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Title: **Impact of Climate Change on U.S. Air Quality using Multi-scale Modeling with the MM5/SMOKE/CMAQ System**

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Research Category: Research Category: Assessing the Consequences of Global Change for Air Quality: Sensitivity of U.S. Air Quality to Climate Change and Future Global Impacts

Research Objectives

In this project, we developed a modeling program to assess global change impact on US air quality by addressing the following questions: 1) How does global warming affect air quality on regional and urban scales? 2) How does land use change due to increased urbanization, global warming, or intentional management (economic forces) affect air quality? 3) How do fire and fire management affect regional air quality and regional haze in the future? 4) What is the role of Asian emissions on US air quality and how does global change influence the impact of Asian emissions? 5) How sensitive is predicted air quality to globally forced boundary conditions (meteorological and chemical)? 6) How sensitive are air quality simulations to changes in emission scenarios, both biogenic and anthropogenic? 7) How sensitive are air quality simulations to uncertainties associated with wildfire projections and with land management scenarios?

Project Results

A comprehensive numerical modeling framework has been developed to estimate impacts of global change upon regional air pollution, specifically ground level ozone and $PM_{2.5}$, while accounting for regional anthropogenic, biogenic and wild-fire emission variations. The system was applied to simulate two 10-year periods: 1990-1999 as the base-case and 2045-2054 as a future case. The Intergovernmental Panel on Climate Change (IPCC) SRES A2 scenario was applied for the future case with the ‘business as usual’ greenhouse gas and ozone precursor projections. The model system coupled global climate and chemistry models, the NCAR Parallel Climate Model (PCM) and MOZART2, with the regional modeling framework, MM5 and CMAQ (Figure 1), over the continental US domain as indicated in Figure 2.

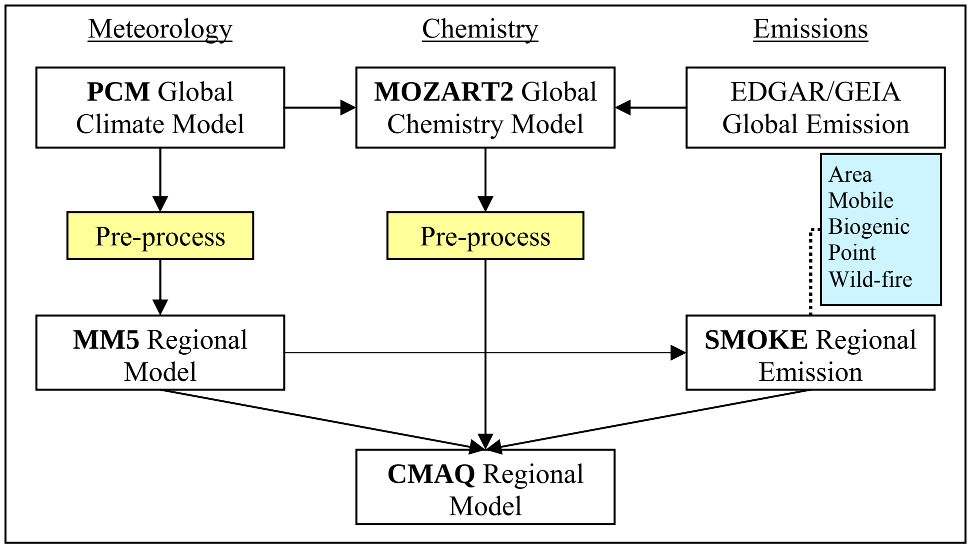


Figure 1. Schematic of the multi-scale modeling framework coupling the large scale global climate and chemistry models with the regional scale meteorology and chemical transport models.

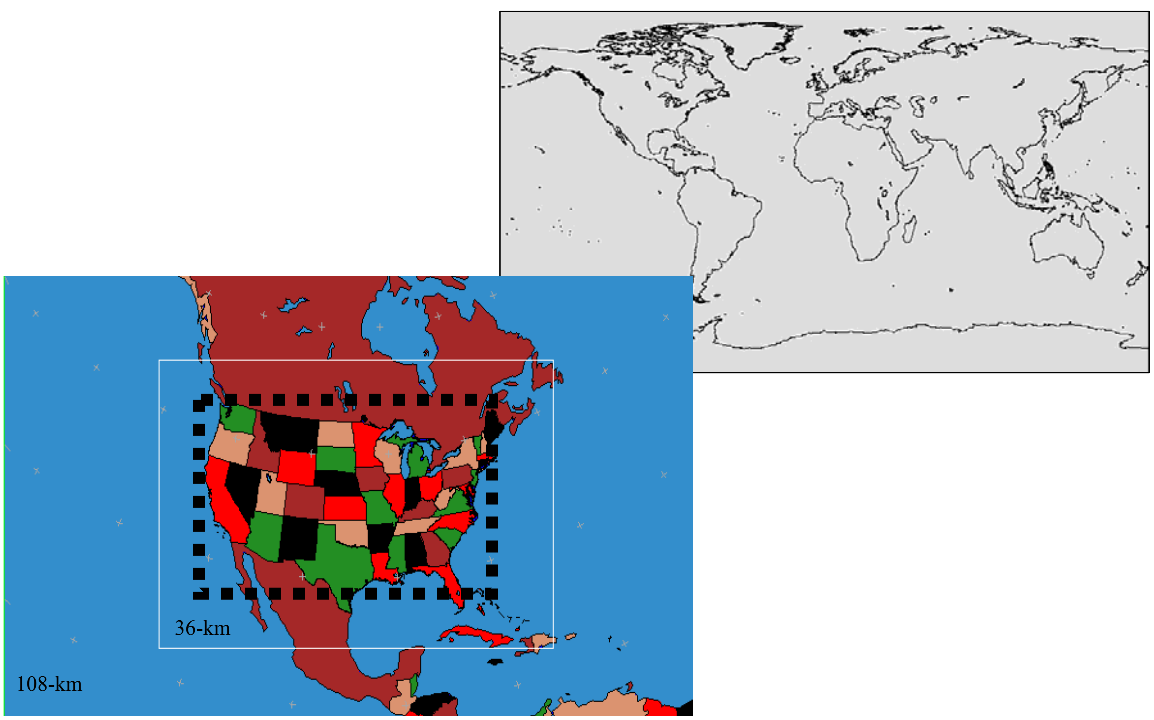


Figure 2. Domains for global models (top) and regional models (bottom). The regional MM5 domains include 108-km parent domain, and 36-km inner nested domain (white line). The regional CMAQ simulation domain is inside the 36-km MM5 simulation domain (black dotted line).

Results from these simulations were summarized in two Ph.D. dissertations (Chen, 2007 and Avise, 2007) and one M.S. thesis (Porter,2007). Five journal manuscripts were derived from this work and are in preparation for submission for publication:

1) Chen, J. J. Avise, C. Mass, E. Salathe, A. Guenther, C. Wiedinmyer, D. McKenzie, N. Larkin, S. O'Neill, and B. Lamb, 2007. Global Change Impacts on Future Regional Air Quality in the United States, for submission to *Atm Chem & Physics*.
2) Avis, J., J. Chen, E. Salathe, C. Mass, A. Guenther, C. Wiedinmyer, L. Horowitz, and B. Lamb, 2007. Attribution of projected changes in U.S. ozone and PM2.5 concentrations to specific global changes, for submission to *Atmos. Chem. & Phys.*
3) Chen, J., J. Avise, C. Wiedenmyer, A. Guenther, and B. Lamb, 2007. Impact of Future Land Use and Land Cover Changes on Regional Air Quality in the United States, for submission to *Atm Chem & Physics*.
4) Avise, J., J. Chen, E. Salathe, C. Mass, A. Guenther, C. Wiedinmyer, J. Lamarque, and B. Lamb, 2007. Impact of episodic long-range transport of Asian emissions on ozone levels in the western U.S., today and in the future, for submission to *Atmos. Chem & Phys.*
5) Porter, M., J. Chen, J. Avise, J. Vaughan, and B. Lamb, 2007. Regional modeling of nitrogen and sulfur atmospheric deposition in the Pacific Northwest, for submission to ES&T.

In this report, the results are presented as described in the preceding manuscripts. All of the results are based upon 36 km gridded simulations for the continental U.S. A preliminary nested 12 km gridded domain simulation was completed, but the results were not used for the analysis in the following. Additional publications and presentations associated with this project are given in a following section.

Base case Simulations for Current and Future Conditions

Regional emissions for the CMAQ model included both anthropogenic and natural sources. The anthropogenic emission inventory was based on the 1999 EPA National Emission Inventory (NEI-1999, http://www.epa.gov/ttn/chief/net/1999inventory.html) and processed with the SMOKE processor. The inventory included categories from area, on-road mobile, non-road mobile and point sources. The area and mobile emissions were imported as county-wide, annual totals, without temperature adjustments. Plume rise for each point source was calculated in SMOKE using MM5 meteorology and the Briggs plume rise algorithm.

The future case anthropogenic emissions were projected to year 2050 using factors from the EPA Economic Growth Analysis System (EGAS, (U.S. EPA, 2004). The EGAS system contains emission factors for each emission category by county. The EGAS module consider factors such as future changes in real personal income, real disposable income, population, employment and estimated future energy consumptions by sectors. The projections from EGAS were applied to area and mobile source categories. Point source emissions were unchanged from NEI-1999, assuming current industrial emissions are at their maximum allowable limits, set by the government. Spatial distribution of future anthropogenic emissions was updated with 2030 population and housing density estimates from the SERGOM model to account for urban area expansion in the future (Theobald, 2005). Comparison between future and current case anthropogenic emission inventory showed significant changes in the future decade. Table 1 summarizes domain-wide emissions by ratios between future and current periods for each category. The biggest change was in the area source category with a predicted increase of at least 30% for all species. Emissions from on-road mobile sources were predicted to stay relatively unchanged with a small 2% increase for CO, NOx and VOC species. Non-road mobile emissions, on the other hand, were predicted to increase by 9% to 30% depending on the chemical species.

Table 1. Summary of domain-wide emissions (kilotons/day) for current year, and projected future case emission ratios (future/current) in the US by source category and species. Biogenic emissions are estimated for the month of July.

	Area	On-Road Mobile	Non-Road Mobile	Point	Wild-Fire	Biogenic (July)
CO	45 / 1.33	184 / 1.02	61 / 1.13	11 / 1.00	1.5 / 1.25	–
NOx	5 / 1.57	23 / 1.02	11 / 1.09	23 / 1.00	–	4.0 / 1.04
VOC	24 / 1.94	15 / 1.02	7 / 1.32	5 / 1.00	0.1 / 1.24	130 / 0.60
SO_2	3 / 1.50	0.8 / 1.00	1.3 / 1.28	42 / 1.00	–	–

In addition to anthropogenic emissions, biogenic and fire emissions were included in the simulations. Biogenic emissions were generated dynamically with the MEGAN (Model of Emissions of Gases and Aerosols from Nature) model (Guenther et al., 2006). The model estimates hourly VOC, isoprene and monoterpene emissions from plants with a seasonal varying vegetation dataset, and predicted hourly temperature and ground level shortwave radiation from MM5. For the base-case simulations, the seasonal vegetation dataset was derived from satellite observations with 1-km grid resolution. The data were up-sampled to match the 36-km regional domain. For the future decade, the vegetation data were updated with results from the Community Land Model to incorporate predicted changes in plant functional types due to simulated future climate change. Similar sets of land cover data were used in the MM5 simulations for consistency. There were significant differences between current and future biogenic emissions due to projected vegetation distributions. Significant reduction was estimated in future isoprene emission capacity due to projected expansion of agriculture and urban areas. In the future, isoprene emitting vegetation is reduced in the southeast and north central states, and replaced with agricultural crops of lower isoprene emission capacity. The reduction is significant such that actual isoprene emissions decrease even when future temperatures were predicted to be higher. Across the domain, total daily biogenic VOC emissions were predicted to decrease in 2050 by -37% from the present case.

Wild fire emissions play important roles in current and future regional air quality conditions. Large fires contribute significant amount of pollutants and pollutant precursors to the atmosphere which, in turn, affect formation of ground level ozone (Malm et al., 2004). To account for the impact of wild-fires in regional simulations, we applied the Bluesky model (Larkin et al., 2007) with a fire occurrence dataset to generate fire emissions at each fire event by location. The coupling of the Bluesky fire emissions model with the CMAQ model has been demonstrated and shown to provide a good representation of regional fire emissions and their impacts on air quality in the Pacific Northwest (Chen et al., 2008). The same system was implemented here for current and future year fire emissions across the US continent. Fire events data from 1990 to 1999 were obtained from the Bureau of Land Management. The dataset contains records of fire location and fire size on federal lands necessary for the Bluesky system. For the future scenario, fire events were generated using the Fire Scenario Builder (FSB) stochastic model, developed by the USDA Forest Service (Mckenzie et al., 2006). The model translates future meteorology from MM5 into probabilistic fields of fire ignitions, fire sizes and fuel consumptions. The results were then used in the Bluesky model to estimate future emissions from predicted fire events. This stochastic method represents the best approach in modeling the highly unpredictable wild-fire occurrences for the future environments. There were approximately 25% increases in VOC and CO emissions in the future. Given the large uncertainties in future climate, the estimated fire emission changes are not unrealistic.

The base-case CMAQ results for the current decade were evaluated in comparison to long-term ozone measurements throughout the US (Figure 3). The system correctly captured episodic ozone conditions and spatial pollution distributions across the continent, however, low ozone concentrations were over-estimated. The mean daily max 8-hr ozone concentration was 58 ppbv, while the mean model prediction was 63 ppbv. The model accurately captured the episodic ozone conditions, represented by 98th percentile concentration values. The average episodic ozone concentration across all sites was 90 ppbv, and the average of peak model predictions was 93 ppbv. Spatially, the system captured the observed ozone conditions with correct representations of higher concentrations in the east, coastal California and northern Texas, as well as lower concentrations for the Pacific Northwest and the north central states.

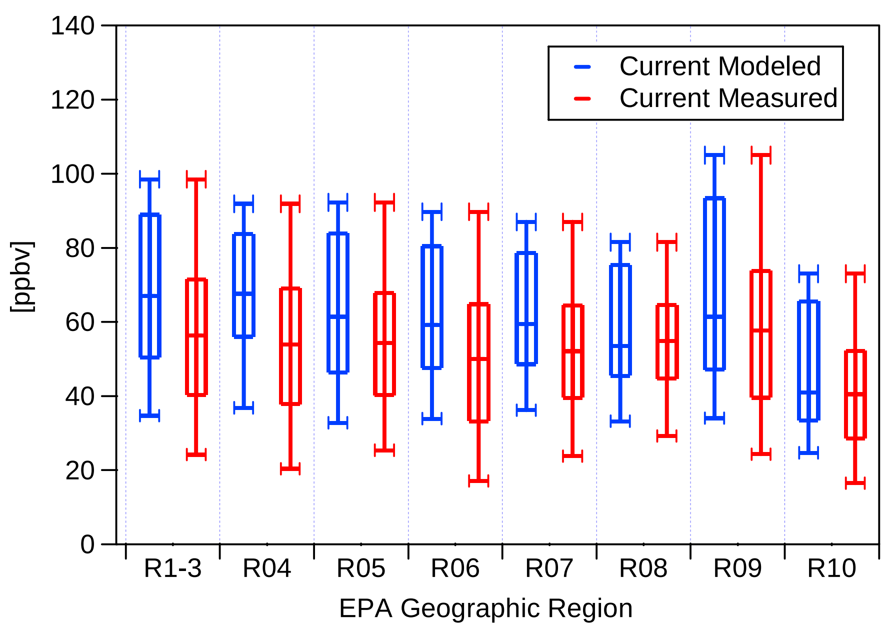


Figure 3. Current base-case modeled (left) and measured (right) daily maximum 8-hr ozone concentration ranges by EPA region. The top and bottom bars represent 98th and 2nd percentile values, the top and bottom box indicates 80th and 20th percentile values, and the center bar represents overall average concentrations across the region.

Significant changes in regional air quality conditions were predicted for 2045-2054 with respect to the current case simulation. Regional ozone pollution worsened from the combination of warmer climate, higher regional emissions and higher global pollution background concentrations. The mean daily max 8-hr ozone concentrations increased by 8 ppbv across the continent, and the 98th percentile of the daily max 8-hr ozone concentration increased by approximately 5 ppbv. Large increases were also predicted for non-episodic ozone, where the 20th percentile ozone concentration increased by up to 15 ppbv when compared with the base-case simulations.

Spatially, changes in ozone pollution in the future vary across the continent (Figure 4). Results show larger ozone concentration differences in the east, south and southwest, as well as smaller increases in the Pacific Northwest and inland northwest. Elevated ozone downwind of urban centers was predicted to impact larger surrounding areas due to simulated expansions in urban landuse and higher projected anthropogenic emissions in the future. The transport of polluted air further downwind of urban areas resulted in higher non-episodic ozone concentrations in surrounding rural regions. Spatial ozone impacts across the US continent were predicted to increase by 60% in the future in terms of areas exceeding 80 ppbv.

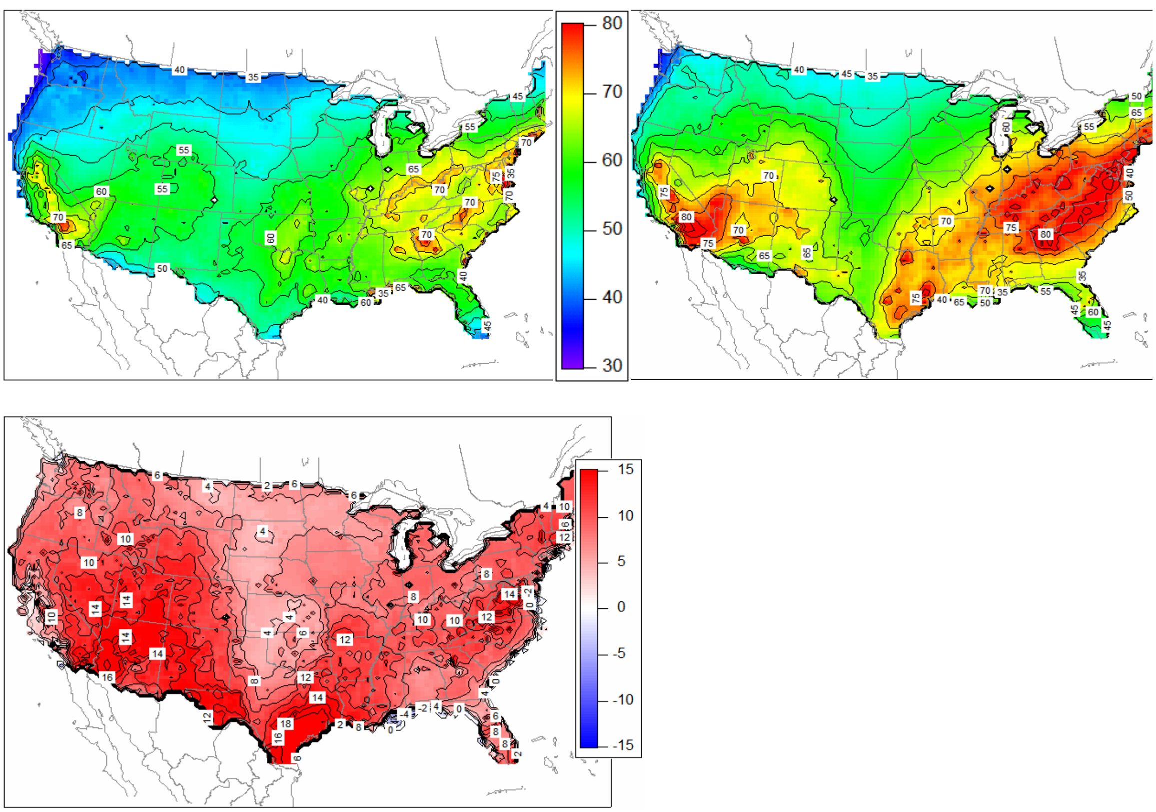


Figure 4. Concentration contour maps of overall averaged daily maximum 8-hr ozone concentrations (ppbv) over the 10 summer periods for (top left) current base-case and (top right) future case simulation results. The bottom map shows the concentration difference (ppbv) in terms of future average ozone change from the current base-case. Contour plots are constructed from 36-km gridded CMAQ model output.

Analysis of the future case also showed air pollution events to occur more frequently, with ozone episodes lasting longer throughout the year. There were more days when daily max 8-hr ozone concentration exceed 80 ppbv in the future simulation. The increase in ozone episode frequency not only occurred during the summer season, as in the base-case, but also in the spring and autumn months (Figure 5). The results also showed higher frequency of longer ozone pollution episodes in the future with more consecutive days when daily max 8-hr ozone concentrations exceed 80 ppbv.

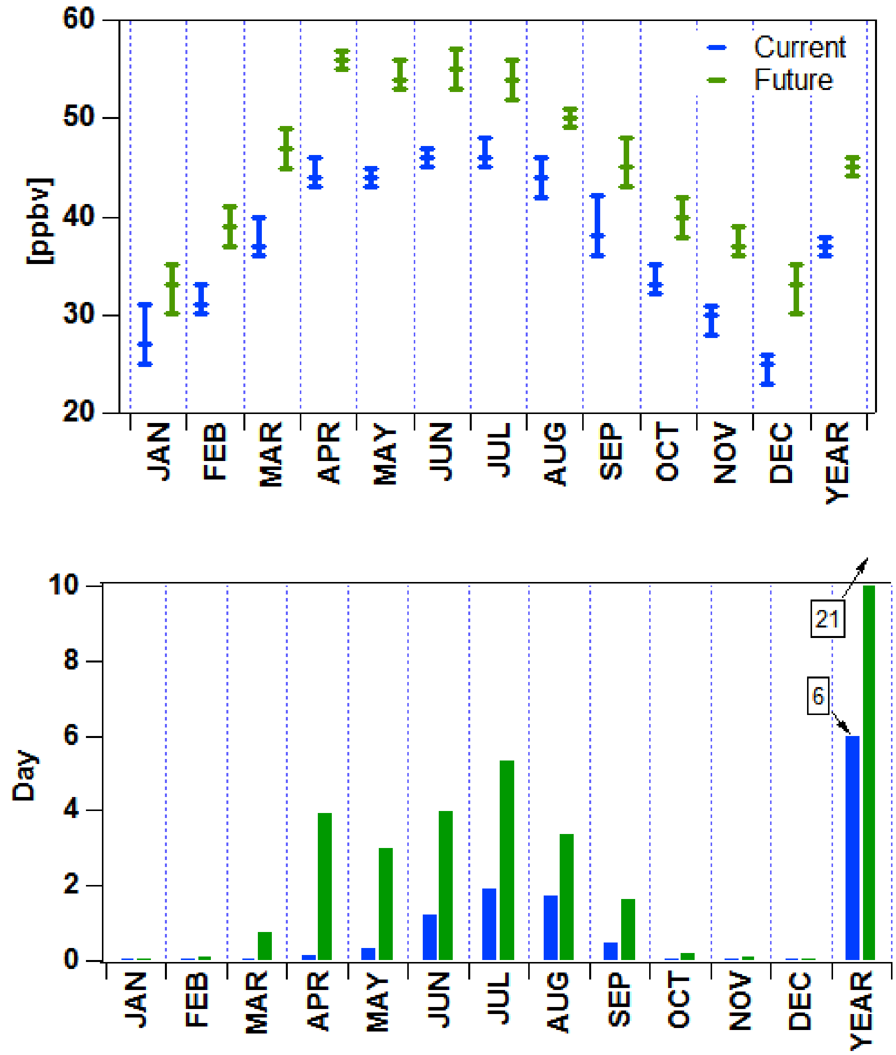


Figure 5. Current and future decade month and annual averaged ozone distributions over the 10 year simulations (top). The top bar represents 10-year maximum, the middle bar represents the 10-year-mean and the bottom bar represents 10-year minimum ozone. The average number of days per month and year daily maximum 8-hr ozone exceeds 80ppbv (bottom). Concentrations were averaged across all grids (6094 grids) in the US domain.

Attribution of Air Quality Changes due to Global Change

To examine the relative importance of future changes in climate, anthropogenic emissions, chemical boundary conditions, and land-use, a matrix of regional air quality simulations using the MM5/CMAQ system was completed. These attribution runs, listed in Table 2, were conducted using five current Julys and five future Julys as the basis for analysis. Changes in U.S. air quality to climate change were obtained via downscaling of the PCM model using the MM5 mesoscale model. Projected future chemical boundary conditions were obtained through the downscaling of MOZART-2 global chemical model simulations based on the SRES IPCC A2 emissions scenario. Projected changes in future U.S. anthropogenic emissions were estimated using the EPA Economic Growth Analysis System (EGAS), and changes in land-use were projected using data from the Community Land Model (CLM) and the Spatially Explicit Regional Growth Model (SERGOM).

Table 2. Designated model inputs for the six attribution cases. The "present-day" parameters refer to input representative of the 1990's, while "future-2050" refers to input parameters representative of the 2050's. Each case is comprised of five separate month long simulations representative of July meteorological conditions.

Simulation Name	Chemical boundary conditions	Anthropogenic emissions	Land-use / land-cover*	Meteorology
CURall	present-day	present-day	present-day	present-day
FUTall	future-2050	future-2050	future-2050	future-2050
futBC	future-2050	present-day	present-day	present-day
futEMIS	present-day	future-2050	future-2050	present-day
futMETcurLU	present-day	present-day	present-day	future-2050
futMETfutLU	present-day	present-day	future-2050	future-2050

* surrogate for biogenic emissions

Land-use changes are projected to have a significant influence on regional air quality due to the impact these changes can have on biogenic hydrocarbon emissions. However, changes in chemical boundary conditions are found to have the most significant impact (+5 ppbv) on average daily maximum 8-hr (ADM8- hr) ozone, followed by anthropogenic emissions changes coupled with land-use changes (+3 ppbv), and climate changes (-1.3 ppbv). When climate changes and landuse (i.e.,, biogenic emissions) changes are considered simultaneously, the average decrease in ADM8-hr ozone is even greater (-2.6 ppbv). These changes are shown in Figure 6.

Changes in average 24-hr (A24-hr) PM2.5 concentrations are dominated by projected changes in anthropogenic emissions (+3 ug m^{-3}), while changes in chemical boundary conditions have a negligible effect (+0.4 ug m^{-3}). On average, climate change reduces A24-hr PM2.5 concentrations by -0.9 ug m^{-3}, but this reduction is more than tripled in the south eastern U.S. (-3 ug m^{-3}) due to increased precipitation and wet deposition. These results are shown in Figure 7.

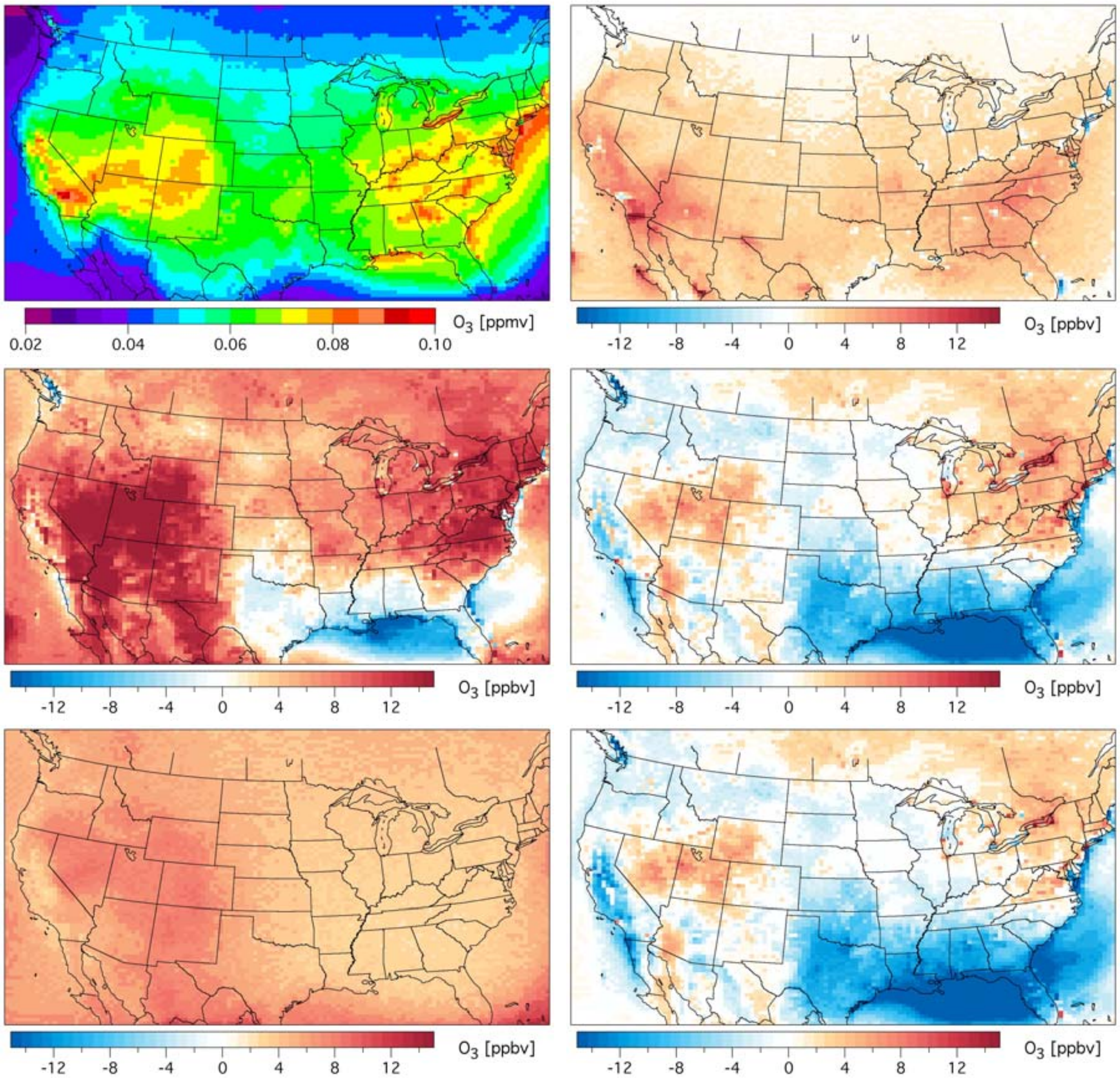


Figure 6. Average daily maximum 8-hr ozone for (upper left) the CURall simulation, (middle left) difference between the FUTall and CURall simulations, (lower left) difference between the futBC and CURall simulations, (upper right) difference between the futEMIS and CURall simulations, (middle right) difference between the futMETcurLU and CURall simulations, and (lower right) difference between the futMETfutLU and CURall simulations.

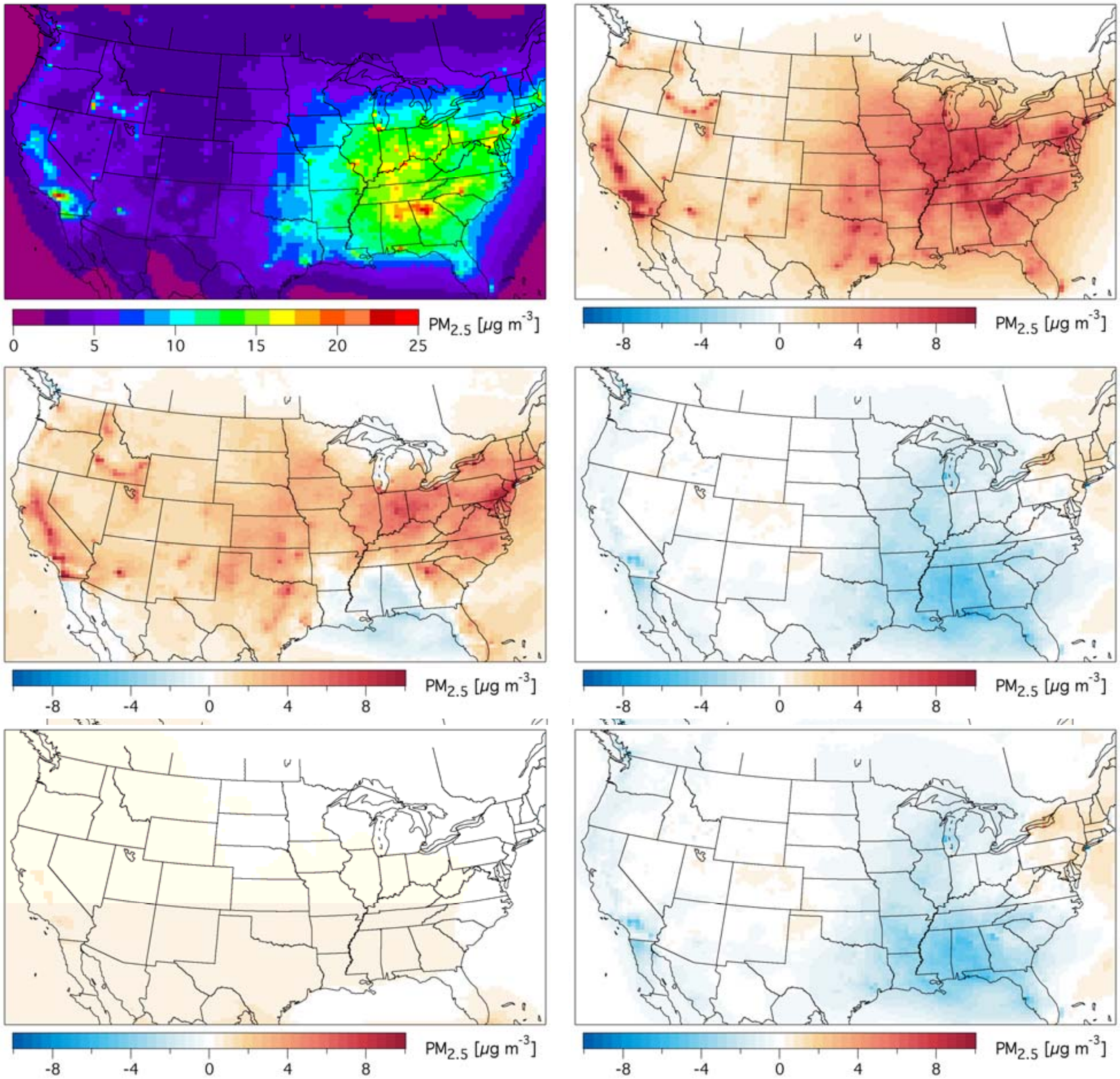


Figure 7. Average maps of 24-hr PM2.5 concentration for (upper left) the CURall simulation, (middle left) difference between the FUTall and CURall simulations, (lower left) difference between the futBC and CURall simulations, (upper right) difference between the futEMIS and CURall simulations, (middle right) difference between the futMETcurLU and CURall simulations, and (lower right) difference between the futMETfutLU and CURall simulations.

Effects of Land-use Change and Management upon U.S. Air Quality

Further analysis of the effects of land-use change and management were examined for several additional attribution cases. Current and future distributions of landuse-landcover (LULC) are shown in Figure 8. These changes were examined in terms of effects on ozone and biogenic secondary organic aerosols (BSOA) in the continental US. The system was applied for five July months for a current base-case (Case 1, 1990 decade) and three future cases (2045 decade). The three future cases included: Case 2 future climate with present LULC; Case 3 future climate with agricultural expansion, and Case 4 future climate with agricultural expansion plus regions of reforestation for carbon-sequestration. Future case simulations included changes in climate, anthropogenic emissions and global pollutant background concentrations as simulated in the base case future run.

Results show changing future meteorology with present LULC in Case 2 produced an increase of average continental emission rates of 25% and 21% for isoprene (Figure 9) and monoterpenes, from the base-case of 9 mg m^{-2} day^{-1} and 2.6 mgC m^{-2} day^{-1}, respectively. However when LULC were changed together with future climate, predicted isoprene and monoterpene emissions decreased and the variability in biogenic emissions also decreased. In Case 3, continental isoprene and monoterpene emissions were reduced by 52% and 31%, and in Case 4, emissions were reduced by 31% and 14%, from the base-case, respectively.

For future air quality, all three future cases have 8 ppbv higher US average 8-hr ozone concentrations due to warmer climate, higher global pollution backgrounds and significant increases in regional anthropogenic emissions (Figure 10). Future BSOA concentrations changed between +7% to -41% from the base-case of 0.4 μg m^{-3}. Spatially, concentrations vary by larger magnitudes following the differences in monoterpene emissions. Overall, the results indicate that on a regional basis, changes in LULC can offset increases in biogenic emissions due to climate warming and thus, LULC must be considered in projections of future air quality.

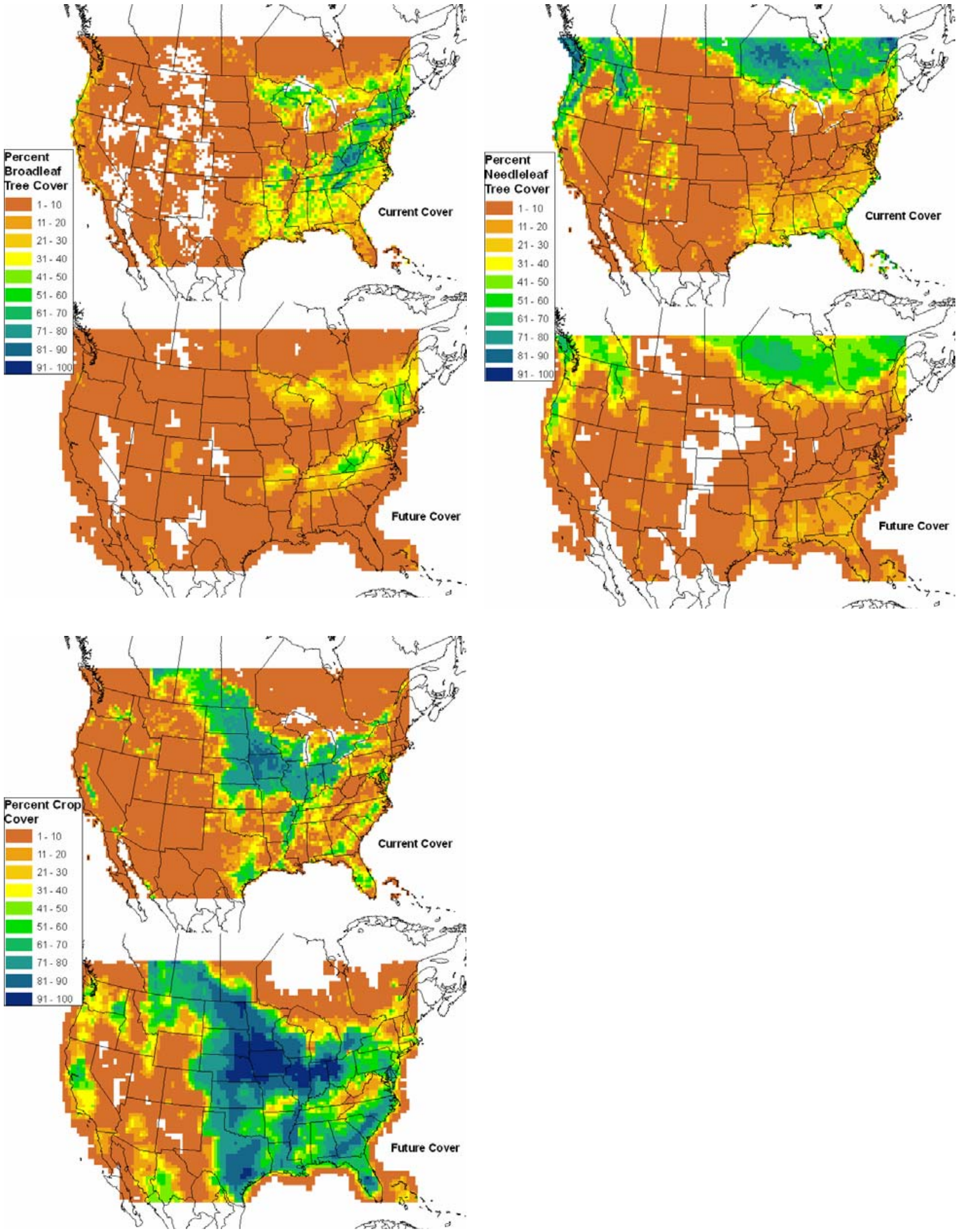


Figure 8. Estimated percent land cover for current (top) and future (bottom) scenario for (a) broadleaf trees, (b) needleleaf trees and (c) cropland.

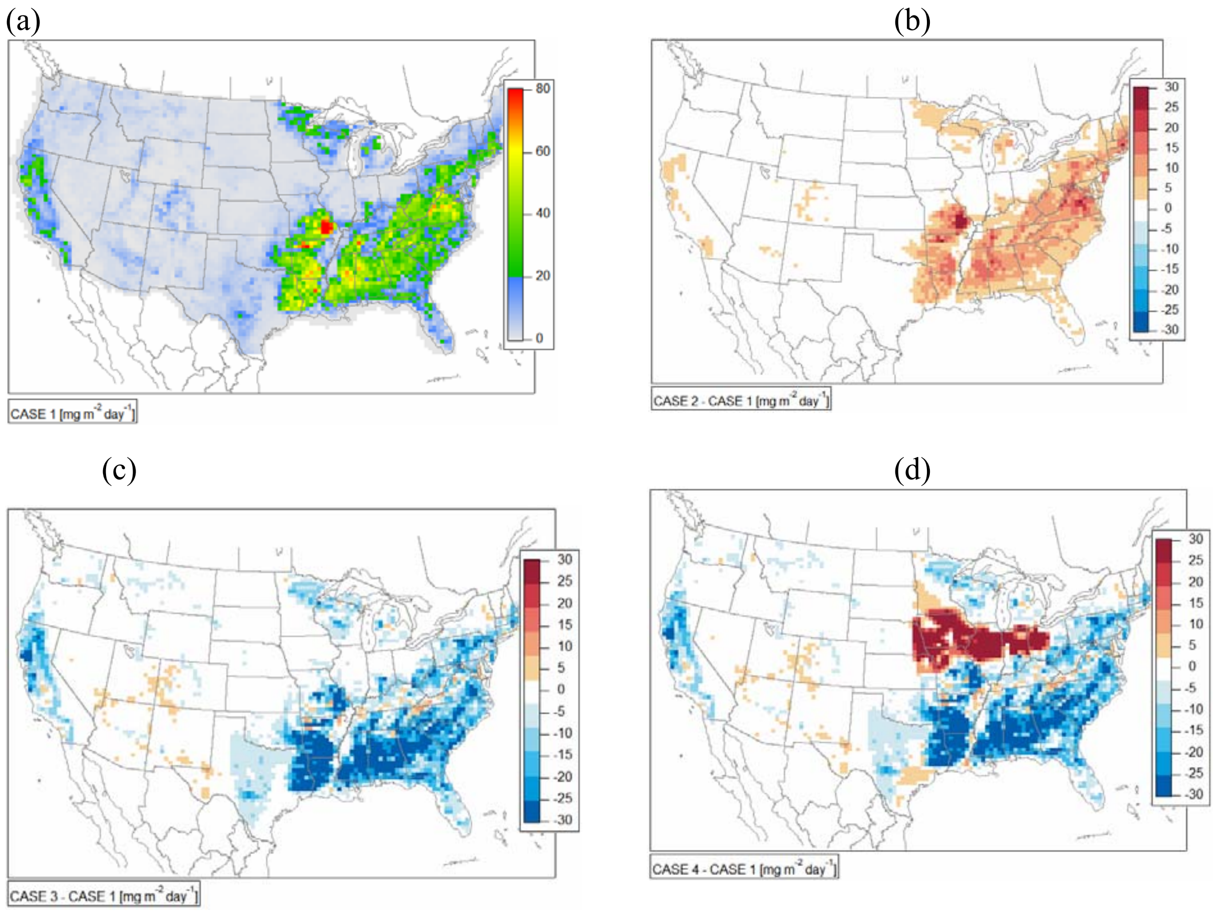


Figure 9. Mean July daily isoprene emissions for the current base-case (a) and magnitude of emission differences between future cases and the current base-case (b, c, and d).

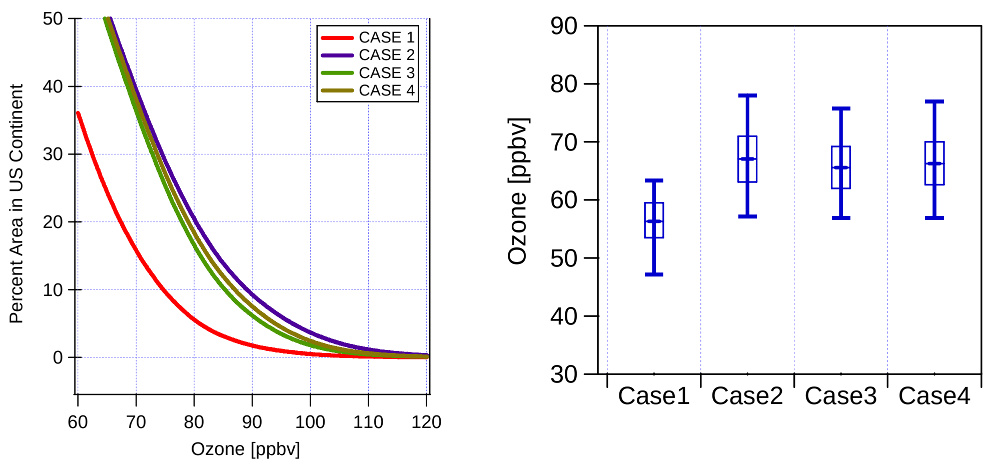


Figure 10. (left) Percent area in US continent with modeled daily maximum 8-hr ozone concentrations exceeding values on the x-axis for the four cases. (right) Continental averaged daily maximum 8-hr ozone concentration ranges across the five simulate July months for the four cases. The top and bottom whiskers represent maximum and minimum values, the box indicates 80th, and 20th percentile values with overall average marked by the middle.

Global Change and Effects of Long Range Transport upon U.S. Air Quality

In this portion of the project, we examined the impact that present-day (1990-1999) episodic long-range transport (LRT) of Asian emissions has on ozone levels in the western United States, and how this impact may change in the future (2045-2054) due to global changes in climate and emissions. The transport of Asian emissions to the western U.S. was modeled using the MOZART-2 three-dimensional global chemical model for the present day and future decades, where the future decade results were based on the IPCC A2 scenario. Regional impacts of the episodic LRT events were analyzed through the downscaling of MOZART-2 using the CMAQ regional photochemical grid model. In this work, a LRT event was defined as a CO concentration exceeding the monthly 85th percentile value for a minimum of 18 consecutive hours. LRT events in the lower (< 2 km) and mid-troposphere (2-6 km) were examined.

For the present-day, 1 to 3 LRT lower and mid-troposphere events occur every month depending on season, and the number of events does not change by more than 40% either way in the future. Enhancements of CO and PAN were found in the LRT air masses regardless of season, while measurable ozone enhancement only occurred in the late spring and summer months. The enhancement for all species is projected to increase in the future. In the Northwest U.S. (Oregon and Washington), surface ozone increases roughly 1-2 ppbv during present-day lower-troposphere LRT events for most seasons. In the future, surface ozone is projected to increase an additional 1 ppbv above present-day increases during LRT events. In California, wintertime surface ozone tends to increase during lower and mid-troposphere LRT events, for both the present-day and future cases, but surface ozone tends to decrease during summertime events. The decrease in ozone during summer events is most likely due to the meteorological conditions associated with these LRT events. Overall, we project background concentrations of CO, PAN, and ozone to increase roughly 40 ppbv, 0.13 ppbv, and 9 ppbv, respectively (Figure 11).

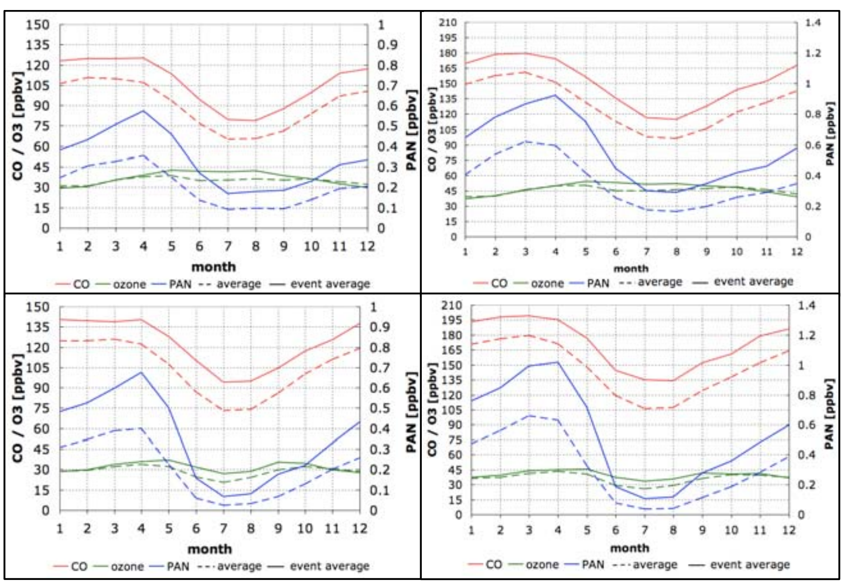


Figure 11. Monthly average CO, PAN, and ozone concentrations compared to CO, PAN, and ozone concentrations during (upper left) present-day mid-troposphere CO events, (lower left) present-day lower-troposphere events, (upper right) future-2050 mid-troposphere events, and (lower right) future-2050 lower-troposphere events.

Current and Future Atmospheric Deposition of Nitrogen and Sulfur in the Pacific Northwest

Nitrogen and sulfur deposition is an important ecological issue for a wide range of stakeholders in the Pacific Northwest (PNW). In this portion of the study, nitrogen and sulfur deposition patterns in the PNW were analyzed from the MM5/CMAQ 36 km gridded simulations for current and future decades. These results show that the relative contribution of nitrogen wet and dry deposition are approximately equal on an annual basis for current conditions. Dry deposition processes dominate during summertime conditions, while wet deposition occurs mainly in non-summer periods (Figure 12). . For current conditions, annual nitrogen deposition ranges from 0.6 to 13 kg/ha and annual sulfur deposition ranges from 0.1 to 14 kg/ha. Sulfur deposition maxima are highly localized to more urbanized areas of the PNW (western Oregon and Washington), while nitrogen deposition maxima are more widespread.

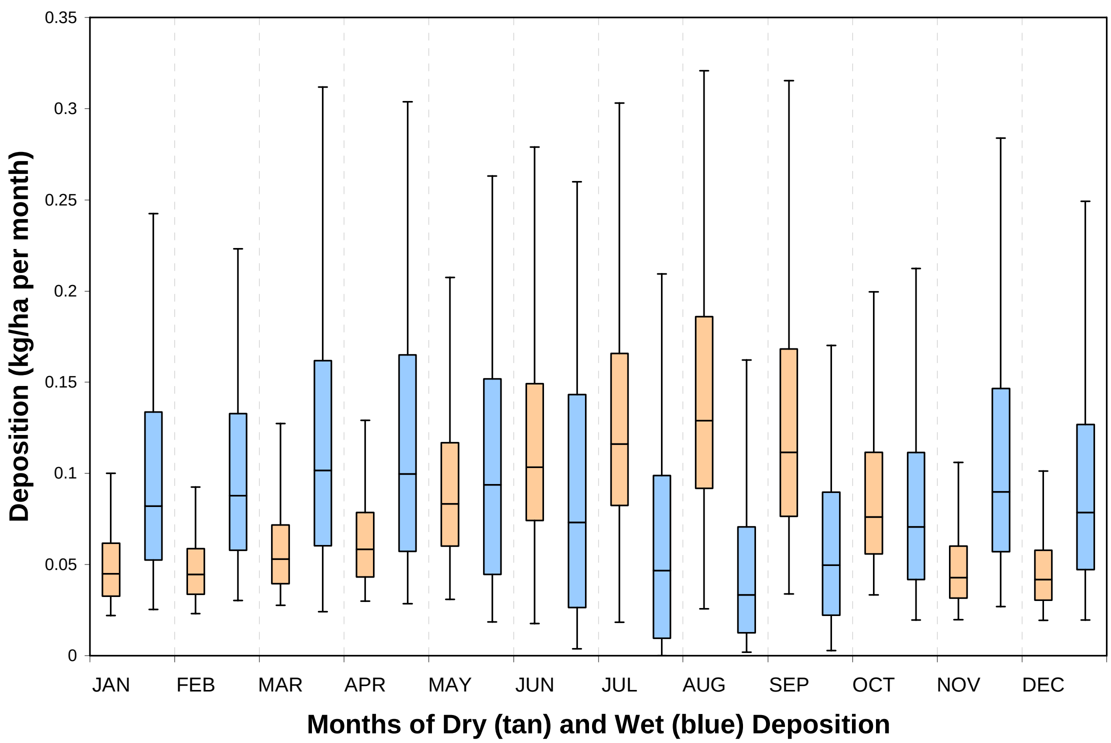


Figure 12. Box plots of monthly nitrogen deposition totals for the current decade within the Pacific Northwest. Dry and wet deposition for each month is shown using 5%, 25%, 50%, 75%, and 95% quantiles.

The current decade model results were evaluated using long term weekly observations from deposition sites within the Pacific Northwest. Results from this evaluation are summarized in Table 3.

Table 3. Monthly wet deposition and weekly dry deposition statistics comparing CMAQ deposition with CASTNET (dry deposition) and NADP (wet deposition) observed deposition. Species compared are in particulate (p) or gaseous (g) forms.

	NADP WET DEPOSITION (MONTHLY TOTALS)			CASTNET DRY DEPOSITION (WEEKLY TOTALS)				
STATISTIC*	NO3 (p)	NH4 (p)	SO4 (p)	HNO3 (g)	NH4 (p)	NO3 (p)	SO2 (g)	SO4 (p)
N	228	228	228	208	208	208	208	208
MB	-0.013	0.023	0.083	0.024	0.000	-0.001	0.018	0.002
ME	0.093	0.037	0.210	0.025	0.001	0.001	0.024	0.005
NMB	-0.053	0.418	0.352	1.064	-0.390	-0.700	1.686	0.438
NME	0.391	0.666	0.897	1.118	0.583	0.781	2.198	1.280
MFB	-0.039	0.314	0.156	0.722	-0.454	-0.805	0.712	0.003
MFE	0.419	0.566	0.613	0.760	0.758	0.984	1.005	0.940
RMSE	0.131	0.052	0.399	0.039	0.001	0.001	0.036	0.008
CMAQ MAX	0.675	0.297	2.065	0.244	0.005	0.003	0.141	0.069
CMAQ AVG	0.226	0.078	0.317	0.046	0.001	0.000	0.029	0.006
OBS MAX	0.791	0.266	1.200	0.108	0.004	0.005	0.041	0.013
OBS AVG	0.239	0.055	0.234	0.022	0.001	0.001	0.011	0.004

*N = number of points, MB = mean bias (kg/ha), ME = mean error (kg/ha), NMB = normalized mean bias, NME = normalized mean error, MFB = mean fractional bias, MFE = mean fractional error, RMSE = root-mean-square error (kg/ha).

The spatial patterns of nitrogen deposition in the PNW in the future decade change substantially (Figure 13). In some areas of the inland PNW, nitrogen deposition during the late fall, late winter, and early spring months doubles in magnitude. Nitrogen deposition increases during the late fall, winter, and early spring months are mostly due to wet deposition. Nitrogen dry deposition in the future is larger than wet deposition earlier in the year compared to the current decade. Nitrogen deposition during the summer months increases more in the inland PNW. Annual nitrogen deposition increases for the PNW range from 7.6 kg/ha in the inland PNW to 0.5 kg/ha along the coast. Annual increases are 1 kg/ha or more for the PNW domain. This is an increase of at least ~60%, however, areas with projected increases in agricultural activity in the inland PNW are predicted to see as much as 100% increase in nitrogen deposition.

Sulfur deposition increases throughout the PNW in the future decade. During most seasons of the year monthly deposition totals increase by at least 0.015 kg/ha in Washington, Oregon, and northern Idaho. This is a ~10% regional increase in sulfur deposition. These increases mainly occur in the fall thru spring months, and are mostly due to sulfur wet deposition. Sulfur dry deposition decreases or stays the same in the range of +/-0.015 kg/ha throughout the PNW. Annual sulfur deposition totals in the PNW increase by more than 0.125 kg/ha regionally. Annual sulfur deposition rates in northern Idaho and northeastern Oregon increase by 0.25 to 0.50 kg/ha. These increases are mostly due to sulfur wet deposition.

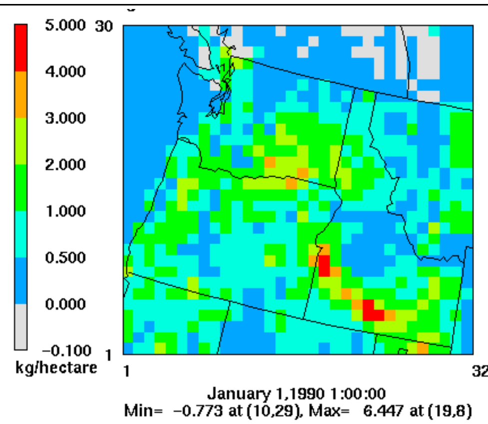
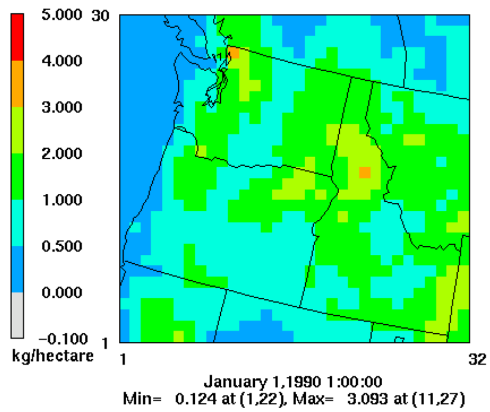
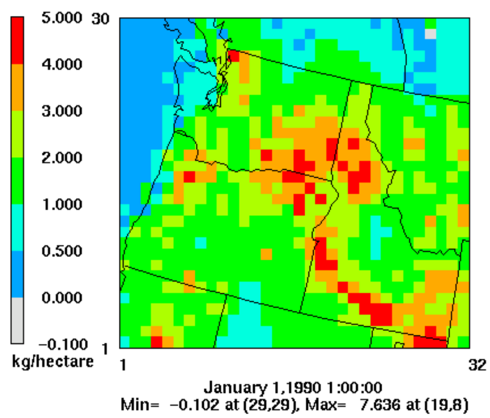
	(2045 to 2054 Annual Average) - (1990 to1999 Annual Average)
Nitrogen Dry Deposition	
Nitrogen Wet Deposition	
Nitrogen Wet+Dry Deposition	

Figure 12**.** Total nitrogen dry, wet, and dry+wet future decade (2045—2054) minus current decade (1990—1999) annual deposition difference plots.

Presentations

Avise, J., J. Chen, B. Lamb, A. Guenther, C. Wiedinmyer, J.F. Lamarque, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin, 2006. Sensitivity of regional air quality to global change parameters, PNWIS/AWMA 46th Annual Conference, Victoria, BC Canada.

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McKenzie, D., S.M. O'Neill, N. Larkin, R.A. Norheim, and J.S. Littell. November 2006 (invited). Stochastic modeling of fire at daily time steps from mesoscale meteorology. Special session on fire modeling at the San Diego Fire Conference, San Diego, CA.

McKenzie, D., S.M. O'Neill, N. Larkin, R.A. Norheim, J.S. Littell, and E. Salathé. June 2006. Scale, air quality, and the Fire Scenario Builder. Invited presentation at the University of Washington CSES Climate Impacts Group.

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. October 2005. Integrating models to predict the effects of wildfire on air quality in parks and wilderness. Invited presentation at the special session on air pollution effects on mountain ecosystems. "Mountains and Global Change" conference, Perth, Scotland, UK.

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. March 2005. How will climatic change affect air quality in parks and wilderness? George Wright Society Annual Meeting, Philadelphia, PA.

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. March 2005. Integrating models to predict regional haze from wildland fire. Annual meeting of the US-IALE (international association for Landscape Ecology), Syracuse, NY.

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Relevant Web Sites

This project is included as part of the activities in the International Northwest Air Quality Environmental Science & Technology Consortium (NW-AIRQUEST) as described on http://www.nwairquest.wsu.edu

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