Project Title:	Sensitivity Analysis of Air Quality to Meteorological Data in Fire Simulations
Final Report:	JFSP Project Number 12-3-01-6
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This research was sponsored in part by the Joint Fire Science Program.
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1. Abstract

Uncertainties associated with meteorological inputs which are propagated through atmospheric chemical transport models may constrain their ability to replicate the effects of wildland fires on air quality. Here we investigate the sensitivity of predicted fine particulate matter ($PM_{2.5}$) concentrations to uncertain wind fields by simulating the air quality impacts of wildland fires on urban areas with the Community Multiscale Air Quality modeling system (CMAQ). Brute-force sensitivity analyses show that modeled concentrations at receptors downwind from the fires are highly sensitive to variations in wind speed and direction. Additionally, uncertainty in weather fields produced with the Weather Research and Forecasting model (WRF) was assessed by evaluating meteorological predictions against surface and upper air observations. Significant differences between predicted and observed wind fields were identified. Simulated $PM_{2.5}$ concentrations at urban sites displayed large sensitivities to wind perturbations within the error range of meteorological inputs. The analyses demonstrate that normalized errors in CMAQ predictions attempting to model the regional impacts of fires on $PM_{2.5}$ concentrations could be as high as 100% due to inaccuracies in meteorological data. Meteorological drivers may largely account for the considerable discrepancies between monitoring site observations and predicted concentrations. The results of this study demonstrate that limitations in fire-related air quality simulations cannot be overcome by solely improving emission rates.

2. Background and purpose

Wildland fires may greatly impact air quality and pose a significant threat to public health (Delfino et al., 2009). The adverse effects of smoke from wildfires and prescribed burns on air pollution levels and visibility have been investigated in numerous studies (Fox and Riebau, 2009; Johnston et al., 2012; Kochi et al., 2010). Air quality models can serve as tools to quantify exposure to fire-related pollution and provide important information to fire and land managers. However, the limitations inherent to numerical models when used to replicate the air quality impacts of fires must be identified and well understood to adequately interpret results and further improve the models' predictive skills.

Multiscale atmospheric chemical transport models provide an appealing framework to simulate the effects of wildland fires on air quality: complex chemical and physical processes are represented; local and regional scales can be jointly treated; and detailed emissions and meteorological fields can be used to drive air quality modeling. Multiple attempts to replicate the impacts of fires on air quality with Eulerian models have been reported (Goodrick et al., 2012). Commonly, model performance in these simulations, assessed by comparing forecasted and observed pollutant concentrations, has been unsatisfactory and a need to improve predictions has been recognized.

Air quality models require two fundamental inputs: meteorological fields and emission rates. The importance of meteorological input fields in air quality simulations has long been acknowledged [Seaman, 2000]. However, prior studies seeking to simulate the impacts of wildland fires with Eulerian air quality models have generally focused on better characterizing fire-related emissions as a strategy to strengthen model performance (Konovalov et al., 2011; Tian et al., 2009; Yang et al., 2011). In contrast, little attention has been given to the implications uncertain meteorological inputs may have on model predictions. Still, weather conditions determine the principal physical driving forces in the atmosphere, making gridded representations of meteorology the foundation of all three-dimensional air quality simulations. While enhanced fire emissions estimates can improve the accuracy of air quality simulations, errors associated with weather data continue to affect model results. Therefore, determining the degree to which uncertainties in meteorological inputs might hinder fire-related simulations is an important step towards successfully modeling the impacts of wildland fires on pollutant levels with atmospheric chemical transport models.

Sensitivity analyses are an important diagnostic tool to evaluate the influence individual inputs may have on specific model outputs. In this study, a regional-scale chemical transport model is used to simulate smoke transport from wildland fires and a series of sensitivity analyses are applied to explore the responsiveness of $PM_{2.5}$ concentrations predicted by the air quality model to uncertainties in three-dimensional meteorological fields. The analyses focus on primary fine carbonaceous particle emissions from fires, the main component of fire-related smoke, and wind, the meteorological variable most directly associated with fire-attributable impacts on $PM_{2.5}$ concentrations. The results of this work indicate the extent to which simulations may be constrained by inaccuracies in meteorological data produced by numerical weather prediction models. Additionally, the study seeks to investigate whether the errors in predicted concentrations can be abated by exclusively focusing on better estimation of fire-related emissions.

3. Study description

Air quality modeling framework

The Community Multiscale Air Quality Modeling system (CMAQ version 4.5, http://www.cmaq-model.org/) was used to numerically simulate the transport and transformation of pollutant emissions (Byun and Schere, 2006). CMAQ is a third-generation air quality model maintained by the U.S. Environmental Protection Agency which has been widely applied for regulatory and policy analysis purposes, as well as atmospheric research. Emission inputs from non-fire sources were processed with the Sparse Matrix Operator Kernel Emission processor (SMOKE version 2.1, http://www.smoke-model.org/index.cfm). Emissions considered by SMOKE include area, mobile, biogenic, and point sources and are derived from emissions inventories and land use data. Emission rates for wildland fires featured in the simulated urban smoke episode were prepared through the Fire Emissions Production Simulator (FEPS version 1.1.0, http://www.fs.fed.us/pnw/fera/feps/). FEPS can provide hourly emissions and heat release rates for prescribed burns or wildfires involving a large variety of forest, shrub, and grassland types. Plume rise estimates from the Daysmoke model (Achtemeier et al., 2011) were used to vertically distribute fire emissions. Daysmoke is an empirical-statistical fire impact model developed by the U.S. Forest service to simulate plume rise and dispersion of smoke from prescribed burns.

Meteorological fields produced with the Weather Research and Forecasting Model (version 2.1.2) were used to drive all air quality modeling (Skamarock et al., 2008). WRF is a mesoscale numerical weather prediction system extensively used for atmospheric research and forecasting purposes. The model has been previously applied to simulate weather at scales varying from less than a kilometer to thousands of kilometers. The meteorological simulations were carried out using the configuration used in an operational air quality forecasting system in Atlanta which has been used by forecasters in the state of Georgia since 2006 (Hu et al., 2010). Simulations were initialized, constrained at the boundaries, and nudged at 6-hour intervals using reanalysis fields from the North American Mesoscale model (nomads.ncdc.noaa.gov).

Sensitivity analyses

A brute-force method was applied to carry out sensitivity analyses. The method relies on successively simulating the same system of interest while varying a specific model input and holding others constant to observe the response of model outputs (Hwang et al., 1997). In air quality modeling, brute-force sensitivity analyses have been frequently used to quantify the responsiveness of simulated concentrations to changes in emissions. Here, the brute-force method is applied to assess the sensitivity of simulated $PM_{2.5}$ concentrations to perturbations in meteorological inputs. A series of simulations under perturbed meteorological fields were carried out to examine the responsiveness of CMAQ-predicted $PM_{2.5}$ concentrations at specific downwind receptors. Meteorological variables were modified within the Meteorology-Chemistry Interface Processor (MCIP, version 3.4.1, (Otte and Pleim, 2010)) used to convert WRF output fields into CMAQ-compatible inputs. For example, the magnitude and direction of wind vectors read in from WRF-generated fields were perturbed to varying extents to produce modified CMAQ inputs, as illustrated in Figure 1. In this manner, perturbations are reflected in all wind-associated variables included in the meteorological input data used to drive the air quality model. It is also important to note that mass conservation was ensured by adjusting vertical winds (Hu et al., 2006).

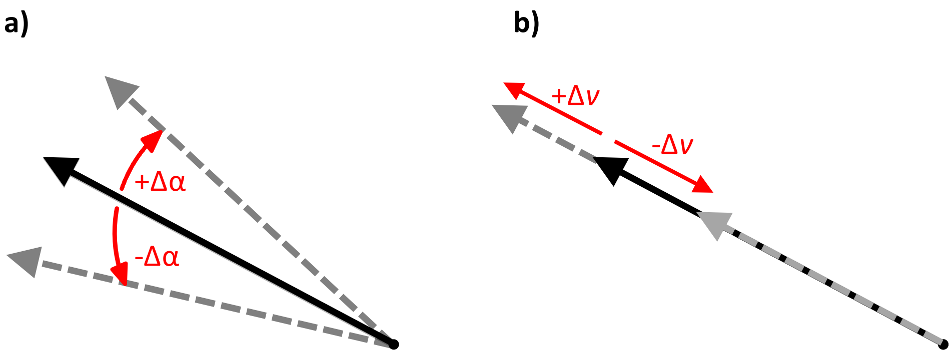

Figure 1. Representation of perturbations applied to (a) wind direction and (b) wind speed in brute-force sensitivity analysis.

Meteorological uncertainty

Meteorological model performance was evaluated to assess the level of uncertainty in weather fields used to drive air quality simulations. Hourly surface observations from the Research Data Archive of the National Center for Atmospheric Research (http://rda.ucar.edu/datasets/ds472.0/) were used to compute model performance metrics by comparing surface-layer observations and predictions. Bias and error in WRF-derived ground-level predictions were estimated for wind direction, wind speed, temperature, and humidity. Additionally, upper air model predictions were evaluated against atmospheric soundings.

Simulated smoke episodes

Several smoke episodes affecting urban areas in the Southeast U.S. were simulated to achieve the project objectives. The selected episodes include both prescribed burns and wildfires, covering different spatial and temporal scales, and involving different numbers of fires. In the episodes downwind urban monitoring stations evidenced a strong increase in observed pollutant concentrations likely attributable to fires. The first case involved a prescribed burn at Fort Benning, GA on Apr. 9th, 2008 which consumed 300 acres. On this day $PM_{2.5}$ concentrations observed at the Columbus, GA airport monitoring site doubled within an hour. The second case was a smoke episode in Atlanta, GA on Feb. 28th, 2007 believed to be caused by two prescribed burns 80 km southeast which consumed close to 3,000 acres. Within hours of ignition $PM_{2.5}$ levels observed at monitoring sites throughout metro Atlanta increased to nearly 150 μg m^{-3}. The final smoke episode selected for simulation was a series of wildfires which occurred in the spring of 2007 along the Georgia-Florida border and burned about half a million acres of vegetation from April to June. For this episode major impacts to pollutant levels were recorded at monitoring stations throughout the Southeast, including sites in Atlanta, Savannah, Macon, and Birmingham. Recorded peak $PM_{2.5}$ concentrations at the affected locations varied from 120 to 350 μg m^{-3}. An example of a simulation attempting to replicate a smoke incident is presented in Figure 2, which shows the surface-level $PM_{2.5}$ concentrations predicted by CMAQ on May 17th, 2007 at the time high $PM_{2.5}$ concentrations were observed in Savannah during the Georgia-Florida wildfires.

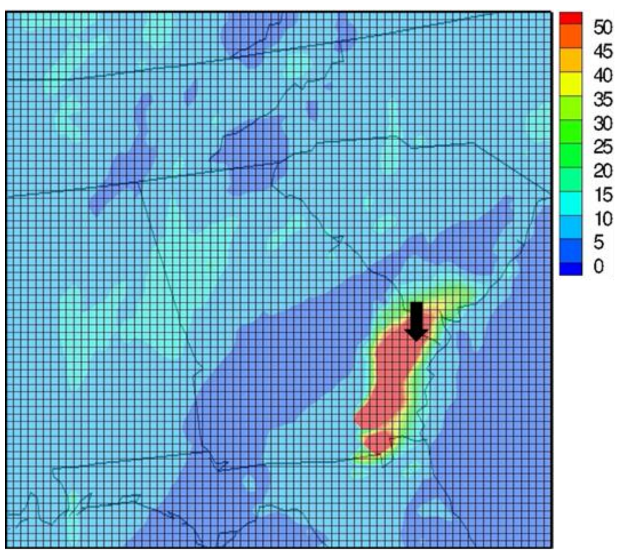

Figure 2. Predicted surface-level $PM_{2.5}$ concentrations (μg m^{-3}) over the southeastern U.S. during the Savannah smoke incident of May 17, 2007 at 14:00 LT (local time). The location of Savannah is indicated by the black marker.

Wind-associated error in $PM_{2.5}$ predictions

Meteorological fields are a key driver in air quality modeling. Errors associated with meteorological inputs propagate through air quality models and affect the accuracy of pollutant concentration predictions. Therefore, it is essential to evaluate the extent to which the performance of air quality models may be limited by uncertain meteorological input data. The process entails (1) determining the output variables most relevant to the modeling application, (2) identifying the input variables that significantly influence the values of the outputs of interest, (3) assessing the range of uncertainty in these model inputs, and (4) quantifying the sensitivity of output variables to input variable perturbations within their uncertainty range. In simulations attempting to replicate the impacts of wildland fires on air quality, ground-level pollutant concentrations at downwind locations are the output variables of greatest interest. Furthermore, in this study we focus on $PM_{2.5}$, the atmospheric pollutant most commonly associated with fire-related air quality impacts. Typically, a few input variables control the value of specific model outputs. For air quality simulations involving wildland fires, wind inputs are clearly among the variables dominating predicted $PM_{2.5}$ concentration. Here, uncertainties in wind inputs were explored by comparing meteorological predictions and observations. Finally, brute force sensitivity analyses were used to determine the potential response of modeled $PM_{2.5}$ concentrations to errors in wind field inputs.

4. Key findings

The air quality modeling system was able to predict the local impact of a single fire with reasonable accuracy, but exhibited inferior performance in an extended regional-scale simulations or when attempting to model multiple fires.

At a local-scale, the modeling system was able to predict the impact of a single prescribed burn smoke plume on air quality at a downwind receptor with reasonable accuracy. For the simulation of a prescribed burn at the Fort Benning, GA on April 9, 2008, CMAQ predicted a sharp increase in $PM_{2.5}$ concentrations that approximately matched the increment in concentration observed at the Columbus Airport, 30 km from the location of the fire. However, when applied to simulate regional-scale smoke transport from multiple wildfires over a prolonged period the system did not perform as well for simulating air quality. On the simulation of the Georgia-Florida wildfires of 2007 CMAQ severely underestimated the impacts on $PM_{2.5}$ concentrations at urban locations downwind. Additionally, the discrepancies between observed and modeled concentrations heightened as distance between the wildfires and receptors increased.

Simulations attempting to model smoke transport from fires with chemical transport models are significantly sensitive to meteorological inputs

The smoke simulations carried-out reflect the importance of meteorological drivers in modeling applications attempting to reproduce the transport of fire-related smoke. The influence of wind fields on predicted pollutant concentrations is evident in the long-range transport of fire-relate emissions within the Georgia-Florida wildfires simulation. Although predicted smoke trajectories agreed with observed concentration peaks during most of the urban air quality incidents explored, in at least one of the locations selected sizable discrepancies between observed and modeled pollutant concentrations seem to be mainly attributable to errors in wind-driven smoke transport. Even at considerably smaller spatial and temporal scales, such as those pertaining to the Fort Benning simulation, a strong influence of meteorological inputs on air quality modeling results is apparent; the severity of predicted impacts at downwind receptors is largely dependent on the meteorological fields used to drive dispersion.

Simulations attempting to replicate the impact of fires on $PM_{2.5}$ concentrations are very sensitive to wind direction in meteorological fields.

To examine the sensitivity of CMAQ-predicted $PM_{2.5}$ concentrations to wind direction, the Atlanta 2007 smoke episode was modeled under a series of perturbed wind fields, produced by uniformly modifying wind direction across the entire domain. The changes were applied at each grid point by rotating all wind vectors in WRF-generated meteorological fields by the same angle. At selected downwind monitoring sites, predicted $PM_{2.5}$ concentrations for each perturbed wind field and the base case were compared to observe the responsiveness to variations in wind direction. For example, Figure 3 shows $PM_{2.5}$ concentrations simulated by CMAQ at the Jefferson St. monitoring site in Atlanta with both perturbed and unperturbed fields. The sensitivity of predicted $PM_{2.5}$ concentrations to wind direction is very high at all sites considered.

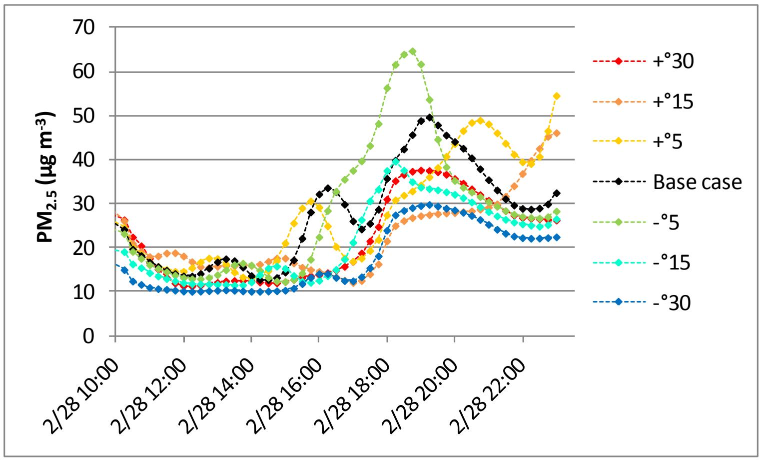

Figure 3. CMAQ-predicted $PM_{2.5}$ concentrations at the Jefferson St. monitoring site using wind direction perturbations on 28 February 2007 (LT). Base case simulation results are also included.

The results indicate that small variations in wind direction can lead to large changes in predicted pollutant concentrations at specific receptors downwind. Peak $PM_{2.5}$ concentrations predicted at sites within Atlanta increased by as much as 8 to 30% with perturbed wind fields. The influence of wind direction on air quality modeling results can be observed in Figure 4 which compares ground-level $PM_{2.5}$ concentration predictions after applying different perturbations to wind direction. The figure shows how a 10° difference in wind direction can completely change a smoke plume's predicted impact at downwind receptors. Within this 10° wind direction variation range, predicted $PM_{2.5}$ concentrations at Atlanta may vary by more than 30 µg m^{-3}. The sensitivity analysis demonstrates that wind direction in meteorological inputs is a key element of air quality simulations attempting to replicate the impacts of fires and accurate wind directions are essential to produce realistic predictions.

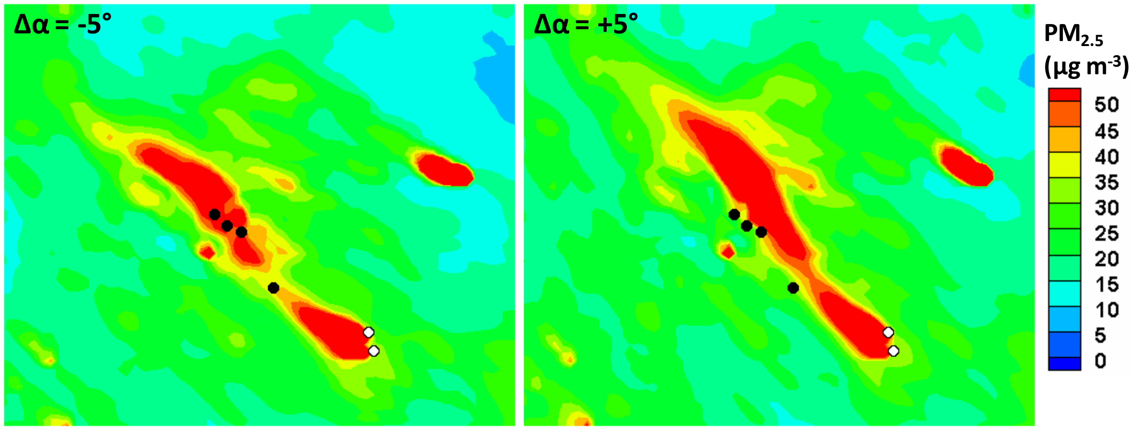

Figure 4. CMAQ-predicted $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) over northern Georgia at 1900 LT on 28 February 2007 using -5° and +5° perturbations to wind direction. Black shaded circles indicate monitoring station locations. Fire sites are denoted by white shaded markers.

Simulations attempting to replicate the impact of fires on $PM_{2.5}$ concentrations are extremely sensitive to wind speed in meteorological input fields.

Similarly to the perturbations on wind direction, modified wind fields were produced by uniformly changing wind speeds across meteorological inputs to explore the sensitivity of CMAQ-predicted $PM_{2.5}$ concentrations to wind speed. Large differences exist between predicted concentrations at downwind receptors under different modified fields. In Figure 5, for instance, simulated $PM_{2.5}$ concentrations at the South DeKalb monitoring site are shown for each perturbation during the Atlanta smoke episode. A strong response to variations in wind speed is evident at all receptors considered; $PM_{2.5}$ concentrations significantly increased and experienced a growing delay with decreasing wind speeds.

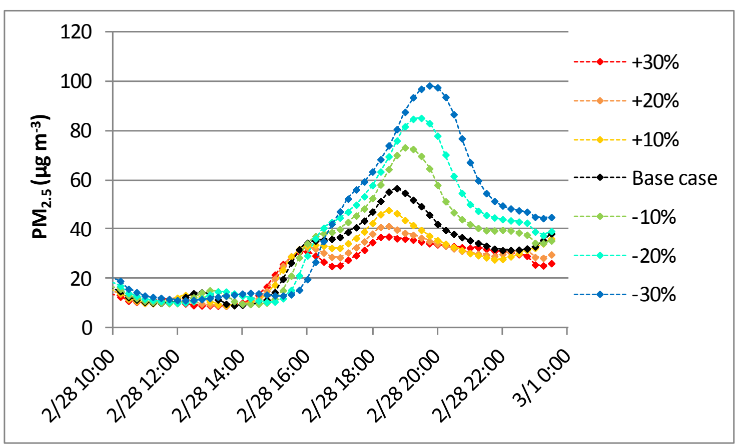

Figure 5. CMAQ-predicted $PM_{2.5}$ concentrations on 28 February 2007 (LT) at the South DeKalb monitoring site with wind speed perturbations. Base case simulation results are also included.

Several factors contribute to the large differences in $PM_{2.5}$ concentration predictions obtained applying different perturbations. Most importantly, changes to wind speed bring about significant differences in the dispersion of fire-related emissions. While larger wind speeds intensify advective transport, decreasing wind speed allows $PM_{2.5}$ emissions to accumulate within a smaller volume and reach higher concentrations. The effect wind speeds can have on smoke plume dispersion in Eulerian models is depicted in Figure 6. As wind speed increases, dispersion of smoke occurs at a higher rate. The sensitivity analyses suggest that uncertain wind speed estimates may play an important role in the underpredictions commonly associated with simulations attempting to replicate the air quality impacts of fires.

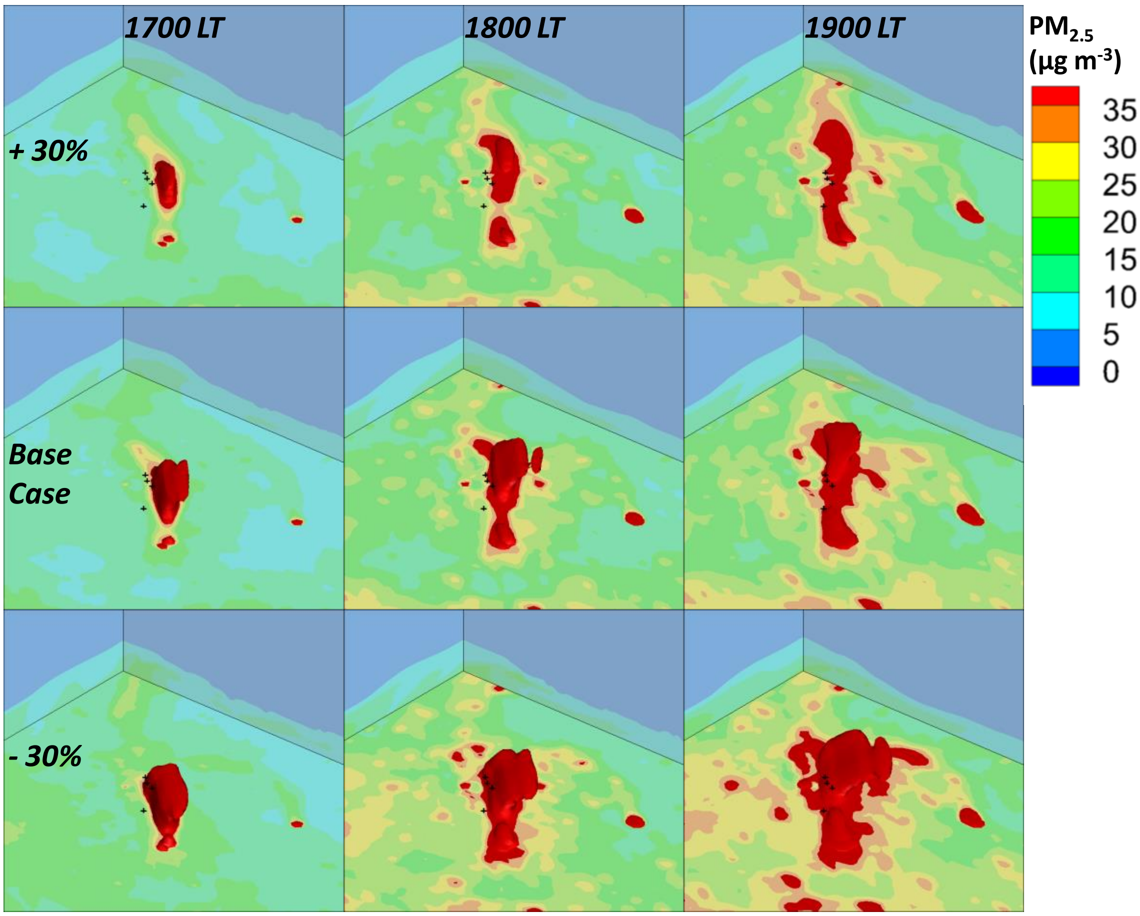

Figure 6. Modeled pollution plumes on 28 February 2007 (LT) shown as three-dimensional iso-surfaces bounded by $PM_{2.5}$ concentration equal to 35 µg m-3 for base case and simulations carried out with ±30% perturbations to wind speed. Ground-level $PM_{2.5}$ concentrations (µg m-3) are also shown. Air quality monitoring sites are indicated by black markers.

The sensitivity of predicted $PM_{2.5}$ concentrations to wind fields increases as grid resolution is refined in regional-scale simulations.

In assessing the responsiveness of modeled concentrations to meteorological inputs, it is important to consider the influence of model resolution on sensitivity estimates. To explore the relationship between grid resolution and the sensitivities of CMAQ-predicted $PM_{2.5}$ concentrations, the Atlanta 2007 smoke episode was modeled under 4 and 12 km horizontal grid resolutions and sensitivities to wind direction and speed were evaluated at each resolution. The analyses showed that simulated $PM_{2.5}$ concentrations at the downwind receptors considered were significantly less sensitive to wind field perturbations under coarser grid resolution. For example, Figure 7 compares the standard deviation of predicted $PM_{2.5}$ concentrations at the Confederate Ave. monitoring site for all simulations carried out under perturbed wind fields using 12 km horizontal grid resolution to that of simulations using 4 km resolution. At Confederate Ave. the average standard deviation for $PM_{2.5}$ concentrations within both the wind direction and wind speed simulation sets decreases by approximately 35% when horizontal grid resolution is coarsened from 4 to 12 km, while maximum hourly standard deviations fall by nearly 50%.

The impact of coarser resolution is similar at other sites within the city of Atlanta. The differences between the sensitivities of $PM_{2.5}$ concentrations to wind fields using 4 and 12 km horizontal grid spacing demonstrate a strong connection between the potential impact of meteorological uncertainty and model resolution. As fire-related air quality simulations undertaken with Eulerian models move towards even finer levels of resolution, the sensitivity of predicted pollutant concentrations to wind fields can be expected to increase.

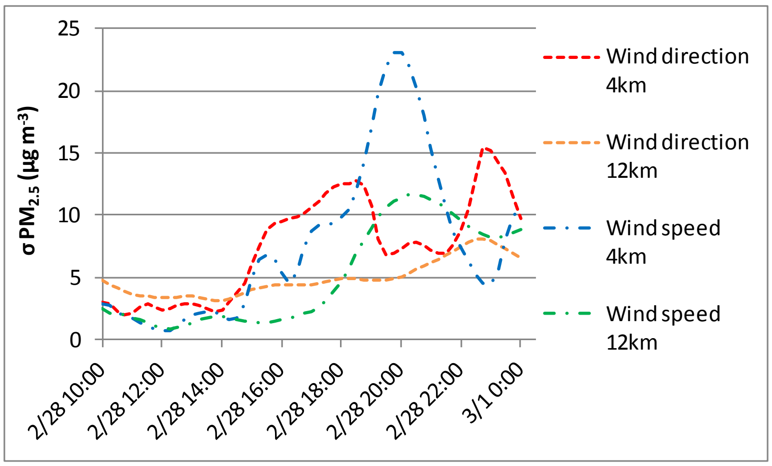

Figure 7. Standard deviation of $PM_{2.5}$ concentration from CMAQ predictions on 28 February 2007 (LT) at Confederate Ave. for all simulations within the perturbation range applied to wind direction (±5°, ±15°, ±30°, and base case) and wind speed (±10%, ±20%, and ±30%, and base case) under 4 km and 12 km horizontal grid resolutions.

Simulated $PM_{2.5}$ concentrations are significantly sensitive to PBL height in meteorological inputs.

Uncertainty in planetary boundary layer (PBL) height fields may propagate in model results and influence their sensitivity to winds. PBL heights influence the wind flow used to transport fire-related emissions and may significantly affect the predictions of air quality models. To explore the sensitivity of CMAQ-predicted $PM_{2.5}$ concentrations at downwind receptors to PBL height, the Atlanta 2007 smoke episode was simulated with modified meteorological inputs, in which PBL heights produced by WRF were perturbed, to evaluate the responsiveness of predicted concentrations to these variations. Significant sensitivities to PBL heights were evident at all downwind receptors considered. Figure 8 shows modeled $PM_{2.5}$ concentrations at Jefferson St. for each simulation carried out under perturbed PBL heights. A continual interaction between PBL height, plume rise, and emissions transport is evident in the predicted concentrations. However, the variation among model predictions is greatest when fire-related emissions contribute significantly to $PM_{2.5}$ concentrations and their injection into the atmospheric boundary layer is most susceptible to changes in PBL height.

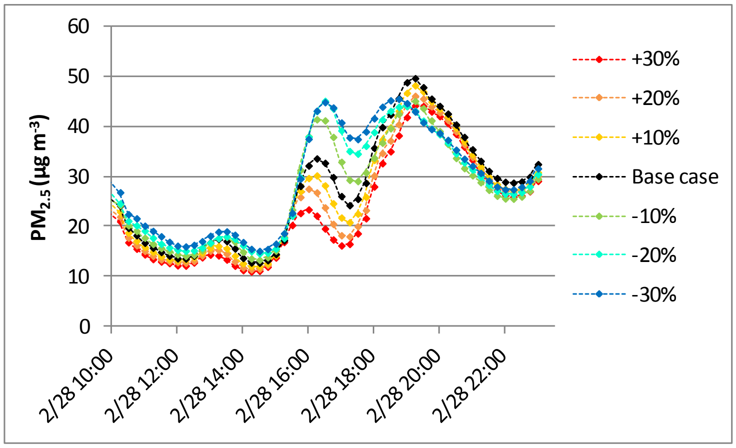

Figure 8. CMAQ-predicted $PM_{2.5}$ concentrations on 28 February 2007 (LT) at the Jefferson St. monitoring site under perturbed PBL heights. Base case simulation results are also included.

There are significant uncertainties associated with the meteorological fields produced by numerical weather prediction models and used to drive air quality modeling.

Meteorological fields generated by WRF were evaluated against surface-layer hourly observations from weather stations located within the modeling domain. The surface-based metrics generally reflect adequate performance by WRF. However, the evaluation did expose a significant positive bias in ground-level wind speed predictions. To evaluate upper air meteorological predictions, sounding data was paired spatially and temporally with WRF predictions. Across the full vertical modeling domain, WRF-predicted wind fields display good agreement with the sounding observations. However, at lower altitudes, where wind flow drives the transport of fire-related emissions, the model significantly overpredicted wind velocity. A bias in wind direction persists in the lower layers as well. Figure 9 compares wind speed and wind direction data from a rawinsonde launched from Peachtree City, GA on 28 February 2007 with WRF-predicted wind fields. The discrepancies between sounding data and WRF-generated wind fields demonstrate that significant uncertainties exist in the meteorological inputs used to drive air quality modeling.

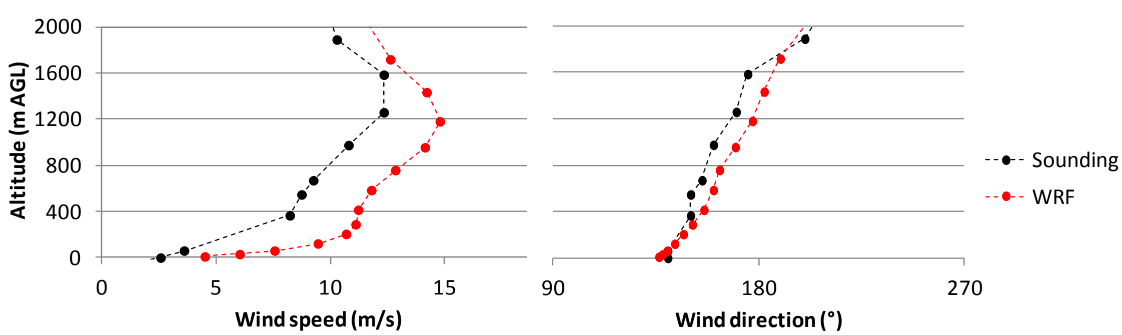

Figure 9. WRF-predicted wind speed and direction and observations from the rawinsonde launched from Peachtree City, GA at 1900 LT on 28 February 2007 for lower 2000 m of the atmosphere.

The errors typically associated with wind fields in meteorological inputs propagate into the results of air quality models and may considerably constrain their performance in fire-related simulations

From the sensitivity analyses carried out in this study it is clear that small errors in wind flow can lead to large variations in $PM_{2.5}$ concentration predictions. Figure 10 compares base case $PM_{2.5}$ concentration predictions for the Atlanta smoke episode to results from simulations in which wind speed was systematically reduced and wind direction was uniformly modified to match observed values from available atmospheric soundings. The differences among predictions exemplify how errors associated with wind fields in meteorological inputs propagate into the output fields thereby limiting model performance. Here, the reduction in wind speed increased the maximum predicted $PM_{2.5}$ concentrations within Atlanta by 47-52 µg m^{-3} (82-103%) and delayed peak concentrations by approximately 1 hour. Modifying wind direction resulted in earlier peak $PM_{2.5}$ concentrations and an 8-24 µg m^{-3} (15-47%) increase to maximum predicted concentrations. Additionally, Figure 10 shows the combined effect of simultaneously modifying wind speed and wind direction in meteorological input fields. The impacts of different perturbations on simulated concentrations are not additive, but rather each wind field produces a unique solution. Under specific conditions, the influence of errors associated with either wind speed or wind direction can dominate concentration estimates. Nevertheless, the analyses show that CMAQ-predicted $PM_{2.5}$ concentrations in simulations attempting to replicate the air quality impacts of fires may carry normalized errors as high as 100% due to uncertain wind inputs.

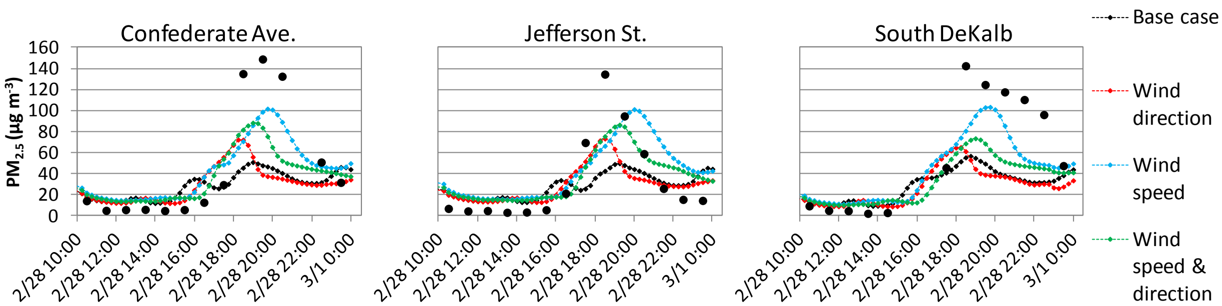

Figure 10. $PM_{2.5}$ concentration predictions on 28 February 2007 (LT) at Atlanta monitoring sites for base case CMAQ simulation, simulations with perturbed wind speed (-27%) and wind direction (-6.8°), and simulation with combined wind speed and wind direction perturbations. Monitoring station observations are also included.

5. Management implications

The performance of regional-scale chemical transport models in fire-related air quality forecasting largely depends on the accuracy of meteorological inputs.

The results of this study show that air quality estimates from chemical transport models attempting to replicate the impacts of wildland fires are extremely sensitive to meteorological fields. For such an application, model performance largely depends on the accuracy of wind inputs. Uncertainty associated with wind data may largely account for considerable discrepancies frequently detected between observations and $PM_{2.5}$ concentration in regional-scale forecasts. Errors in lower atmosphere wind fields generated by numerical weather prediction models may be especially significant. Transport errors, largely due to wind inputs, significantly influence air quality predictions.

The ability of current air quality models to replicate the impacts of wildland fires may be limited by the capabilities of existing numerical weather prediction systems.

In the fire-related air quality modeling completed for this study, the influence of uncertainty in wind inputs on concentration predictions substantially outweighed the effect all other sources of error identified, including uncertain emission rates. Furthermore, simulated pollutant concentrations displayed large sensitivities to variations in wind fields well within the uncertainty range of numerical weather prediction. This suggests that fire-related simulations with chemical transport models are limited by the performance of existing numerical weather prediction systems. In the simulations described within this study, CMAQ-predicted $PM_{2.5}$ concentrations attempting to replicate the air quality impacts of fires carried normalized errors that could be as high as 100% due to uncertain meteorological fields. Additionally, as air quality modeling moves towards finer grid resolution, errors associated with meteorological inputs can be expected to constrain model accuracy even further.

To improve meteorological modeling should be considered as one of the goals in any strategy designed to improve fire-related air quality simulations.

The response of $PM_{2.5}$ concentration predictions to wind flow perturbations signals a need to include meteorological inputs in any strategy designed to improve fire-related air quality simulations. Furthermore, it is important to recognize the limitations inherent to weather forecasts in the context of air quality modeling. Uncertain wind fields are an intrinsic component of numerical weather prediction and mitigating errors in short term and small scale wind forecasts produced by existing models is a challenging task. Concerns about the ability of meteorological models to capture intraday wind variations have been previously raised (Hogrefe et al., 2001). Additionally, substantial variability exists in meteorological predictions from different models and different configurations of the same model (Vautard et al., 2012). In light of this, air quality forecasts predicting the impact of fires on air quality produced by atmospheric chemistry and transport models must be considered substantially uncertain. These uncertainties must be considered when air quality modeling is used to steer fire management decision-making.

6. Relationship to other recent findings and ongoing work on this topic

This study has served to complement the doctoral thesis, *High-Resolution Three-Dimensional Plume Modeling with Eulerian Atmospheric Chemistry and Transport Models*, by Fernando Garcia Menendez in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. In this work, three-dimensional adaptive grid refinement is developed as a strategy to achieve high-resolution simulations of atmospheric pollutant plumes. The findings of this project enhanced the dissertation by determining that superior model performance in atmospheric plume simulations requires more accurate meteorological inputs, in addition to improving the grid resolution of air quality models.

This project largely builds on the work and findings of JFSP Project 08-1-6-04, *Evaluation of Smoke Models and Sensitivity Analysis for Determining their Emission Related Uncertainties*. In this prior study, sensitivity analyses focused on fire-related emissions in simulation attempting to reproduce the impacts of wildland fires on air quality signaled to the potentially large influence of meteorological drivers. Modeling tools and findings produced in Strategic Environmental Research and Development Program (SERDP) project, SI/RC-1647, *Characterization of Emissions and Air Quality Modeling for Predicting the Impacts of Prescribed Burns at DoD Lands*, were used in the research conducted as a part of this work. Additionally, the findings of this study are being applied in the research presently being conducted in NASA Air Quality Applied Science Team project NNX11AI55G, *Improving Operational Regional Air Quality Forecasting Performance through Emissions Correction Using NASA Satellite Data and Surface Measurements* and in US EPA Science to Achieve Results (STAR) project 83521701, *Dynamic Management of Prescribed Burning for Better Air Quality*.

7. Future work

The strong influence of meteorological data on air quality predictions from simulations attempting to replicate the effects of fires with regional-scale chemical transport models was extensively explored in this study. The modeling system applied in this work, uses one-way coupling between a meteorological model and the system's chemical transport model. In the past, the feedback of air pollution to atmospheric dynamics has been regularly ignored by air quality modelers. However, the impacts of atmospheric concentrations on weather, by altering the radiation budget and cloud formation, are also accepted (Grell and Baklanov, 2011). The feedback to meteorology may be particularly important in simulations centered on wildland fires, where high aerosol loads could lead to significant changes in planetary boundary layer height, photolysis rates, and temperature profiles. The effects of fires on these meteorological variables would subsequently influence air quality predictions. In addition, heat released by fires may directly affect microscale meteorology.

Recently, operational systems that allow two-way coupled air quality and meteorological modeling have become available, either as meteorological models that include an air quality component or as coupled independent models that continuously exchange feedback. The Weather Research and Forecasting model coupled with chemistry (WRF-Chem) simultaneously simulates meteorology and the transport and transformations of trace gases and aerosols (Grell et al., 2005) and has been used to explore the effects of fire emissions on weather forecasts (Grell et al., 2011). WRF-Chem simulations investigating the influence of fire emissions on ozone photochemistry have also suggested that two-way coupling may be necessary to better predict the air quality impacts of large fires (Jiang et al., 2012). Similarly, the latest release of CMAQ enables two-way coupling between CMAQ's chemical transport model and the Weather Research and Forecasting model (WRF) (Wong et al., 2012). Two-way coupled systems offer an extremely interesting framework to carry out simulations investigating fire-related plumes. Through online modeling, it may be possible to capture the effects of fires on smoke transport and plume rise. The benefits of two-way coupling would likely be heightened in high-resolution air quality simulations. Smoke episode simulations, diagnostic model evaluations, and uncertainty analyses similar to those undertaken here should be carried out under a two-way coupled framework to gain additional insight into fire-related air quality impacts and improve the ability of chemical transport models to replicate the phenomenon.

8. The deliverables crosswalk

Proposed	Delivered	Status
6 month progress report	A mid-project progress report was submitted to the Joint Fire Science Program on 02/15/2013.	Completed
Conference presentation	Results of this work were presented at the 2012 American Geophysical Union's Annual Fall Meeting (San Francisco, CA; 12/07/20120)	Completed
Ph.D. dissertation	Completed Ph.D. thesis: *High-resolution three-dimensional plume modeling with Eulerian atmospheric chemistry and transport models* Copy submitted to the Joint Fire Science Program on 09/30/2013.	Completed
Refereed publication	Findings published in: *Garcia-Menendez, F., Y. Hu, and M. T. Odman (2013), Simulating smoke transport from wildland fires with a regional-scale air quality model: Sensitivity to uncertain wind fields, J. Geophys. Res. Atmos., 118, 6493–6504, doi:10.1002/jgrd.50524.*	Completed
Final Report	This document is the final report.	Completed

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