrations among modeling studies may be attributed, in part, to differences in the choice of photochemical mechanism. Each mechanism, in turn, will have characteristic uncertainties as well as biases in simulated O_3 concentrations, due to uncertain information about the chemical reactions represented by the model mechanism, and the simplifying assumptions used to optimize computational speed.

For example, Atkinson (2000) listed several sources of scientific uncertainty in air quality photochemical modeling mechanisms. Note that most of these uncertainties relate to the oxidation of biogenic compounds:

- Quantitative knowledge of the rate constants and mechanism of the reactions of organic peroxy (RO_2) radicals with NO, HO_2 radicals, and other RO_2 and NO_3 radicals
- Additional data concerning the organic nitrates yields from the reactions of organic peroxy radicals with NO as a function of temperature and pressure
- Knowledge of reaction rates of alkoxy radicals for decomposition, isomerization and reaction with O_2, especially alkoxy radicals other than those formed from alkanes and alkenes (for example, from hydroxyl-compounds, ethers, glycol ethers, and esters)
- The detailed mechanisms of the reactions of O_3 with alkenes and VOCs containing >C=C< bonds (this involves understanding the reactions of the initially energy-rich biradicals and of the thermalized biradicals formed in these reactions)

- Studies of the thermal decompositions of other atmospherically-important reactions of the higher PANs, including, for example, $CH_2=C(CH_3)C(O)OONO_2$ formed in the atmospheric photo-oxidation of isoprene
- Further understanding of the products and mechanisms of the reactions of monoterpenes and oxygenated VOCs (including 2-methyl-3-buten-2-ol) emitted from vegetation with OH radicals, NO_3 radicals and O_3
- Improved knowledge of the mechanisms and products of the reactions of OH-aromatic adducts with O_2 and NO_2
- An improved understanding of the tropospheric chemistry of many oxygenated VOCs formed as first-generation products of VOC photooxidations, including but not limited to carbonyls (including unsaturated dicarbonyls), di-unsaturated dicarbonyls, and unsaturated epoxy-carbonyls), hydroperoxides, and esters
- A quantitative understanding of the reaction sequences leading to products which gas/particle partition and lead to secondary aerosol formation

Compounding the uncertainties created by incomplete information about the chemical pathways, and their associated rate constants, is the practical necessity for abbreviating the overall chemical reaction scheme to improve the computational speed of the air quality model. A photochemical oxidation mechanism that explicitly treated all of the known atmospheric reactions would have to include more than 20,000 reactions and several thousand organic reactants and products (Dodge, 2000). Reaction schemes like those used by the research teams participating in the EPA assessment program have been streamlined to minimize the number of reaction steps, either by lumping several relevant organic compounds into classes that are given "average" reaction rates, or by ignoring reaction pathways that appear to be unimportant in determining the concentrations of the targeted pollutant. These design choices are made through a process of evaluation against observational data. Mechanisms may also be fine-tuned to produce output that better fits the ambient data by adjusting the reaction rate constants within the laboratory-established experimental uncertainty range. Furthermore, differences exist amongst models in the size of the time steps used for calculating pollutant concentrations. Given the complex, nonlinear, nature of O_3 production, these differences tend to result in differences in predicted O_3 concentrations among models. See also Fine et al. (2003) for additional discussion of many of these issues.

A number of intercomparison studies of photochemical mechanisms have been reported in the air quality literature: e.g., see Russell and Dennis (2000), Jimenez et al. (2003), and Faraji et al. (2008), among many others. For example, Jimenez et al. (2008) compared box model calculations, with identical inputs and boundary conditions, for several state-of-the-art photochemical mechanisms. They found that the calculated average and maximum O_3

concentrations, along with the concentrations for nine related chemical species, varied widely between these mechanisms. Gilliland et al. (2008) evaluated the performance of the CB-IV and SAPRC99 chemical mechanisms in a study of model response to NO_x reductions associated with the implementation of the NO_x SIP Call. They found that CB-IV significantly underestimates the contribution of O_3 (and its precursors) from long-range transport, and it is less successful than the SAPRC99 mechanism at capturing the effects of meteorological changes on O_3 concentrations.

Variability in simulated O_3 concentrations among photochemical mechanisms does not necessarily imply that any one mechanism is incorrect: rather, that each may have been optimized for different local or regional conditions. Given the necessity of simplifying photochemical mechanisms for the sake of computational efficiency, future studies of climate change-induced air quality change might reasonably include photochemical mechanisms that have been tailored to perform best under a range of well defined conditions consistent with the emissions, meteorological, and land-use conditions under consideration.

Additional detailed discussions of both well understood and highly uncertain O_3 photochemistry can be found in the U.S. EPA Air Quality Criteria Document for O_3 (U.S. EPA, 2006).

3.5 SYNTHESIS CONCLUSIONS AND FUTURE RESEARCH NEEDS

This section concludes by collecting and summarizing the major points that have emerged from the scientific synthesis. These help address the goals of this report by addressing questions like "What new findings are emerging from the body of work that EPA has made possible?" and "What have we learned about our ability to simulate potential future changes in U.S. regional air quality due to climate change?" Specifically,

- Across all of the modeling experiments, global and regional, carried out by the different groups, simulated global climate change causes increases in summertime O_3 concentrations over substantial regions of the country. For nearly every region of the country, at least one (usually multiple) of the modeling groups found that climate change caused increases in summertime O_3 concentrations.
- For summertime-mean MDA8 O_3, the increases are in the 2−8 ppb range.
- The largest increases in O_3 concentrations in these simulations occur during peak pollution events. For example, the increases in 95^{th} percentile MDA8 O_3 tend to be significantly greater than those for summertime-mean MDA8 O_3.
- Though in agreement on the above points, the different modeling systems did not necessarily simulate the same regional patterns of climate-induced O_3 changes, with the individual simulations showing some regions of little change, or even decreases, in addition to the O_3 increases.

- These differences in the regional patterns of O_3 changes result from variations across the simulations in the patterns of mean changes in key meteorological drivers, such as temperature and surface insolation. The modeling experiments provide examples of regions where simulated future changes in meteorological variables either have reinforcing or competing effects on O_3 concentrations. Figure 3-11 shows the mean and standard deviation in future-minus-present MDA8 O_3 differences across all seven sets of simulation results displayed in Section 3.3.
- For example, regions where the changes in simulated temperature and insolation are in the same direction tend to experience O_3 concentration changes in a similar direction, while temperature and insolation varying in opposite directions tends to correspond with mixed O_3 changes. Figure 3-12 shows regional averages across MDA8 O_3 concentration differences and the differences in these drivers for the sub-regions shown in Figure 3-13.
- Large-scale circulation patterns play an important role in modifying these local meteorological drivers. For example, how a given modeling system simulates changes in key circulation features, like the mid-latitude storm track or the Bermuda High, has a strong impact on the simulated future O_3 concentrations.
- Other factors to which the patterns in the simulated meteorological variables appear to be highly sensitive include the choice of convection scheme and whether or not the global model outputs are dynamically downscaled with an RCM.
- Certain regions show greater agreement than others. For example, there is very generally more agreement on the spatial patterns of climate-induced increases for the eastern half of the country than for the West, though parts of the Southeast show some of the strongest disagreements across the modeling groups. Even for these regions, however, at least some of the models show substantial climate-induced O_3 increases.
- Across nearly all simulations, climate change is associated with simulated increases in biogenic VOC emissions over most of the United States, with especially pronounced increases in the Southeast.
- These biogenic emissions increases do not necessarily correspond with O_3 concentration increases, however, depending on the region and modeling system.
- One factor in this, as highlighted by the global modeling results, is that the response of O_3 to changes in biogenic emissions may depend sensitively on how isoprene chemistry is represented in the model. Models that recycle isoprene nitrates back to NO_x may tend to simulate greater O_3 concentration increases in regions with biogenic emissions increases than models for which isoprene nitrate is a terminal sink for NO_x.
- Interannual variability plays a critical role in determining seasonal-average O_3 levels in a given year. Some of the modeling groups found that, in some regions of the United States, the average increase in MDA8 O_3 concentrations from the present to the 2050s as a result of climate change was as large as the present-day year-to-year variability. In other words, climate change has the potential to push O_3 concentrations in extreme years beyond the envelope of natural interannual variability.

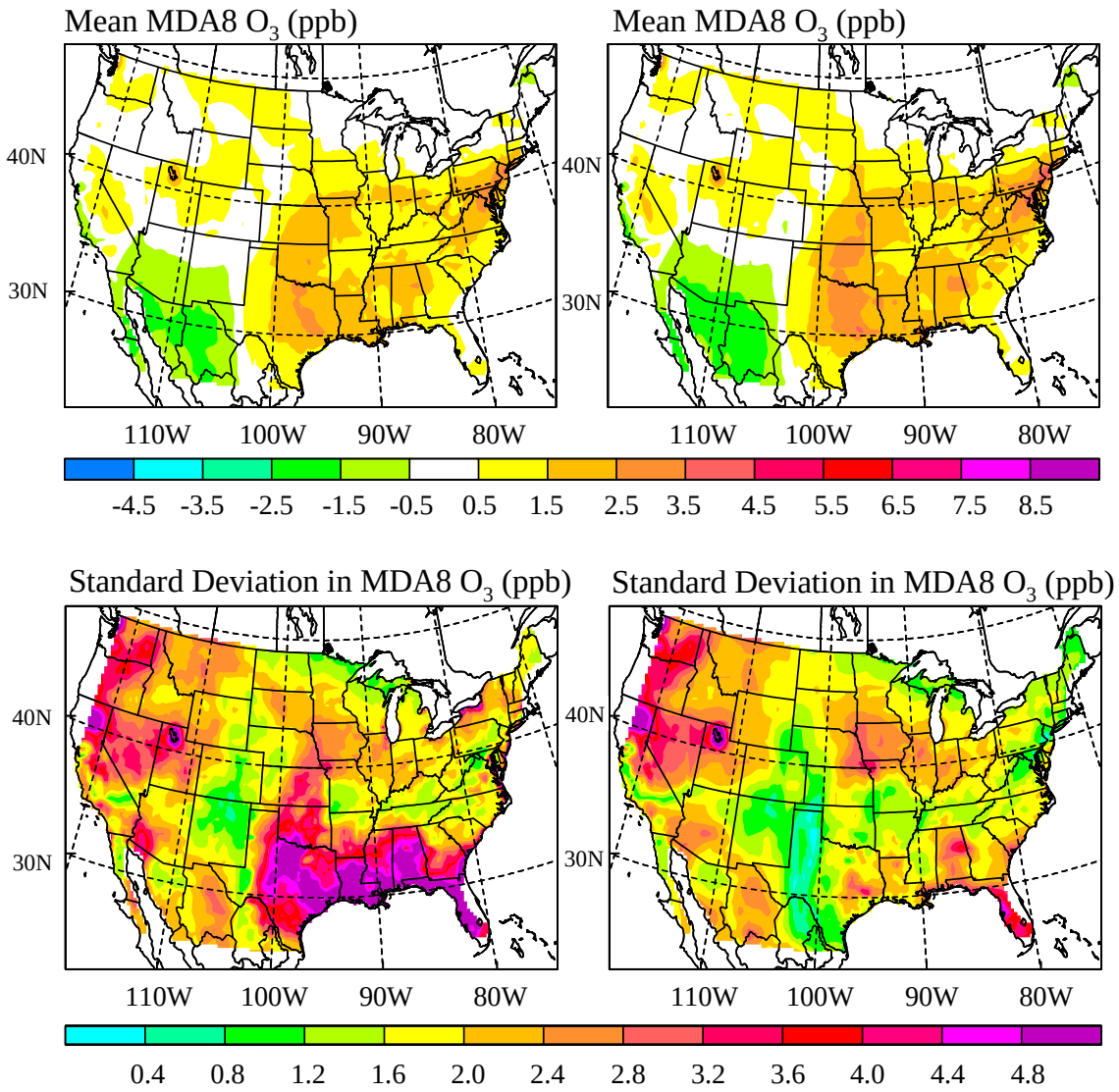


Figure 3-11. The mean (top two panels) and standard deviation (bottom two panels) in future-minus-present MDA8 O_3 concentration differences across (left-hand panels) all seven experiments (five regional and two global) shown in Figures 3-1, 3-9, and 3-10 and, for comparison purposes, (right-hand panels) not including the WSU experiment because it shows differences for July only, while the other experiments show JJA differences.

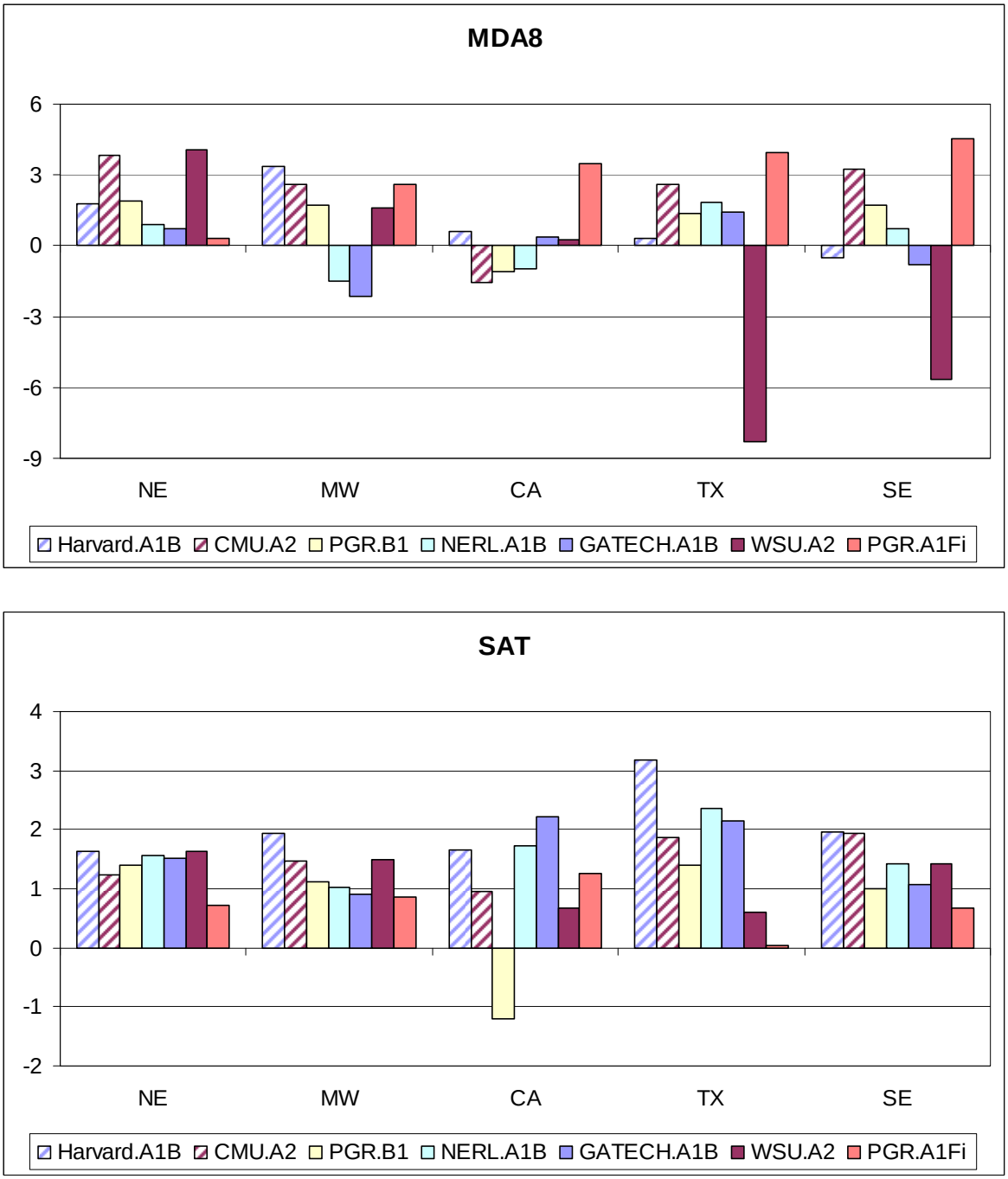
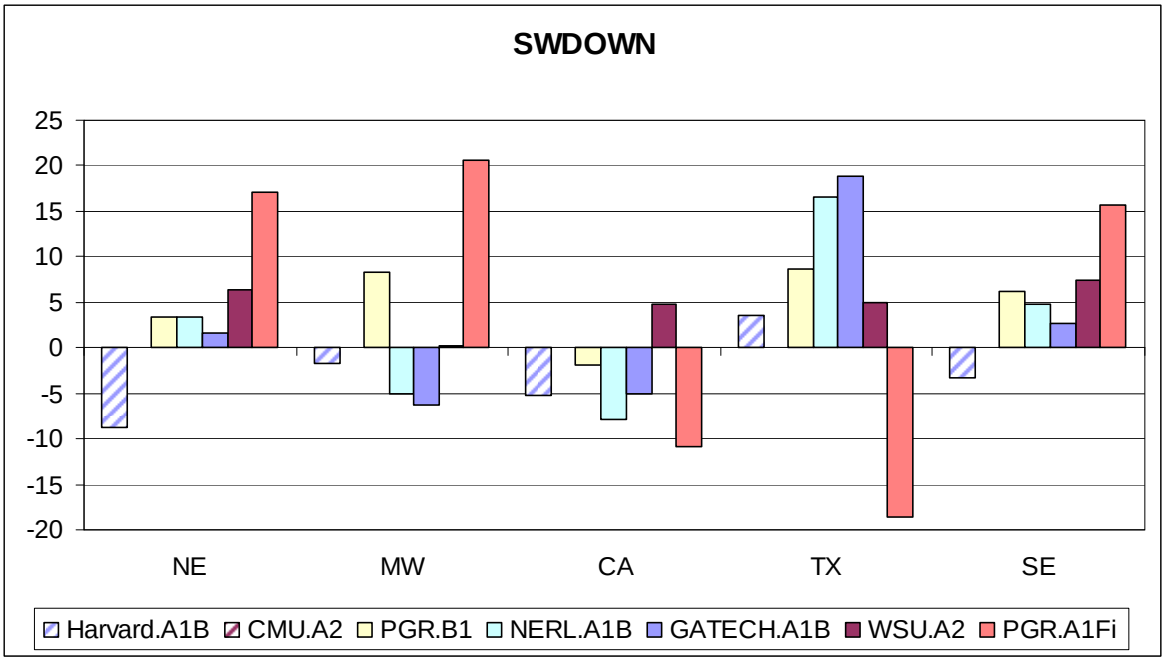


Figure 3-12. Averages across the subregions shown in Figure 3-13 for each of the simulations for (a) mean MDA8 O_3 (ppb); (b) near-surface air temperature (ºC).



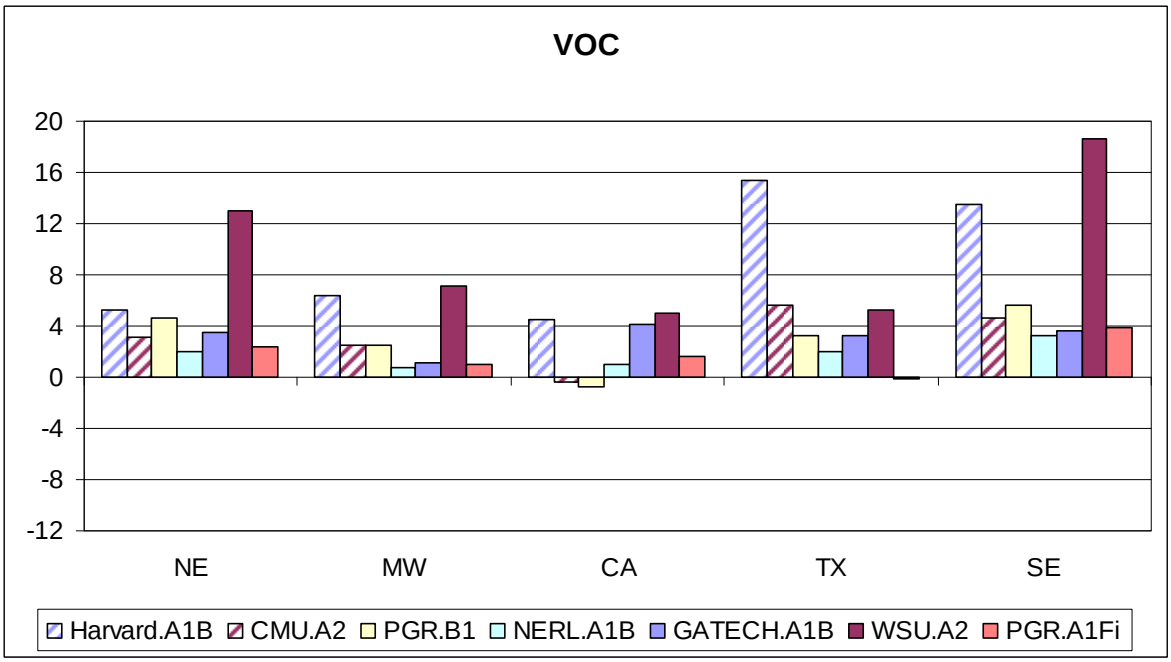


Figure 3-12 continued. Averages across the subregions shown in Figure 3-13 for each of the simulations for (c) surface insolation (W m^{-2}); and (d) biogenic isoprene emissions (g Carbon m^{-2} sec^{-1}).

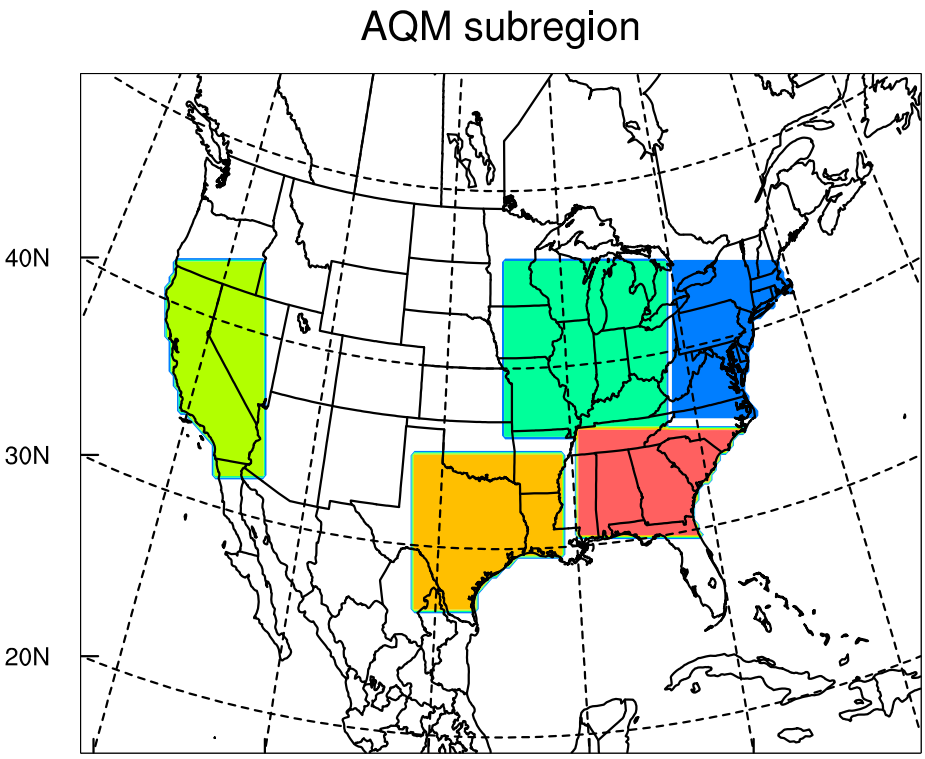


Figure 3-13. The averaging subregions used in Figure 3-12.

- It also highlights the fact that the amount of future-minus-present change in O_3 concentration simulated will likely depend strongly on the choice of present and future simulated years to compare, and that multi-year simulations are desirable for producing findings that are more robust.
- In addition, while this analysis focuses on summertime results, some of the groups also found increases in O_3 concentrations in some regions in the spring and fall, suggesting the possibility of an extension of the O_3 season under climate change.

These findings should be interpreted as speaking to the question, "How does the system work?" rather than the question, "What will happen in the future?" They provide insight into the subtleties and complexities of the interactions between climate, meteorology, and air quality, thereby helping to build intuition about the richness, and range of behaviors, of the climate-air quality system. They also illustrate how valuable the modeling systems developed for this assessment can be for exploring this problem.

This improved system understanding, combined with a clear appreciation of the important uncertainties, opens the doors to a wide range of future applications based on this knowledge and these tools. For example, the results of modeling experiments have the potential