NCER Assistance Agreement Annual Report

Period Covered by the Report: September 1, 2005 through August 31, 2006
Date of Report: November 8, 2006
EPA Agreement Number: RD 83096201
Title: **Impact of Climate Change on U.S. Air Quality using Multi-scale Modeling with the MM5/SMOKE/CMAQ System**

Investigators: Brian Lamb blamb@wsu.edu
Clifford Mass cliff@atmos.washington.edu
Alex Guenther guenther@acd.ucar.edu
Susan O'Neill*, susan.oneill@por.usda.gov Sim Larkin larkin@fs.fed.us and
Donald McKenzie donaldmckenzie@fs.fed.us
Institutions: Washington State University, Pullman, WA
University of Washington, Seattle, WA
National Center for Atmospheric Research, Boulder, CO
USDA Forest Service, Pacific Northwest Research Station, Seattle, WA
***now with USDA, NRCS, Portland, OR

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

Project Period: September 1, 2003 through August 31, 2007

Objective of Research: In this project, we have 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? Directly through warmer temperatures? Indirectly through changes in circulation patterns and changes in land cover? 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?

Progress Summary/Accomplishments: Our approach uses the Parallel Climate Model and the MOZART global chemistry model to provide the necessary boundary and initial conditions to allow continental and regional simulations of air quality using the MM5/SMOKE/CMAQ system. Figure 1 shows a schematic of the global to regional scale simulation system.

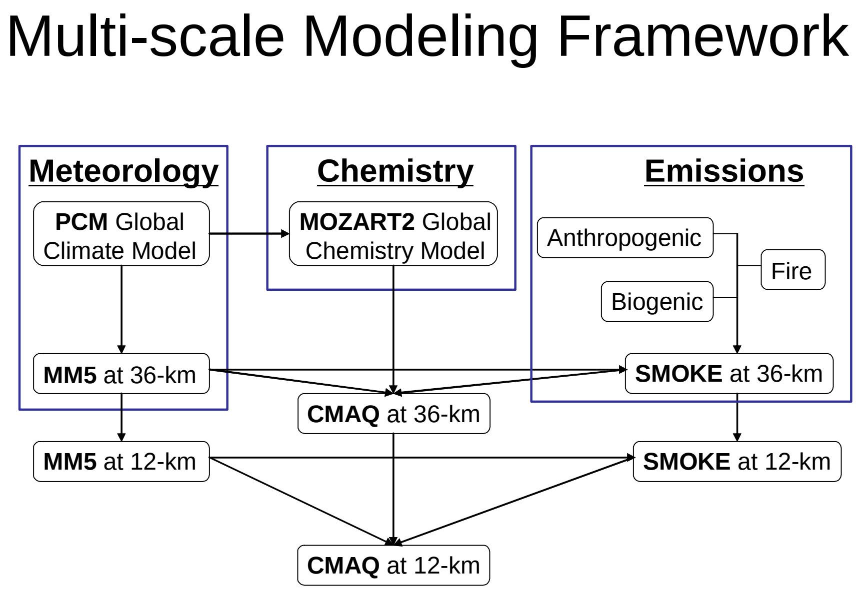


Figure 1. Schematic of global-continental US-regional air quality modeling process.

During the third year of this research, we completed long term simulations at 36 km grid scales for the continental US and are just finishing long term runs at 12 km grid scales for the Pacific Northwest. Results from recent analyses of the 36 km current and future decade simulations include the following:

- Comparison of future July conditions with current conditions indicates that US ozone concentrations (hourly 95th percentile) will increase by 10 ppbv (from 70 ppbv) and hourly peak PM2.5 concentrations (95th percentile) will increase by 5.7 ug/m3 (from 20.5 ug/m3).
- For ozone, a series of attribution simulations show that changes in global chemical conditions and changes in local US anthropogenic emissions are the dominant cause of future increases in ozone levels and that changes in regional meteorology due to climate change do not have a large effect.
- Increases in projected urban and agricultural land use will result in a net decrease in biogenic emission capacity even though warmer temperatures cause an increase in emission rates.
- Comparison of MM5 meteorological output with current climatology indicates that the downscaling of global PCM output produces a reasonable representation of current climate, although the PCM periodically produces unrealistically cold outbreaks during winter periods.
- Comparison of CMAQ ozone and PM2.5 concentrations with current air quality levels indicates that the model produces a reasonable representation of current conditions. In

the Pacific Northwest, peak hourly ozone concentrations are somewhat underestimated, but in the northern Midwest, peak concentrations are better estimated.

- Future projections of fire emissions based upon a new Fire Scenario Builder, driven with future regional meteorology, yields higher occurrences of fire and higher pollutant emissions within western states.
- A sensitivity test of the effects of widespread use of poplar plantations for carbon sequestration showed that these plantations would significantly increase isoprene emissions within the midwestern and eastern US and result in significant increases in 8-hr average ozone levels.

Details concerning the modeling methods and these recent results are addressed in the following sections.

Regional Climate Modeling

We have developed a high-resolution climate model of the Pacific Northwest based upon the MM5 mesoscale weather model to downscale simulations from the National Center for Atmospheric Research-Department of Energy (NCAR-DOE) Parallel Climate Model (PCM). Nested grids are used in MM5 to downscale from the climate model resolution. To match the climate model grid spacing of approximately 300 km, we have used 108, 36, and 12 km grids (Figure 2). The outer grid covers much of the Northeast Pacific and North America to encompass all large-scale processes critical to Pacific Northwest climate. The intermediate grid encompasses the conterminous United States. The innermost grid covers the states of Washington, Oregon, and Idaho. A second inner domain encompasses portions of the northern Midwest, and results within this area have been used for comparisons to the Pacific Northwest based upon the 36 km grid simulations. Initial and boundary conditions as well as interior nudging for MM5 runs are taken from the global climate model simulations. In the vertical dimension, the model uses 28 full-sigma levels and is run in non-hydrostatic mode.

An upper-radiative boundary condition is used to allow gravity waves to radiate through the model top without being reflected. Other parameterizations include: MRF (or Hong-Pan) planetary boundary layer scheme, explicit moisture scheme (including simple ice physics but no mixed phase processes), Kain-Fritsch cumulus parameterization, CCM2 radiation, and the simple five layer soil model. Detailed land use information for each domain is derived from the 1-km USGS digital database, with some subjective modification using other data sources.

To perform multi-year runs and maintain stability and mass conservation of the simulation, we employ nudging (Newtonian relaxation) of the outer nest toward the global climate model simulation, thus the 108-km nest is constrained tightly to the global model simulation and yields a smooth transition from the global model to MM5. With this technique, we can run MM5 continuously for long periods, without periodic restarts. One week and one month test runs using this technique were completed to validate the method. The use of nudging in this model is an important distinction from other approaches. Nudging preserves the large-scale state provided by the global model. Thus, the downscaling provides the regional meteorological details consistent with that large-scale state without attempting to improve the large-scale state, which is assumed to be well resolved by the global model.

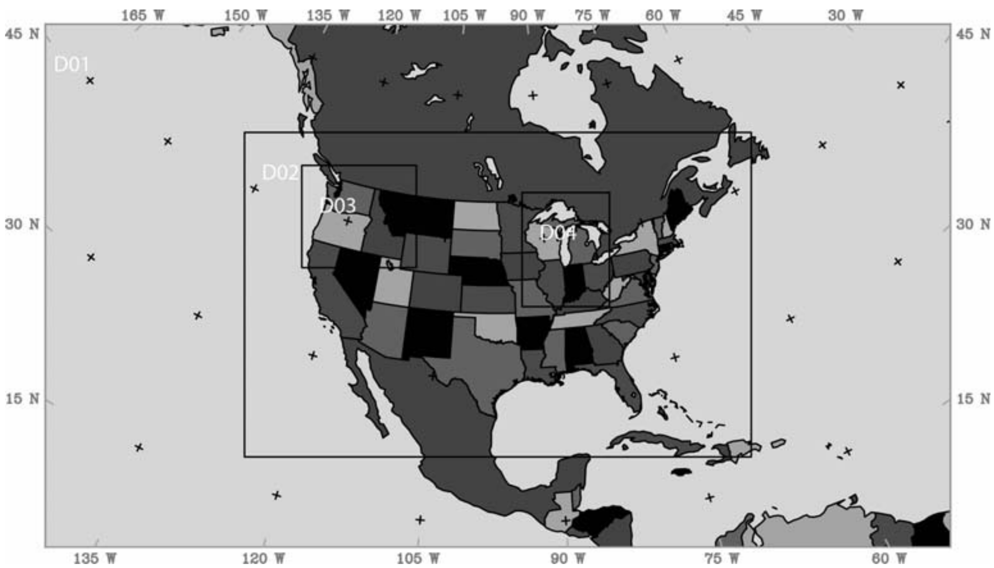


Figure 2. Nested domains used for MM5 simulations; grid spacing is 108 km for D01, 36 km for D02, and 12 km for D03 and D04.

Using this modeling system, we have completed simulations for the 36-km continental U.S. domain for the baseline climate period, 1990-2000 and for the future climate, 2045-2055. Initial validation of the 1990-2000 run shows a reasonable depiction of current climate, although analyses presented last year showed that the PCM model produces periodic unreastically cold outbreaks. These outbreaks appear to be related to a lack of vertical resolution in the global model. Figure 3 shows monthly mean output form the MM5 simulation for January 1999. Shading indicates 2 m air temperature; white contours are the 850 mb heights; yellow contours are sea level pressure. Simulations for the 12-km Pacific Northwest domain have been completed for the 1990-2000 period and are near completion for the 2045-2055 period. Figure 4 shows the 2-m air temperature further downscaled to 12-km resolution and illustrates the additional level of detail and complexity that can be obtained using the higher resolution results.

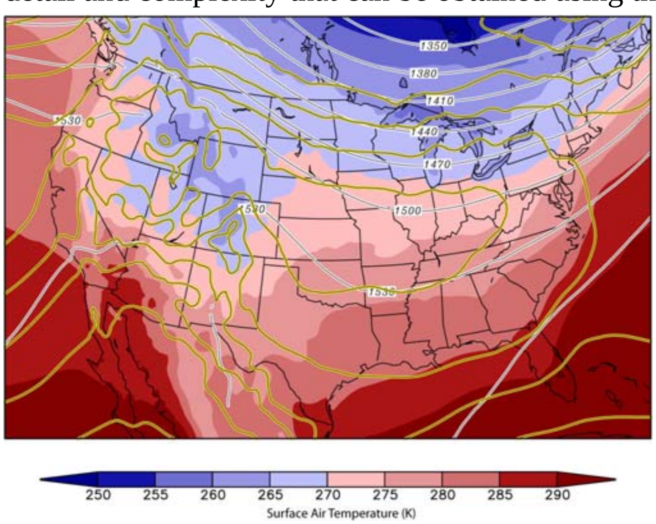


Figure 3. January 1999 monthly mean pattern from MM5 simulation. Shading indicates 2m air temperature; white contours 850 mb heights; yellow contours sea level pressure

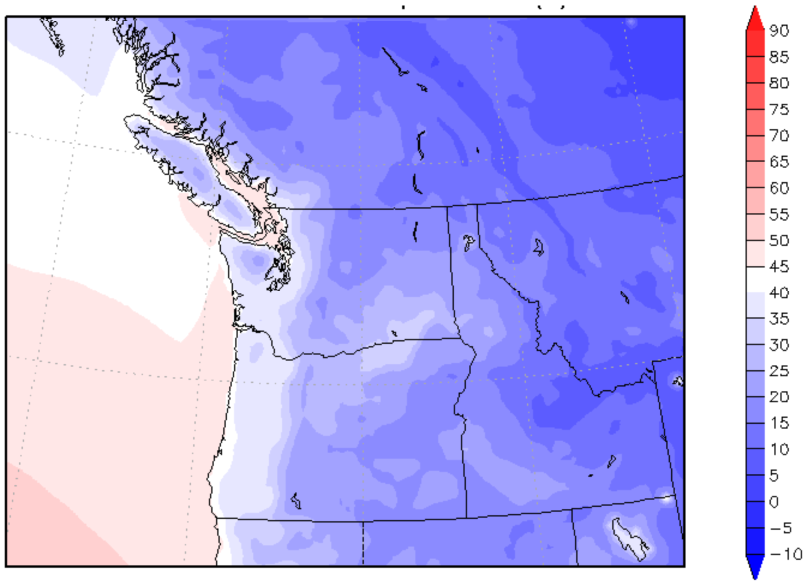


Figure 4. January 1999 monthly mean pattern from MM5 simulation. Shading indicates 2 m air temperature in degrees F.

Validation of Regional Simulation

The regional climate simulations may be verified against observed climatology at weather stations. Here we show validation results for simulations forced by NCAR-NCEP reanalysis fields (NNRP-MM5) and by the ECHAM5 global climate model (ECHAM5-MM5) for the period 1990-2000. The reanalysis fields should accurately represent the large-scale state of the atmosphere, thus disparities between this simulation and station climatology reflect deficiencies in the mesoscale model. While the simulations used for this project are driven by the PCM climate model, the issues presented below apply generally to MM5-bases climate simulations.

Two stations Washington State are chosen for validation: SeaTac, west of the Cascade Range, and Kennewick, east of the Cascade Range. A 365-day composite annual cycle of simulated daily maximum (Tmax) and minimum (Tmin) temperature was obtained by calculating a 10-year average for each day of the year. The ECHAM5-MM5 and the NNRP-MM5 composites of Tmax at SeaTac are shown in Figure 5a and at Kennewick in Figure 5b. Included on the plot are the observed climatological mean daily Tmax values and the record high- and low-Tmax values spanning the period 1948-2005. The record high-Tmax values have been adjusted with a 10-day window that selects the maximum value in that 10-day period in an effort to both smooth the plot and represent a "highest conceivable value" for each day. Record low-Tmax values have been treated conversely, representing the "lowest conceivable value" for each day. All model composite plots were smoothed with a 20-day running mean. Similar results for Tmin at the two stations are shown in Figure 6.

The results for Tmax (Figure 5) show reasonable agreement between the model results and the station observations, particularly for the reanalysis run. There is a cold bias in winter for the ECHAM5-MM5 simulation, which does not appear in the reanalysis-based simulation. The better performance of the reanalysis run relative to the for winter indicates this cold bias is due to deficiencies in the global model, not the regional model (MM5). For Tmin (Figure 6), however, a cold bias in summer is present in both simulations, suggesting that the regional model introduces a cold bias during nighttime.

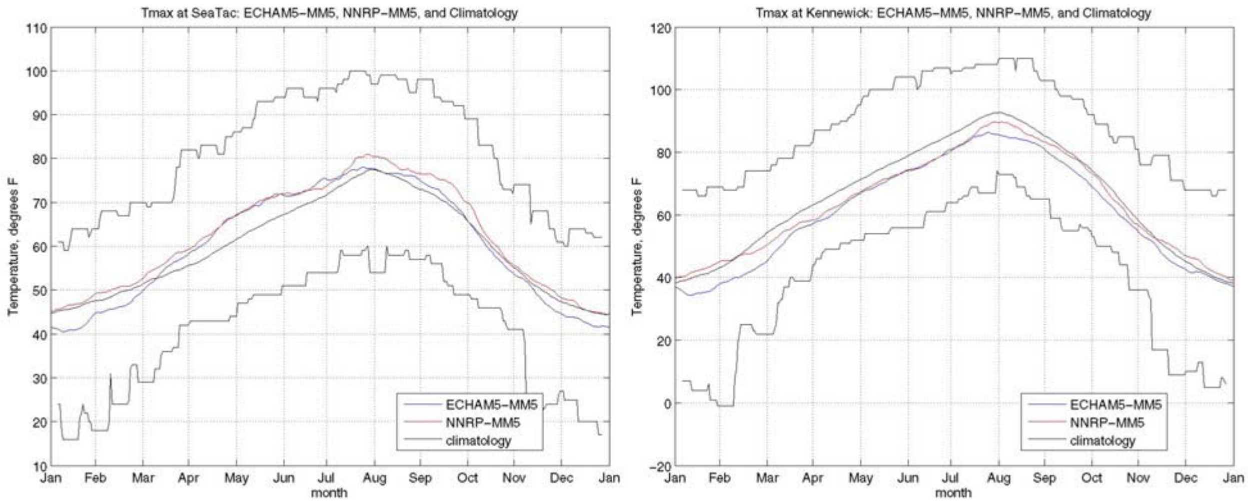


Figure 5. Tmax validation of MM5 results at a) SeaTac and b) Kennewick

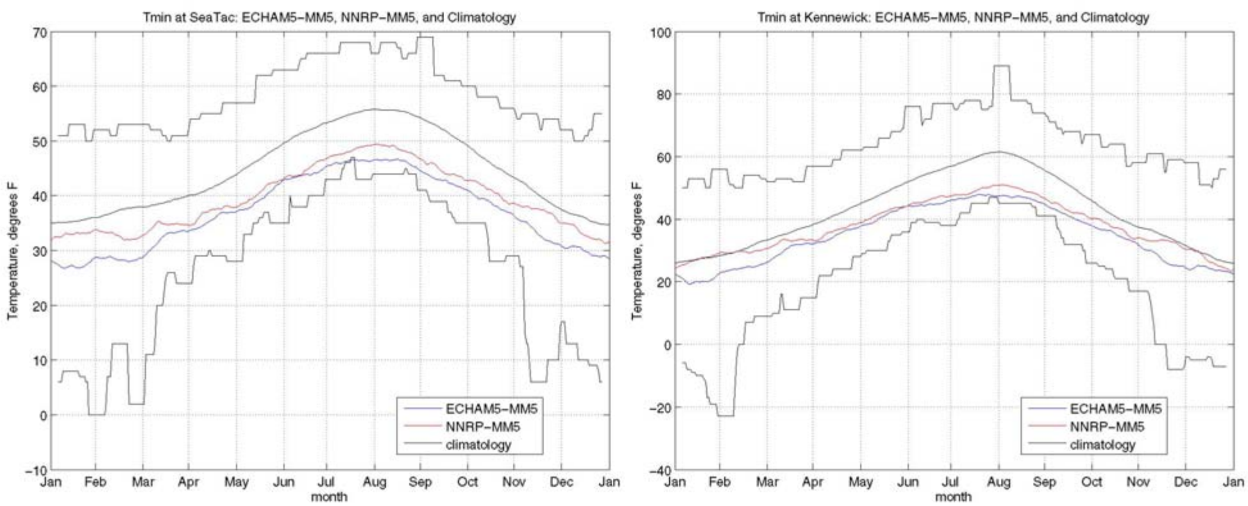


Figure 6. Tmin validation of MM5 results at a) SeaTac and b) Kennewick

Results from ECHAM5-MM5 simulations

Because of the wintertime cold outbreaks that were much colder than observed using the PCM global forcing, we have also performed simulations using the MM5 regional model forced by global fields from the ECHAM5 climate model. This global model is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (ECHAM5) coupled to the Max Planck Institute ocean model (MPI-OM). For the current study, we have used a simulation forced with the IPCC SRES A2 emissions scenario, which is the same as used for the PCM simulation used primarily in this project. Using multiple forcing models to create an ensemble of regional simulations is an important step in understanding the uncertainty in regional climate and air quality projections over the next 50 to 100 years.

Mesoscale processes operating at very fine spatial scales can have important implications for the simulated regional climate. We present here two examples from the ECHAM5 downscaling experiment for the Pacific Northwest 12-km domain. The first example shows how warming is intensified in regions where snow cover is lost. This snow-albedo feedback is also important in global climate model simulations, but these coarse-resolution models do not realistically represent the effect at regional scales since they do not resolve the slopes and elevations of the regional topography. The regional model represents the significant features of the regional topography and thus simulates this feedback in detail. Snow-albedo feedback follows from the increased albedo of the underlying land surface relative to snow and the consequent increased absorption of solar radiation when snow cover is lost. Figure 7 shows the warming from 1990-2000 to 2044-2055 from the regional climate. Relative to the global model, the regional model produces amplified warming along the western slopes of the Cascades and in the high plateaus of Eastern Washington and Oregon. This amplified warming is produced by increased absorption of solar radiation at the surface as snow cover is eliminated and albedo increases (Fig 7). The effect is most pronounced near the present-day snowline where snow cover is most sensitive to warming.

A second effect follows from mesoscale circulation established by the local temperature gradients in spring (March-April-May). Warming of the continental interior, relative to the oceans, establishes an anomalous on-shore pressure gradient, which increases the climatological onshore flow and produces increased low-level cloudiness as indicated by the concentration of cloud water (change from 1990s to 2050s, Figure 8). Increased cloudiness reduces the incident solar radiation at the surface, producing a cooling effect. West of the Cascades, this increase in cloudiness tends to reduce the warming during the daytime, while nighttime warming is amplified (Figure 8). As in DJF, there is substantial snow loss in this season, which amplifies warming in the high elevation areas, particularly during the day.

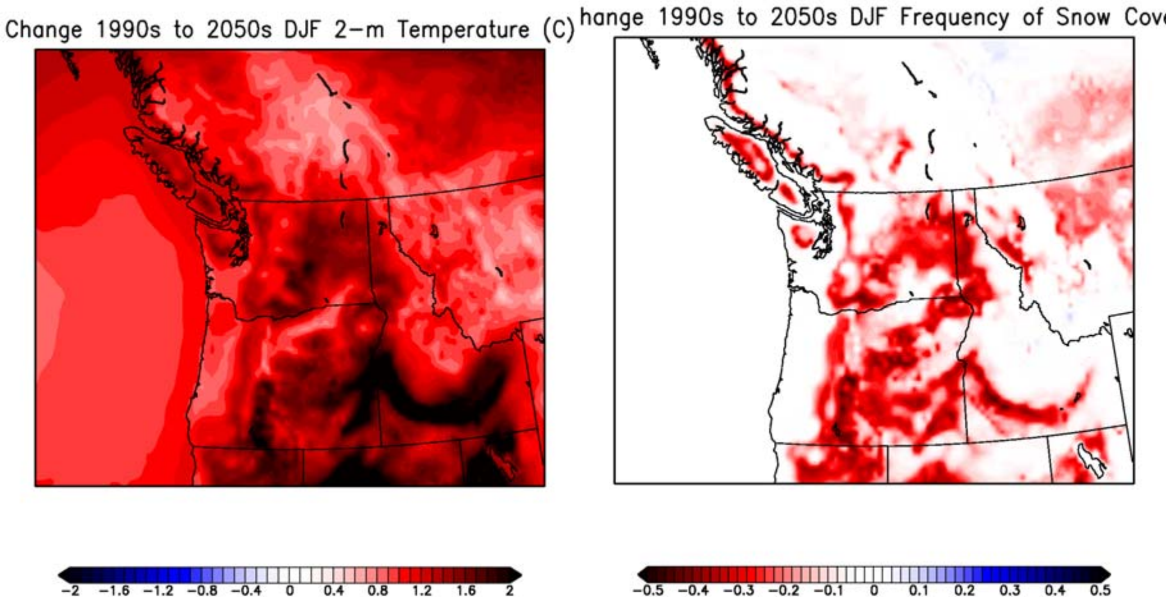
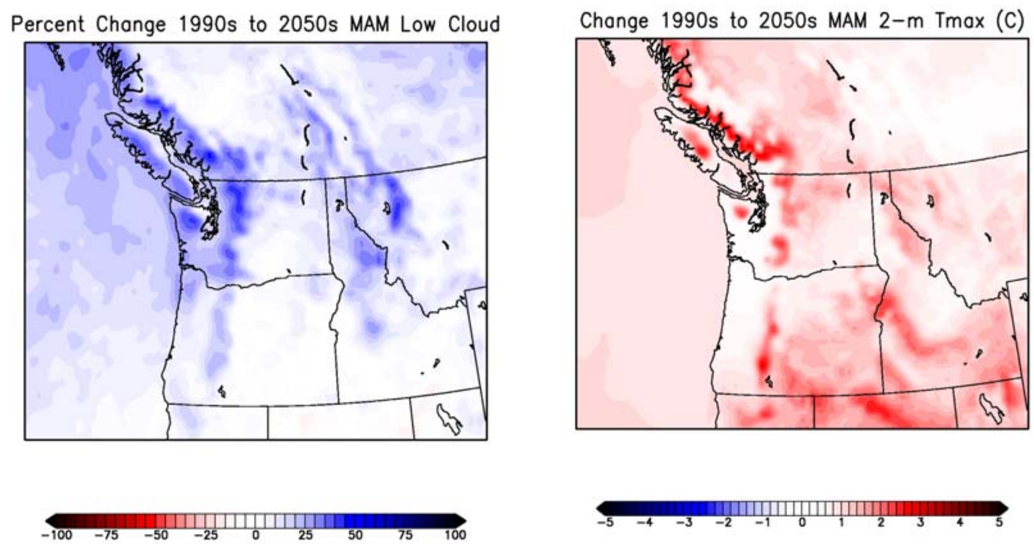


Figure 7. Warming from 1990-2000 to 2045-2055 from the ECHAM5-MM5 12-km simulation (left panel) and change in frequency of snow cover over same time period (right panel).



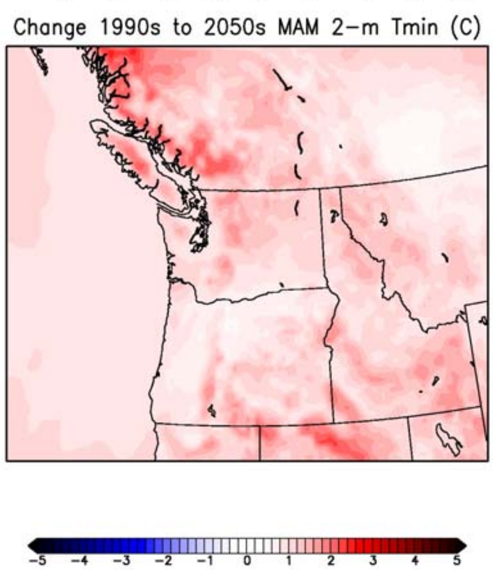


Figure 8. Increase in cloudiness 1990-2000 to 2045-2055 from the ECHAM5-MM5 12-km simulation (top left). Change in daily maximum temperature (top right) and minimum temperature (bottom left) over the same time period

MOZART Global Chemical Modeling

The Model for Ozone and Related Chemical Tracers (MOZART) is a global chemical transport model developed partly in the Atmospheric Chemistry Division (ACD) at NCAR. This model was run without cost in stand-by mode on the supercomputers located at NCAR for two 10-year periods: 1990-2000 and 2045-2055. The model was driven by the PCM winds and meteorology and included an updated MOZART2 chemical mechanism and an aerosol module developed by Xuexi Tie and Jean-Francois Lamarque (NCAR, unpublished). The emissions used in the 1990-2000 runs were from the EDGAR-HYDE database (http://arch.rivm.nl/env/int/coredata/edgar/intro.html). The emissions for the 2045-2055 runs were based upon the IPCC SRES A2 scenario and were developed by Claire Granier (NCAR/NOAA, unpublished). The runs were performed and completed by Jean-Francois Lamarque in August 2004. We have acquired the MOZART output files and constructed a pre-processor to derive CMAQ initial and boundary condition files for the decadal simulations periods. We completed analyses of the MOZART output to create time-varying vertical profiles for use as the chemical boundary conditions for the CMAQ 36 km decadal simulations, and we have compared these boundary conditions to observations along the west coast of the U.S. Figure 9 shows the average vertical ozone profile from over 440 weekly ozonesonde measurements made between August 1997 and August 2005 at Trinidad Head, located in northern California (Trinidad Head data was obtained from the NOAA ESRL Global Monitoring Division; http://www.cmdl.noaa.gov/). On the same figure, the yearly average ozone profile, derived from MOZART-2 output, for the boundary grid cell corresponding to Trinidad Head is shown. The average profile from MOZART-2 matches the observations relatively well near the surface, but misses the magnitude of the vertical ozone gradient and underestimates the ozone concentrations in the free troposphere by as much as 20 ppbv. Figure 9 also shows a similar result for observations in the eastern Pacific Ocean off the coast of Washington State for aircraft measurements made from May-August 2003 during the PHOBEA 2003 campaign (Bertschi and Jaffe 2005) compared to the MOZART-2 yearly average profile from the corresponding boundary grid. These results are in contrast to those published by Horowitz et al. (2003), which show good agreement between MOZART-2 simulated vertical ozone profiles and ozonesonde measurements, throughout the surface layer and free troposphere. One possible explanation for these discrepancies is that in the work presented here the model vertical resolution was decreased to 18 vertical levels for computational efficiency, compared to 34 vertical levels used by Horowitz et al. (2003).

O_3 BC's: modeled vs. observed

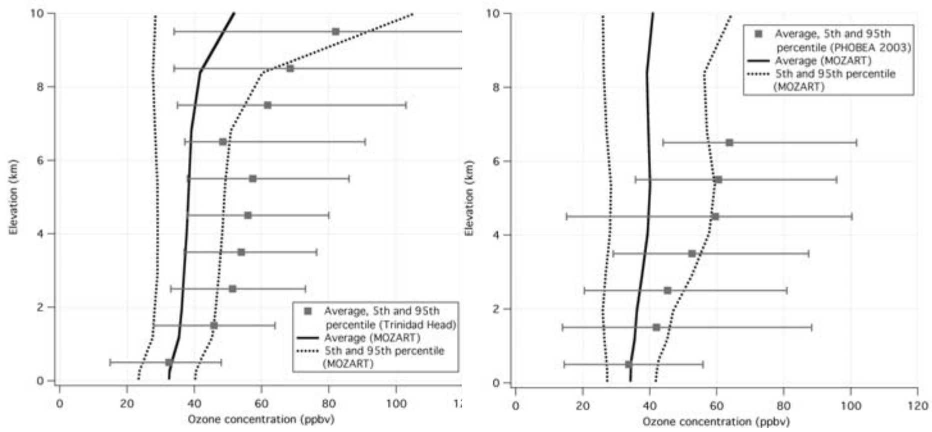


Figure 9. Comparison of observed vertical profiles of O3 along the west coast of the US with results averaged from the global MOZART simulations.

MEGAN Biogenic Emissions Modeling

The Model of Emissions of Gases and Aerosols from Nature (MEGAN) was developed by Dr. Alex Guenther and Dr. Christine Wiedinmyer at the National Center for Atmospheric Research (NCAR) (Guenther et al, 2006). This new model represents the latest NCAR version of the Biogenic Emission Inventory System (BEIS). The purpose of MEGAN is to quantify the net emission of gases between the atmosphere and terrestrial ecosystems. MEGAN uses an approach similar to previous terrestrial biogenic emission models (e.g., BEIS, BEIS2 and GLOBEIS) but is easier to update, use, and expand to other compounds. MEGAN input files and the User's Guide can be downloaded from the NCAR Community Data Portal (https://cdp.ucar.edu/).

In the current project, we have linked MEGAN to the SMOKE emissions processor and have used MEGAN to develop the appropriate emission input files for our 36 km and 12 km CMAQ simulations. The methodology for allocating 1 km resolved MEGAN input variables to the appropriate CMAQ model grids, and further calculating emissions of isoprene, monoterpenes, and other VOC with the MEGAN model framework has been developed and applied for the model simulations. The results are shown in Figure 10a in terms of the July isoprene emission capacity at 30 ^oC for current landcover and in Figure 10b for future landcover. The details of the projection of future landcover are given in the next section. The comparison of these two figures shows that isoprene emission capacity will be significantly reduced in the future due to projected expansion of agriculture and urban areas. Actual July emissions (not shown) are also significantly reduced even though future temperatures will be higher than present day conditions.

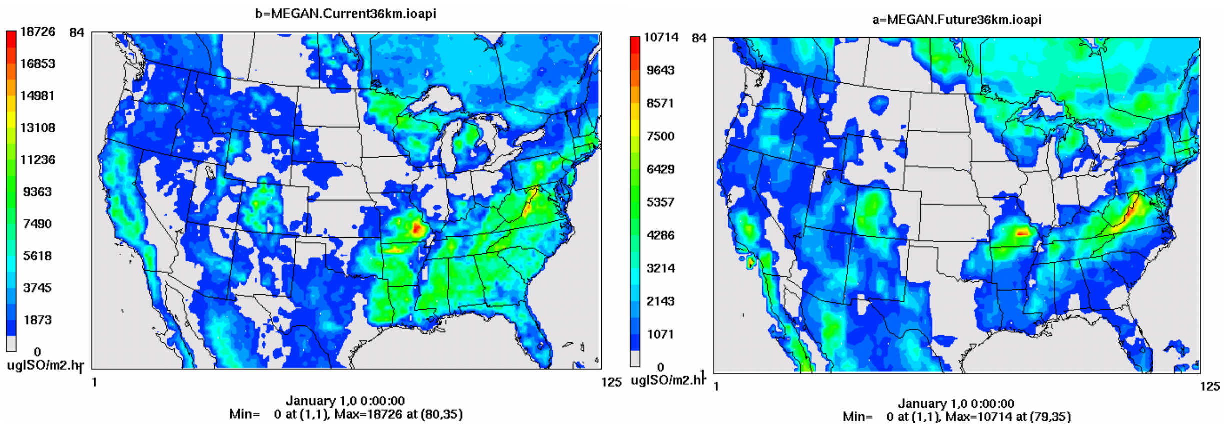


Figure 10. July isoprene emission capacity at 30 ^{o}C for current landcover conditions (left panel) and for future landcover conditions (right panel).

Future Land Cover Scenarios

Investigation into potential land cover scenarios for future years has been on-going. These land cover scenarios are needed to estimate potential changes in biogenic emissions due to climate- and anthropogenically-driven changes. Some potential land cover projections include output from the Community Land Model and the Community Land Model with a Dynamic Global Vegetation Model (CLM and CLM-DGVM; Bonan et al. 2002; Bonan et al. 2003), or output from the MC-1 model (Bachelet et al. 2001). Other researchers have developed potential maps of species distributions in the U.S. (e.g., Shafer et al. 2001).

We have developed a future land use/land cover (LULC) scenario for the 36 km CMAQ domain for 2050 using several available land cover and land use projections. These include the CLM plant functional type (pft) maps for 2050 developed by Johannes Feddema (University of Kansas/NCAR**)** at 0.5 degree horizontal resolution**.** J. Feddema and colleagues have created transient maps (yearly) of land cover from the current time period through 2100 based on an interpolation of the 2100 land use and land cover projections from IMAGE-2 (http://www.mnp.nl/image/). Changes in species distributions in the eastern U.S. for future years and different CO2 background levels as developed by A. Prasad (http://www.fs.fed.us/ne/delaware/atlas/domspp.html) are being used to redistribute tree species within the pfts assigned across of the modeling domain by the CLM maps. This enables a better representation of the redistribution of biogenic emission factors. The distribution of urban and suburban land use throughout the continuous U.S. was determined from the output of the SERGOM model developed by David Theobald of the Colorado State University [Theobald 2005]. The SORGEM model predicts decadal population density for the continental U.S. at high spatial resolutions (100 m) up to 2030. These results were used to determine high resolution changes in high and medium density urban areas across the entire U.S. The combination of these various future land cover and land use projections resulted in a final LULC map used for the 2050 model simulations.

The 36 km future LULC map was reinterpreted to the USGS classifications and further used as input to MM5. The use of this mapping ensures consistency between the modeled meteorology, emissions, and chemistry. For this mapping, the pfts of the CLM 2050 map were assigned to one of the 24 USGS land cover classifications needed by the MM5 model. Each 36 km grid cell was ultimately assigned 1 USGS land cover category based on the CLM pft distributions and the SERGOM population density predictions. The urban SERGOM output was also applied to create spatial surrogates for the redistribution of anthropogenic emissions for the future simulations. These LULC projections were also used to redistribute the biogenic emissions. This new LULC map ultimately reduced potential biogenic emissions due to reduced forest coverages (as shown previously in Figure 10).

Our first effort to examine the sensitivity of air quality to land management decisions was to apply a scenario representing the widespread use of poplar plantations, primarily in the midwestern and eastern US, to sequester carbon (Jackson et al., 2005). The isoprene emission capacity for this scenario is shown in Figure 11 along with the corresponding change in 8 hr ozone concentrations (relative to current conditions). These results show that widespread use of poplar plantations can have a dramatic effect upon isoprene emissions, which will produce a significant increase in ozone concentrations over a relatively large portion of the eastern US. These changes are much larger than any effects due to changes in regional meteorology associated with global climate change.

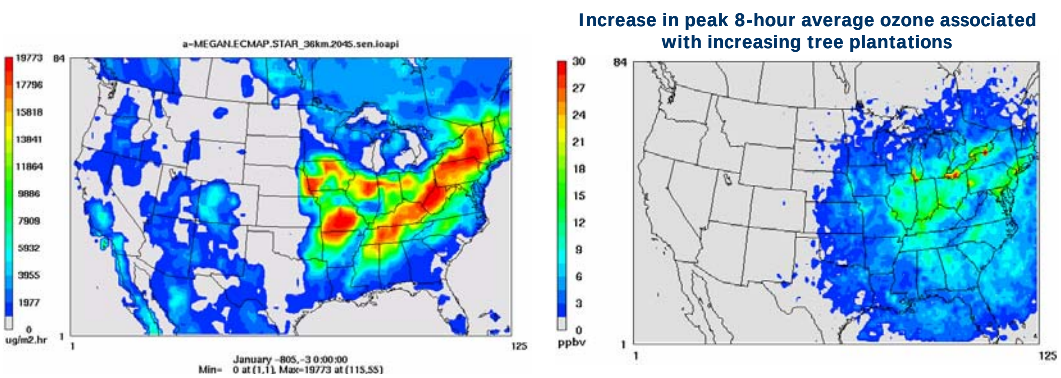


Figure 11. Isoprene emission capacity due to increased use of poplar plantations (left panel) and associated changes in 8 hr average ozone concentrations relative to current conditions (right panel).

Fire Emissions

A fire emissions inventory for 1990-2000 for the continuous U.S. was developed and used as input to the 1990-2000 simulations. This inventory was created using a historical dataset of reported fires from all U.S. federal agencies that has been compiled (Susan Goodman, U.S. Bureau of Land Management, personal communications, 2005). These data are available via ftp://ftp.blm.gov/pub/gis/wildfire/firehistory2003/. Only fires that occurred on federal lands and within the continental U.S. are reported in this database. These data were evaluated and quality assured so that very small fires were removed, as were fires with incomplete or inconsistent associated information. These data were processed for input to the BlueSky-EM emission processor, which calculated specific fire emissions and output CMAQ-ready emissions files for input to the 1990-2000 CMAQ simulations.

To develop gridded fire emissions for future conditions, we have developed a method to account for meteorological controls on wildfire during each year. The primary tool for this process is called the Fire Scenario Builder (FSB). Specifically, the Fire Scenario Builder translates mesoscale meteorology from downscaled climate scenarios into probable fire ignitions and sizes, suitable for consumption and speciation calculations to develop a fire emissions inventory. The design and implementation of the FSB are being led by the Fire and Environmental Research and Applications (FERA) and Atmosphere and Fire Interactions Research and Engineering (AirFIRE) teams of the U.S.D.A. Forest Service Pacific Northwest Research Station.

The FSB incorporates a multitude of underlying models (Figure 12). Initial development focused on validating the FSB by comparing its aggregate output for a single fire season (2003) to wildfire area burned. Küchler potential vegetation types and their associated historical fire cycle are used to determine fire return intervals and a baseline of fire activity. Utilizing convective available potential energy (CAPE) from the mesoscale model to determine lightning activity level, the FSB calculates the availability of ignition sources (lightning + human). Utilizing fuel moisture and energy release component codes from the NFDRS, the FSB calculates flammability, the likelihood of a fire starting and spreading given an ignition source. The FSB then combines these in a Monte Carlo Fire Generator that produces a set of fire locations, times, and sizes.

For future projections, we have combined downscaled meteorology for the decade 2045-2054, predicted mean fire area at the spatial scale of Bailey's ecoprovinces (Littell et al. 2006), and projected changes in life-form (to adjust fuel loadings, e.g., if forest changes to savanna or shrubland). Predicted mean fire areas are used to initialize the FSB with a measure of central tendency for simulated fire-area distributions. The FSB can then simulate fire ignitions and a range of fire sizes as input for future emissions calculations.

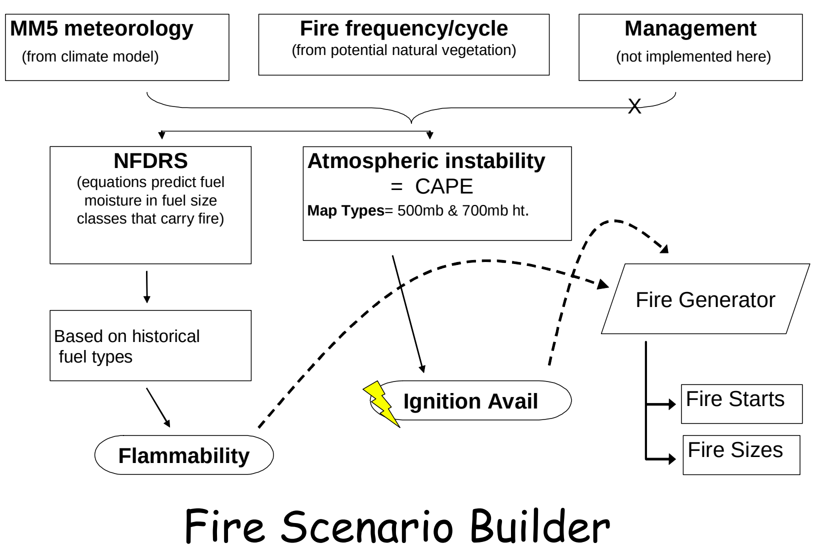
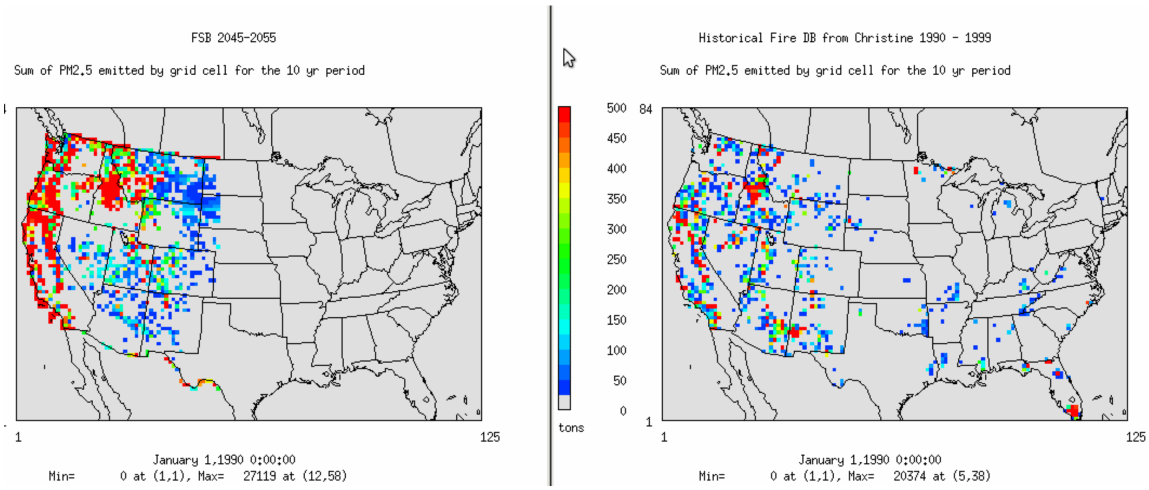


Figure 12. Components of the Fire Scenario Builder.

We compared simulated fire area burned and total emissions from the future projections to empirical values from the current decade (Figure 13). Total fire area was significantly higher in the future runs, as were total emissions, but the two sets of calculations were not entirely comparable, because current-decade results came from inventory data and future-decade results from simulations. Given that the FSB was within 10% of total fire area in the calibration runs for 2003, we can be confident that outputs were roughly comparable. FSB simulations from the current decade, to be conducted next, will further resolve differences between current and future fire emissions.



Simulated future fires　　　　Current decade fires

Figure 13. Comparison of PM2.5 emissions from wildfires for the future and current decades. The results for the current decade are based upon historical fire data, while the results for the future decade are based upon application of the Fire Scenario Builder and downscaled meteorology.

CMAQ Continental and Regional Modeling

During the past year, we have completed the 36 km current and future decade simulations and are very nearly finished with the 12 km decade runs for the Pacific Northwest. We have continued to analyze the results from the completed simulations in terms of comparisons to current observations, and we have begun to analyze differences between current and future air quality conditions. These analyses have focused upon summertime ozone and PM2.5. We have also conducted a series of 'attribution' runs in which we have investigated the effects of changes in future US emissions, future global emissions, and future meteorology upon summertime ozone and PM2.5 concentrations. Results from these different analyses are presented in the following sections.

<u>CMAQ Current decade and Long-term Observations</u> Model output for years 1990-1999 was compared with observed surface ozone data for summers from years 1992-2003 for sites in Pacific Northwest (PNW) and Northern Midwest (NMW). These observations were taken from the EPA AIRS database. Since all chemical transport model runs were performed without observation or analysis nudging, comparisons were made in terms of July monthly maximum concentrations paired only by site. Results for sites in the PNW show that there is generally

good agreement between simulated and observed ozone maxima. For the peak values, the model tends to underestimate, and for concentrations less than approximately 30 ppbv, the model overestimates those lower concentrations. The underestimation of peak values may be due to use of the relatively coarse 36 km grids; this analysis will be repeated using the 12 km results to see if this is true at higher resolution. Figure 14 shows the ratio of predicted/observed ozone concentrations vs observed ozone concentrations for sites within the Pacific Northwest.

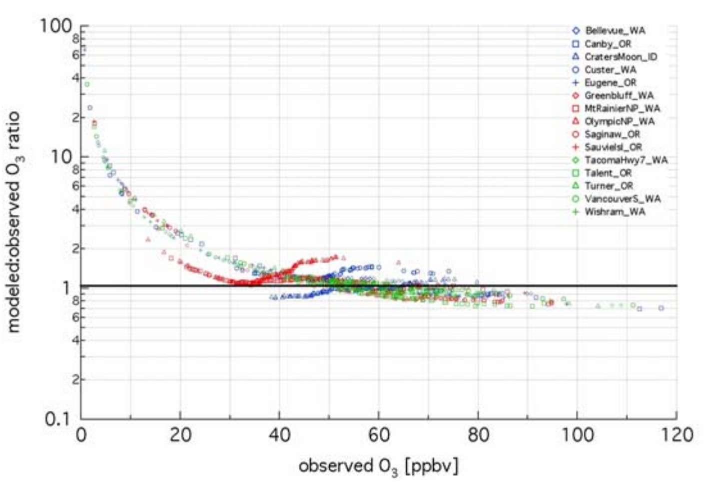


Figure 14. Comparison of observed and CMAQ modeled July monthly maximum ozone concentrations for sites in PNW in terms of the ratio of predicted/observed concentrations vs observed.

We have conducted similar analyses of results for the northern Midwest (NMW) and find that the model tends to predict better at the higher ozone concentrations characteristic of the NMW (Figure 15).

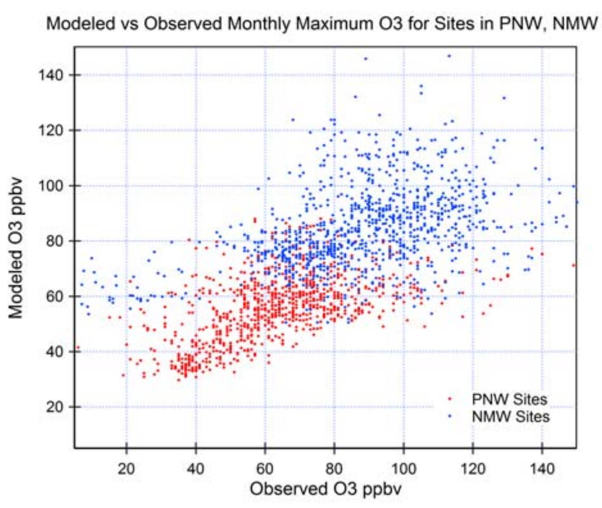


Figure 15. Quantile - quantile plot for modeled and observed ozone monthly maximum for sites in PNW (red dot) and NMW (blue dot), data are paired by both site and month for years 1990-1999.

Similar analyses for monthly maximum hourly PM2.5 concentrations showed a greater range of over and under-prediction as indicated in Figure 16. Close inspection of the results by site suggests that the model tends to overestimate at some of the urban sites (e.g., Beaverton, OR, Hillsboro OR) and significantly underestimates in smaller cities or locations characterized by very complex terrain (e.g., Klamath Falls, OR). Again this may be related to the relatively coarse grid and these results will be re-examined using the 12 km model simulations.

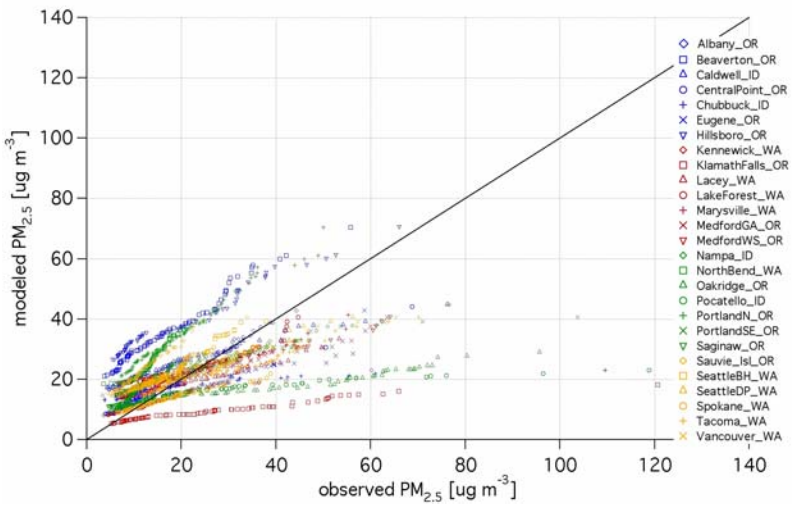


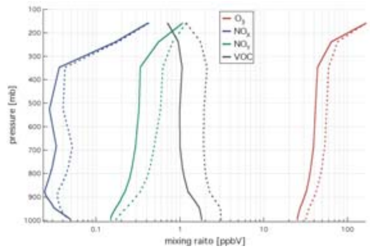
Figure 16. Predicted vs observed hourly monthly maximum PM2.5 concentrations for sites in PNW for years 1990-1999.

Future US Air Quality Conditions

Using the 36 km current and future decade simulations, we have begun an analysis of future air quality conditions in the US. The changes we see are due to (1) changes in global chemical boundary conditions, (2) changes in US emissions, and (3) changes in regional meteorological conditions. The effects of changes in landuse are incorporated into the changes in emissions (although these also play a role in future meteorology and deposition patterns). The changes in global BC are shown in Figure 17 for our west coast and northern continental boundaries.

Boundary Condition Changes

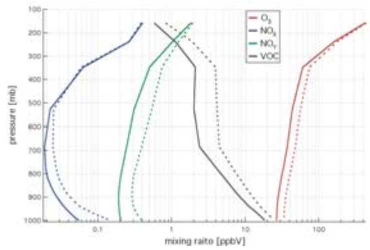
	West BC [ppbv]		
	Current	Future	% Δ
O_3	37.6	50.7	34.8
NO_X	0.030	0.043	44.1
NO_Y	0.279	0.470	68.6
VOC	1.126	2.107	87.1



west

up to 500 mb

	North BC [ppbv]		
	Current	Future	% Δ
O_3	37.1	47.6	28.2
NO_X	0.024	0.034	39.8
NO_Y	0.256	0.424	65.6
VOC	4.390	7.138	62.6



north

Figure 17. Summary of changes in chemical boundary conditions from the current to the future decade for the continental west and north boundaries averaged along the boundary for the month of July.

For ozone, nitrogen oxides and VOCs, there are significant increases in levels in the incoming air masses. These are averages for July months from current and future decades. Along the west coast, ozone concentrations averaged from the surface to the 500 mb level increase by approximately 13 ppbv, while VOC concentrations almost double from 1.1 to 2.1 ppbv. We are also analyzing the MOZART output to identify periodic events with significant impact of Asian air masses.

Changes in US emissions are also significant in the future decade. These changes are based upon EPA projections. These are summarized in Table 1 in terms of anthropogenic and biogenic emissions. Anthropogenic VOC mobile and area source emissions are projected to increase by close to 100%, while NOx emissions will increase by 60% to 90% for area and mobile sources, respectively. As discussed previously, biogenic emissions will actually decrease due to expansion of urban and agricultural areas.

Table 1. Summary of projected changes in US emissions for 2045-2055 relative to 1990-1999 (July averages).

species		anthropogenic				biogenic
		area	mobile	nonroad	point	
CO	1000's ton/day	42.5 (30)	157.1 (92)	68.7 (11)	540 (0)	14.5 (-3.4)
NO		2.4 (62.3)	13.5 (92)	7.5 (9)	344 (0)	4 (2.1)
NO_2		0.2 (62)	1.1 (92)	0.6 (9)	0.03 (0)	0 (0)
CH_4		5.0 (120)	0.2 (101)	0.7 (32)	0.2 (0)	0 (0)
NH_3		15.1 (151)	0.7 (91)	0.01 (5)	0.04 (0)	0 (0)
SO_2		2.7 (56)	0.8 (91)	1.4 (31)	0.3 (0)	0 (0)
$PM_{2.5}$		13.8 (79)	0.5 (91)	0.9 (15)	0.2 (0)	0 (0)
PM_{10}		56.4 (93)	0.6 (91)	1.0 (15)	0.3 (0)	0 (0)
VOC	1000's tonC/day	15.7 (102)	11.3 (90)	5.3 (31)	0.6 (0)	160.1 (-38)

In terms of changes in meteorological conditions, we are examining a variety of meteorological parameters. Examples are shown in Figure 18 in terms of July maximum temperature changes for the US and in Figure 19 in terms of changes in PBL height for locations in the PNW. While there is an overall warming apparent, there are also significant differences between parts of the US. For Seattle, the changes indicate that temperatures will be warmer, which will lead to higher PBL heights. While warmer temperatures may be conducive to higher ozone concentrations; this effect could be offset by a deeper mixed layer and more dilution of pollutants.

The net effects of all of these changes are inherently incorporated into the future simulations of ozone and PM2.5 concentrations as shown in Figures 20 and 21. Figure 20 shows the difference in the occurrence of 8-hr ozone exceedances of 80 ppbv between the current and future decades. This figure shows that the potential to exceed the 8 hr average NAAQS for ozone increases significantly in the future. For PM2.5, there are also significant increases in concentrations, particularly in the eastern US. In terms of changes in the hourly 95th percentile PM2.5 concentration, the average increase for the US for July conditions is 5.7 ug/m^3, compared to the current US average of 20.7 ug/m^3. This is an increase of approximately 25%.

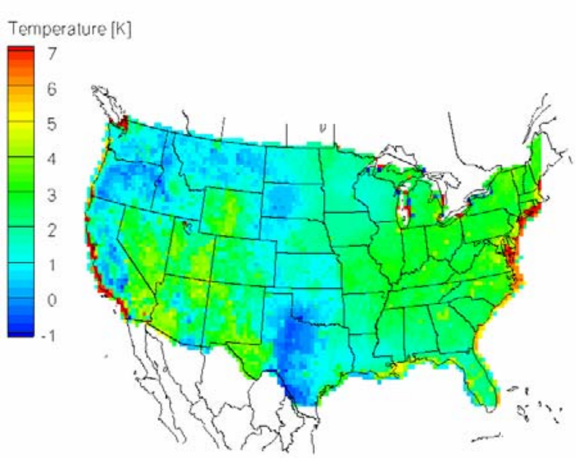
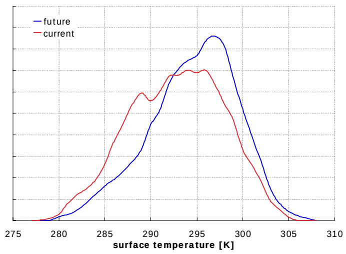
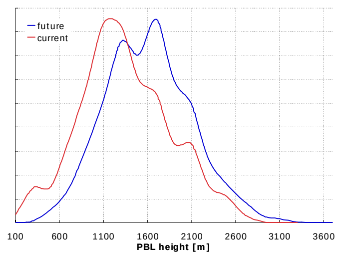


Figure 18. Difference between future-current July maximum temperatures in the US.

Seattle Daytime Meteorology



	average		average maximum		maximum	
	cur	fut	cur	fut	cur	fut
Temp [K]	293.3	+1.8	301.9	+1.1	307.0	+0.9
PBL [m]	1349	+260	2294	+169	3014	+434
wind speed [m s^{-1}]	1.00	-0.07	3.00	-0.92	5.05	-0.48
cloud fraction [%]	21	-4	91	-10	100	+0



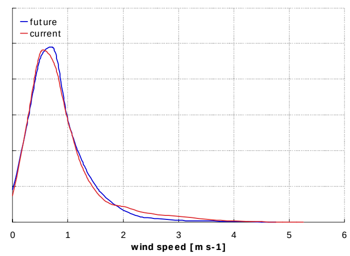


Figure 19. Changes in the frequency distribution, averages and maximum values of meteorological parameters for the Seattle urban area from the current decade to the future 2045-2055 decade. The distributions show a shift toward higher temperatures and higher PBL heights, but little change in wind speed.

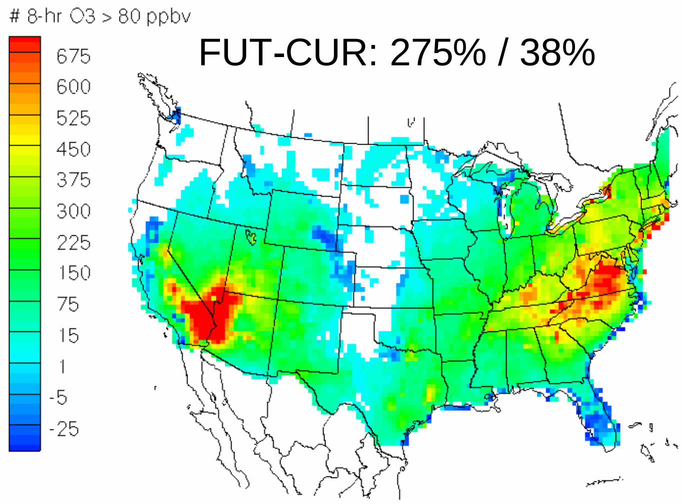


Figure 20. Difference between future and current July conditions in terms of number of times the 8-hr average ozone concentration exceeds 80 ppbv. This is based upon running 8 hr means and thus can include multiple exceedances per day. The numbers listed in the title refer to the average percentage change in the number of US grid hours/day with 8-hr O3>80 ppbv (275%) and the number of U.S. grids with at least one grid hour where 8-hr O3 > 80 ppbv (38%).

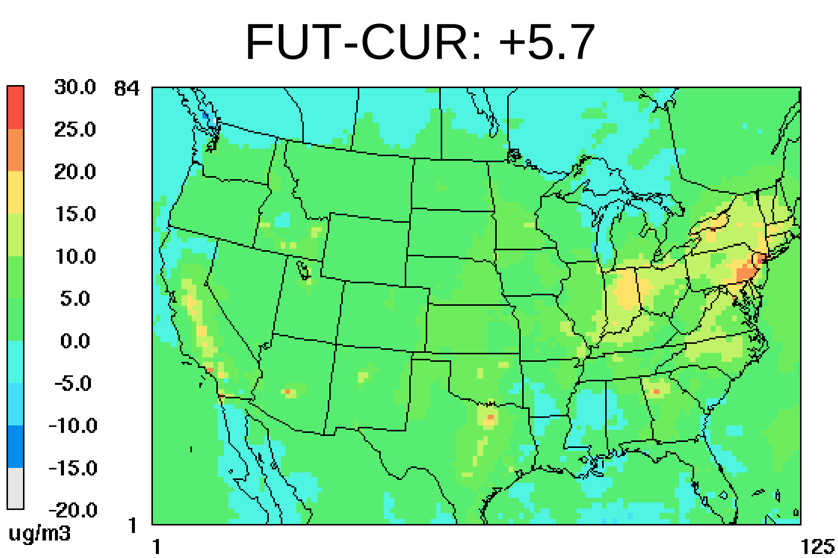


Figure 21. Difference between future and current July conditions in terms of the 95th percentile hourly PM2.5 concentrations. The average increase is 5.7 ug/m^3 for the U.S.

Attribution Analyses

To investigate the importance of changes in global chemical conditions vs local US emissions and local meteorology, we have conducted a series of attribution runs using five current July months and five future July months at the 36 km grid scale. In these runs, we used current conditions for all categories except one which was set to future conditions. These runs are summarized as:

- CUR: current met current BC's current emissions
- FUT: future met future BC's future emissions
- MET: future met current BC's current emissions
- BC: current met future BC's current emissions
- EMIS: current met current BC's future emissions

We are examining the results in terms of changes for the US and also in terms of changes in the PNW specifically. For the US, the changes for each case are summarized in Figure 22 in terms of difference maps relative to the current case (CUR) for the US.

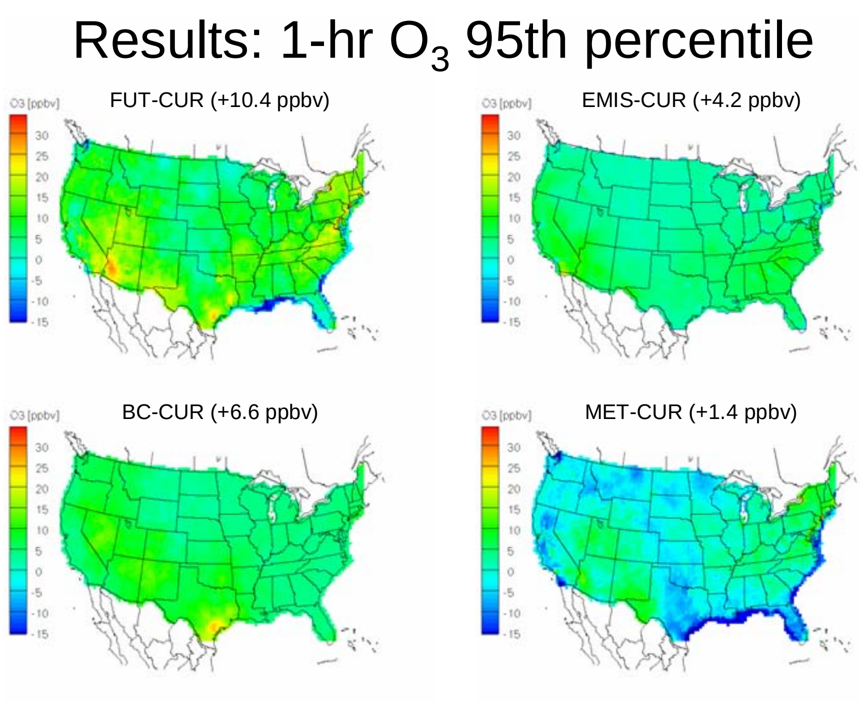


Figure 22. Differences between sensitivity runs and the current case for July hourly ozone concentrations (95th percentile). The numbers in parentheses are the average difference in concentration for the US.

These results show that overall changes in global boundary conditions (BC) and changes in US emissions (EMIS) will dominate the projected changes in ozone concentrations. For the BC case, the change due only to BC changes is 6.6 ppbv and for the EMIS case, the change due only to US emissions is 4.2 ppbv. In comparison, changes in meteorology (MET), are relatively small (1.4 ppbv) for the US. These results highlight the need to account for uncertainties in global modeling and global emission scenarios and to account for uncertainties in projected US emissions. However, it is also important to recognize that the differences for these various cases have different spatial distributions and the effects of BC or EMIS can be quite different in various US locations. The changes due to BC appear to be somewhat higher in the western US, while changes due to EMIS appear to be more significant in the populated eastern US and along the west coast of the US.

For PM2.5 we find similar results, except that the MOZART global BC do not exhibit a significant increase in PM2.5 concentrations in the future. We are working with NCAR to determine why the global PM2.5 doesn't show significant increases similar to other emissions. In the PNW, the changes in hourly maximum PM2.5 (95th percentile) are shown in Figure 23. These results show that changes in local emissions dominate future changes and that changes in meteorology for these July conditions actually leads to a slight reduction in PM2.5 concentrations.

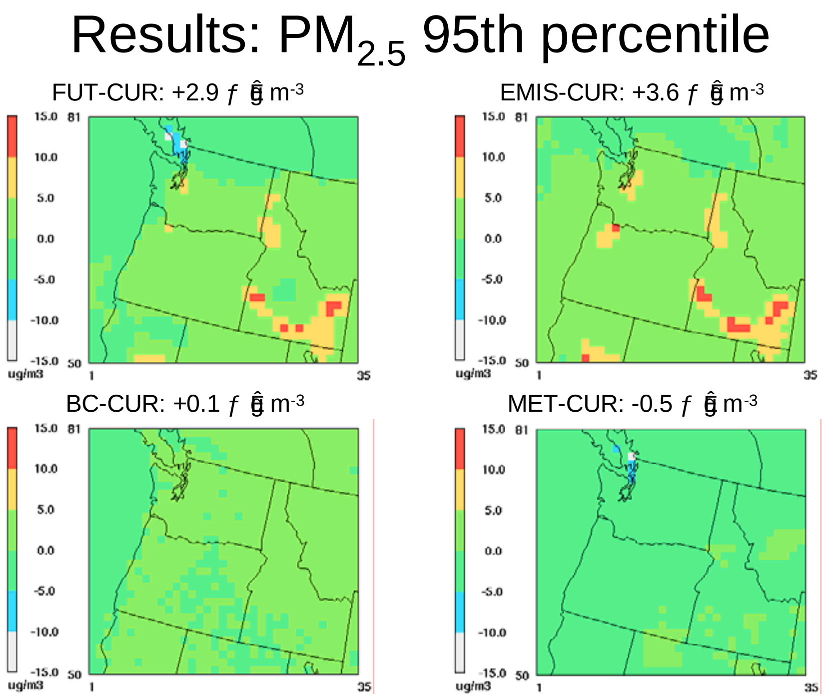


Figure 23. Differences between sensitivity runs and the current case for July hourly PM2.5 concentrations (95th percentile) for the PNW. The numbers are the average differences for this domain.

Budget Expenditures

We requested a no-cost time extension for one year for this project through August, 2007. We have some remaining funds for this additional year and these funds are being used to support Jeremy Avise and Jack Chen as they complete their PhD dissertations.

Quality Assurance Procedures

As indicated above, we have completed 36 km current and future decade simulations and are nearing completion of the future 12 km simulations. As these results have become available, we have analyzed the MM5 and CMAQ output in terms of spatial contours of various parameters, time series of parameters at specific locations, calculation of means, standard deviations and other statistics. These analyses have two objectives. First, we are interested in understanding the characteristics of the decadal simulations and differences between decades. Second, these analyses of the input parameters provide a level of quality assurance on our input data. In addition to these analyses, we are following the modeling guidelines in terms of code documentation, data backup, and other QA steps. We have acquired AIRS air quality observations for the 1994-2005 and these have provided the basis for comparing the air quality climatology represented by the observations with the model climatology for this recent decade. This is important for confirming that the modeling system performance is adequate for further analysis of future impacts.

Publications/Presentations
(updated 10/29/2006)

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.

Avise, J., J. Chen, B. Lamb, A. Guenther, C. Wiedinmyer, C. Mass, E. Salathe, S. O'Neill, 2005. Influence of Global Change on Regional Air Quality in the Pacific Northwest and Northern Midwest Regions, *EPA Science Forum, Collaborative Science for Environmental Solutions.* Washington, DC.

Avise, J., J. Chen, B. Lamb, C. Wiedinmyer, A. Guenther, J.-F. Lamarque, E. Salathe, C. Mass, S. O'Neill, D. McKenzie, N. K. Larkin, 2005. Influence of Global Change on Regional Air Quality in the Pacific Northwest and Northern Midwest. *2005 NOAA/EPA Golden Jubilee Symposium on Air Quality Modeling and Its Applications*. Durham, NC.

Chen, J., J. Avise, J. Vaughan, B. Lamb, A. Guenther, C. Wiedinmyer, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin, S. Furguson, 2004. Impact of Climate Change on US Air Quality using Multi-Scale Modeling with the MM5/SMOKE/CMAQ System. *American Geophysical Union (AGU) Annual Meeting*, San Francisco, CA.

Chen, J., J. Avise, B. Lamb, A. Guenther, C. Wiedinmyer, J.-F. Lamarque, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin, 2005. Influence of Global Change on Regional Air Quality in the Pacific Northwest Region. *PNWIS/A&WMA 45th Annual Conference*. Blaine, WA.

Chen, J., J. Avise, B. Lamb, A. Guenther, C. Wiedinmyer, J.-F. Lamarque, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin, 2006. Influence of Global Change on Regional Air Quality in the Pacific Northwest Region. *American Meteorological Society 86th Annual Meeting*. Atlanta, GA.

Chen, J., J. Avise, B. Lamb, A. Guenther, C. Wiedinmyer, J.-F. Lamarque, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin, 2006. Influence of Global Change on Regional Air

Quality in the Pacific Northwest Regions. *EPA Science Forum, Global Challenge.* Washington, DC.

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. 2006. How will climatic change affect air quality in parks and wilderness? In: D. Harmon, ed. Proceedings of the George Wright Society Annual Meeting, Philadelphia, PA.

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.

McKenzie, D., S.M. O'Neill, N. Larkin, R.A. Norheim, and J. Lenihan. August 2004. Modelling regional haze from prescribed and wildland fire. Annual meeting of the International Society for Ecological Modelling, Quebec City, Quebec, Canada.

O'Neill, S.M., and D. McKenzie. June 2006. Climate change and air quality. Invited presentation at the University of Washington CSES Climate Impacts Group.

Publications

Avise, J., J. Chen, B. Lamb, C. Wiedinmyer, A. Guenther, J.-F. Lamarque, E. Salathe, C. Mass 2006. Sensitivity of regional air quality due to globally-forced boundary conditions. Submitted to *Journal of Applied Meteorology*

Chen, J., J. Avise, B. Lamb, A. Guenther, C. Wiedinmyer, J.-F. Lamarque, C. Mass, E. Salathe, S. O'Neill, D. McKenzie, N. Larkin (2006). Global Change impacts on Regional Air Quality in the United States. *In preparation*

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. 2006. Integrating models to predict regional haze from wildland fire. Ecological Modelling Volume 199, issue 3, pages 278-288.

Wiedinmyer, C., B. Quayle, C. Geron, A. Belote, D. McKenzie, S. O'Neill, K. K. Wynne, 2006. Estimating emissions from fires in North America for air quality modeling, Atmospheric Environment, **40**, 3419-3432.

Future Activities

Our primary objectives in the coming year are threefold: 1) to complete the long term MM5/SMOKE/CMAQ simulations for the regional case and to analyze the results of these simulations, 2) to conduct additional sensitivity simulations to help evaluate uncertainties in the analysis; and 3) compile these results in a number of papers for publication.

Relevant Web Sites

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

References

Bachelet, D., J.M. Lenihan, C. Daly, R.P. Neilson, D.S. Ojima, W.J. Parton (2001) MC1. A dynamic vegetation model for estimating the distribution of vegetation and associated ecosystem fluxes of carbon, nutrients and water. Technical Documentation Version 1.0. General Technical Report PNW-GTR-508. Corvallis, OR. USDA Forest Service, Pacific Northwest Research Station.

Bertschi, I. T., D. A. Jaffe, L. Jaeglé, H. U. Price, and J. B. Dennison, 2004: PHOBEA/ITCT 2002 airborne observations of transpacific transport of ozone, CO, volatile organic compounds, and aerosols to the northeast Pacific: Impacts of Asian anthropogenic and Siberian boreal fire emissions. *J. Geophys. Res.*, **109**, D23S12, doi:10.1029/2003JD004328.

Bonan, GB; Levis, S; Sitch, S; Vertenstein, M; Oleson, KW. 2003. A dynamic global vegetation model for use with climate models: concepts and description of simulated vegetation dynamics. *GLOBAL CHANGE BIOLOGY* 9 (11): 1543-1566.

Bonan, GB; Oleson, KW; Vertenstein, M; Levis, S; Zeng, XB; Dai, YJ; Dickinson, RE; Yang, ZL. 2002. The land surface climatology of the community land model coupled to the NCAR community climate model. *JOURNAL OF CLIMATE* 15 (22): 3123-3149.

Cohen, J.D., J.E. Deeming, 1985. The National Fire-Danger Rating System: Basic Equations. PSW GTR PSW 82 16p.

Guenther, A., T. Karl, P. Harley, C. Wiedinmyer , P. I. Palmer, C. Geron, Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), *Atmospheric Chemistry and Physics*, 6, 3181–3210, 2006.

Horowitz, L. W., S. Walters, D. L. Mauzerall, L. K. Emmons, P. J. Rasch, C. Granier, X. Tie, J. F. Lamarque, M. G. Schultz, G. S. tyndall, J. J. Orlando, and G. P. Brasseur, 2003: A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2. *J. Geophys. Res.*, **108**, D24, 4784, doi:10.1029/2002JD002853.

Littell, J.S., McKenzie, D., and Peterson, D.L. 2006. Ecological Context of Climate impacts on fire: Wildland fire area burned in the western U.S. 1916-2003. submitted to Ecological Applications.

McKenzie, D., S.M. O'Neill, N. Larkin, and R.A. Norheim. 2005. Integrating models to predict regional haze from wildland fire. Ecological Modelling, Volume 199, issue 3, pages 278-288.

Shafer, S. L., P. J. Bartlein, R.S. Thompson (2001) Potential Changes in the Distributions of Western North America Tree and Shrub Taxa under Future Climate Scenarios, *Ecosystems*, 4: 200–215.

Theobald, D. (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society* **10**(1): 32. [online] URL: http://www.ecologyandsociety.org/vol10/iss1/art32/

Vavrus, S., Walsh, JE, Chapman, WL, and Portis, D (2005) Simulations of Wintertime Arctic Air Surges into Middle Latitudes. *Amer. Meteorol. Soc., 16th Conference on Climate Variability and Change.*