USE OF PHOTOCHEMICAL GRID MODELING TO QUANTIFY OZONE IMPACTS FROM FIRES IN SUPPORT OF EXCEPTIONAL EVENT DEMONSTRATIONS

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1. INTRODUCTION

Smoke from biomass burning contains a number of pollutants, including nitrogen oxides (NO_x), volatile organic compounds (VOC), and fine particulate matter ($PM_{2.5}$) (Jaffe et al., 2008; McKeen et al., 2002), which contribute to enhanced ozone and $PM_{2.5}$ concentrations in the atmosphere under a variety of conditions (Pfister et al., 2006). Ozone enhancement due to biomass burning is highly variable and depends on fuel type, combustion efficiency, available solar radiation, and other factors (Jaffe and Wigder, 2012). Smoke and precursor emissions from fires can impact downwind cities, cause negative health effects, and trigger violations of National Ambient Air Quality Standards (NAAQS) for particulate matter and ozone.

The U.S. Environmental Protection Agency (EPA) defines exceptional events as unusual or naturally occurring events that can affect air quality but are not reasonably controllable. State agencies can flag ambient data for exclusion from regulatory determinations if they can demonstrate to EPA's satisfaction that the measurements were influenced by an exceptional event, such as wildfires. Technical evidence of such influences must be submitted to EPA in the form of a demonstration package, which must include analyses clearly showing no NAAQS exceedance would have occurred "but for" the exceptional event.

Fires events can trigger violations of the NAAQS for ozone. Because ozone is a secondary pollutant formed by reactions involving precursor species emitted by fires and other sources, significant technical challenges are associated with meeting the "but for" criterion. Rather than simply establish a line of transport from the fire to the impacted ambient monitor, "but for" demonstrations must evaluate ozone levels that would be typical for a particular time and place in the absence of fire emissions, and must provide a quantitative assessment of ozone levels with and without the influence of fire. Several analysis techniques, including statistical (Jaffe et al., 2013) and numerical modeling (Pfister, 2013) methods, are available to address the "but for" criterion. Here, we present an example of how numerical modeling was used develop a "but for" analysis in support of an exceptional event demonstration request that was approved by EPA.

In April 2011, widespread smoke from numerous fires in the Kansas Flint Hills region, as well as other large fires in Texas and Mexico, impacted air quality in Kansas metropolitan areas. Fires in the Flint Hills were particularly extensive on April 6, 12, and 13. Smoke that was transported downwind from the fires on these days contributed to ozone formation and exceedance of the NAAQS for 8-hr ozone at several air quality monitors in eastern Kansas. On April 29, smoke was transported northward into Kansas from several large fires in Texas and Mexico, contributing to ozone formation and exceedance of the NAAQS for 8-hr ozone at air quality monitors in the Wichita area.

The Kansas Department of Health and Environment (KDHE) developed an exceptional event demonstration package to have these NAAQS exceedances excluded from regulatory determinations. The full exceptional event demonstration package meets all of EPA's criteria and includes a complete weight of evidence analysis that establishes a clear causal relationship between the fires and ozone exceedances, shows that measured ozone concentrations were in excess of normal historical fluctuations, and demonstrates that the NAAQS exceedances would not have occurred "but for" the fire events. This paper focuses on the Community Multiscale Air Quality (CMAQ) modeling analysis performed by Sonoma Technology, Inc. (STI) in support of the "but for" portion of the demonstration package.

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2. METHODOLOGY

2.1 Modeling System

The BlueSky Gateway air quality modeling system (Strand et al., 2012; Craig et al., 2007) was used to assess the impact of Flint Hills fires on ozone concentrations during April 2011. BlueSky Gateway is an operational air quality forecasting system developed by the USDA Forest Service (USFS) and STI to predict nationwide air quality impacts due to wildfires and other emission sources at 36-km resolution. BlueSky Gateway components include the BlueSky Framework for estimating fire emissions, the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) for predicting meteorological conditions, the CMAQ air quality model for predicting gaseous and particulate pollutant concentrations, and the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system for incorporating anthropogenic emissions.

2.2 Emissions Inventory

For fires outside the Flint Hills region, daily fire locations and sizes were provided by the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SmartFire) version 1 (Raffuse et al., 2006), which integrates and reconciles human-recorded wildfire incident data with satellite-detected fire data and human-analyzed smoke plume products. The USFS BlueSky Framework (Larkin et al., 2009) was used to develop emissions estimates from the SmartFire burn area predictions using a methodology similar to the one currently used by EPA for developing national fire emission inventories (Sullivan et al., 2009).

A unique approach was required to develop a suitable fire emissions inventory for the Flint Hills region. County-level burn acreage data were developed by KDHE and Kansas State University using satellite fire detects and local burn scar information. KDHE also provided fuel loading data, typical burn size distributions, and sub-county spatial burn distributions based on local knowledge of the vegetation present during April 2011 and typical burning practices in the Flint Hills. A refined spatial allocation approach was used to provide appropriate inputs to the BlueSky Framework and to develop gridded hourly Flint Hills fire emissions data. The default fuel loading maps in the BlueSky Framework were bypassed in favor of local fuel loading data from KDHE. A 100% consumption efficiency was assumed because prescribed burns in the Flint Hills consume most available grassland fuel. Although most of the fuel in prescribed fires is consumed by the flaming fire phase, some smoldering does occur after the flame front passes, therefore we assume that 90% of the available fuel is consumed by the flaming fire phase, while 10% is consumed by the smoldering phase. A diurnal time profile was applied to all Flint Hills fire emissions to simulate a typical Flint Hills prescribed burn that starts at 10:00 CDT and burns evenly across the landscape for 8 consecutive hours.

Non-fire anthropogenic emissions from the 2008 National Emission Inventory Version 1.5 were processed through SMOKE. These emissions were not projected to 2011 because an economic recession limited growth in most anthropogenic emission source categories. Average meteorological conditions for April 2011 were used to prepare temperature-dependent emissions, such as mobile and biogenic sources.

2.3 Analysis Method

The BlueSky Gateway simulations were carried out as a series of overlapping two-day runs initialized each day at 00 UTC. Each daily simulation was initialized from previous days' modeled concentrations to account for the carryover of primary and secondary pollutants produced from prior days' emissions. Simulations were started on March 25, 2011 to provide an adequate spin-up period. Although the analysis focuses on the four ozone exceedance dates, BlueSky Gateway was executed each day of the month to preserve pollutant carryover effects, provide day-to-day continuity to the concentration fields, and establish context for assessing model performance. Peak 8-hr average ozone concentrations were calculated from the raw hourly model predictions.

To isolate the impacts of Flint Hills fire emissions on ozone concentrations in Kansas, two simulations were performed: (1) A base case simulation to model ozone concentrations due to all anthropogenic, biogenic, and fire emissions sources, including emissions from Flint Hills fires; and (2) a sensitivity simulation with Flint Hills fire emissions removed from the emissions inventory. The difference in ozone concentrations between these two simulations provides a quantitative estimate of the impact of Flint Hills fires on ozone concentrations.

3. RESULTS

This section summarizes the results of the modeling analysis for each day in April 2011 when 8-hr ozone concentrations were above the 8-hr NAAQS of 75 ppb. Brief synopses of important meteorological and air quality conditions are presented and summarized in a plot containing analyzed smoke plumes, fire locations, and air trajectories. Each daily analysis also includes a table showing the monitored 8-hr average ozone concentrations, the modeled ozone concentration from both model simulations, and the impact of Flint Hills fires on ozone levels at the eastern Kansas air quality monitors.

Finally, each daily analysis includes a plot of the difference in modeled peak 8-hr average ozone concentrations between the base case (with Flint Hills fires) and sensitivity (no Flint Hills fires) simulations; the differences represent the modeled impact of Flint Hills fire emissions on ozone concentrations. Because the plots indicate the areas where NO_x and VOC emissions from Flint Hills fires were sufficient to impact ozone production, they also represent the approximate spatial extent of the modeled smoke plume.

Importantly, results from the April 29 case are omitted here. Modeling analysis showed no ozone impacts at the Kansas monitors due to the few Flint Hills fires that burned on this day. Therefore, the NAAQS exceedances on this day cannot be explained by local Flint Hills burning.

3.1 April 6, 2011

On April 6, 2011, nearly 250,000 acres were burned in the Flint Hills of Kansas. A cold front moved across Kansas on April 6, with northerly surface winds behind the cold front and southerly winds ahead of the front. As the front moved through the Wichita area around midday, northerly winds transported smoke from fires in the Flint Hills to the Wichita Health Department (WHD) and Peck monitors. Ahead of the front, southwesterly winds transported smoke from fires in the southern Flint Hills to the Mine Creek monitor. As a result, a large smoke plume was present over southern and eastern Kansas (Fig. 1).

The modeled fires also produced a smoke plume over the same area. The modeled plume looked similar to the observed plume and affected all three monitors that recorded 8-hr ozone concentrations above 75 ppb. The additional NO_x and VOC emissions from the fires led to an enhancement of ozone concentrations over these areas (Fig. 2).

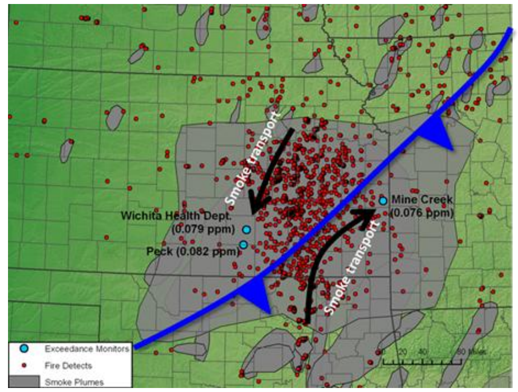

Fig. 1. Summary of conditions on April 6, 2011. Red dots indicate fire locations; black arrows denote the direction of smoke transport; blue line denotes approximate location of cold front at noon. Peak 8-hr ozone concentrations are in parentheses at impacted monitors.

When compared with the predicted concentrations at monitors unaffected by the smoke plume, the base case simulation captures a significant ozone enhancement at all three impacted monitors (Table 1). The base case simulation also captures a less significant ozone enhancement at the Sedgwick monitor, although ozone concentrations there remained below the federal 8-hr ozone standard. The KNI-Topeka and Konza Prairie monitors were largely unaffected by the smoke plume, and the model accurately predicted regional background ozone levels at those monitors. Modeled ozone concentrations were 5 to 8 ppb higher than the observations at the impacted monitors.

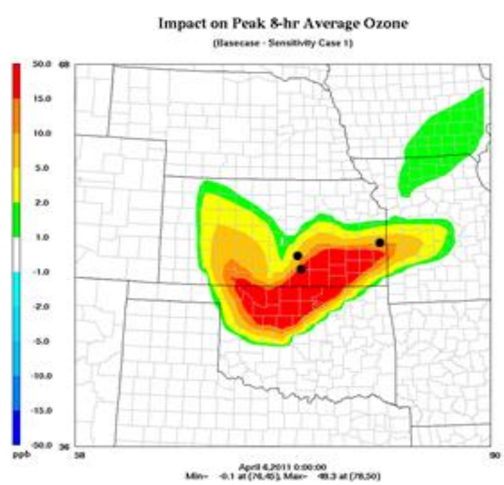

Fig. 2. Ozone difference plot representing modeled ozone concentrations directly caused by fires in the Flint Hills region on April 6. Black dots represent approximate locations of impacted monitors.

The difference between the base case simulation and the sensitivity simulation suggests that the ozone enhancement at the impacted monitors was caused by emissions from fires in the Flint Hills region. The modeled impact of Flint Hills fires was 20 ppb at the WHD and Peck monitors and 10 ppb at the Mine Creek monitor. At both monitors, modeled ozone concentrations for the sensitivity simulation were well below the federal 8-hr ozone standard.

Table 1. Modeled impact of Flint Hills fires on 8-hr average ozone concentrations at the Kansas air monitors on April 6, 2011. Bold values indicate data at the impacted monitors.

Monitor	Peak 8-hr Average Ozone Concentration (ppm)			
	Observed	Base Case (All Fires)	Without Flint Hills Fires	Impact of Flint Hills Fires
Mine Creek	**0.076**	**0.070**	**0.060**	**0.010**
Wichita Health Department	**0.079**	**0.074**	**0.054**	**0.020**
Sedgwick	0.064	0.057	0.052	0.005
KNI-Topeka	0.054	0.053	0.052	0.000
Peck	**0.082**	**0.074**	**0.054**	**0.020**
Konza Prairie	0.053	0.052	0.051	0.001

3.2 April 12, 2011 Event

On April 12, 2011, nearly 300,000 acres were burned in the Flint Hills. Light to moderate southerly winds in eastern Kansas transported smoke from Flint Hills fires to the KNI-Topeka and Konza Prairie monitors. This wind pattern also transported smoke away from the Wichita area monitors in southern Kansas and the Mine Creek monitor in eastern Kansas. A large smoke plume was present over eastern Kansas, primarily over the Flint Hills region with some northward extension into northern Kansas (Fig. 3).

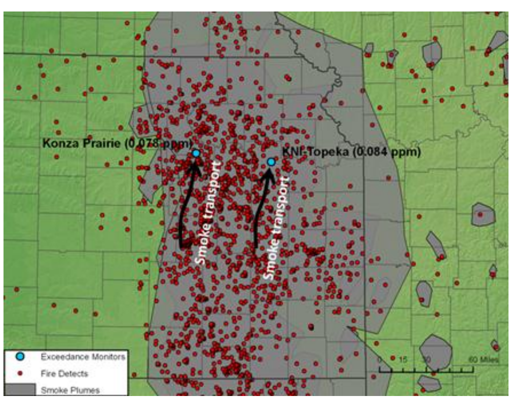

Fig. 3. Summary of conditions on April 12, 2011. Black arrows denote smoke transport by southerly winds.

The modeled fires and wind patterns on April 12 produced an elongated smoke plume over the Flint Hills region (Fig 4.) The modeled plume impacted both the KNI-Topeka and Konza Prairie monitors, and the additional NO_x and VOC emissions from the fires led to an enhancement of ozone concentrations over these same areas.

Because the modeled smoke plume is directly over the KNI-Topeka monitor, the base case simulation captures a significant ozone enhancement at KNI-Topeka and accurately depicts the peak 8-hr ozone concentration at that site. However, the modeled smoke plume was too narrow and mostly missed the Konza Prairie monitor; therefore, the model did not fully capture the ozone enhancement at that site. Also, some fires burning in the area of the Mine Creek monitor and the observed 8-hr ozone concentration of 67 ppb at that site suggests some ozone enhancement which was not captured in the model. The WHD and Peck monitors were unaffected by the smoke plume, and the model correctly predicted ozone concentrations below 60 ppb at those sites (Table 2).

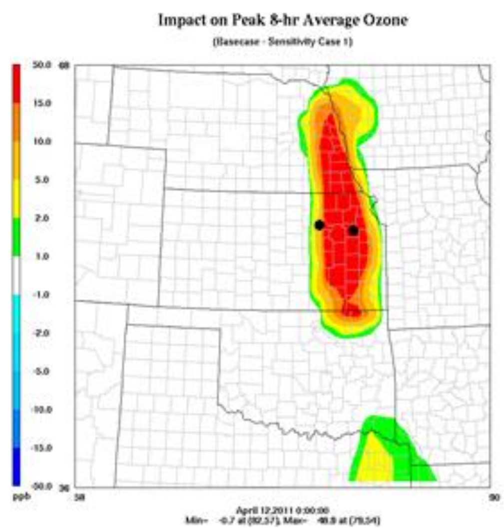

Fig. 4. Ozone difference plot representing modeled ozone concentrations directly caused by fires in the Flint Hills region on April 12. Black dots represent approximate locations of impacted monitors.

Table 2. Modeled impact of Flint Hills fires on 8-hr average ozone concentrations at the Kansas air monitors on April 12, 2011. Bold values indicate data at the impacted monitors.

Monitor	Peak 8-hr Average Ozone Concentration (ppm)			
	Observed	Base Case (All Fires)	Without Flint Hills Fires	Impact of Flint Hills Fires
Mine Creek	0.067	0.060	0.060	0.000
Wichita Health Department	0.055	0.054	0.053	0.001
Sedgwick	0.061	0.054	0.054	0.000
KNI-Topeka	**0.084**	**0.082**	**0.054**	**0.028**
Peck	0.059	0.054	0.053	0.001
Konza Prairie	**0.078**	**0.060**	**0.053**	**0.007**

3.3 April 13, 2011 Event

On April 13, 2011, nearly 300,000 acres were burned in the Flint Hills. Light to moderate southeasterly surface winds in eastern Kansas transported smoke from fires in the Flint Hills region to the Konza Prairie monitor (Fig. 5). Unlike April 12, when smoke was largely confined to the Flint Hills region, smoke on April 13 was observed over most of Kansas and in portions of neighboring states. Some of this smoke was likely from fires that burned on the previous day.

The combination of modeled fires and wind patterns on both April 12 and 13 produced a significant region of smoke over much of the central United States. The modeled smoke impacts were most concentrated over the Flint Hills region (Fig. 6), and NO_x and VOC emissions from the Flint Hills fires led to a large ozone enhancement in this region, which includes the Konza Prairie monitor. Modeled ozone impacts outside the Flint Hills were the result of smoke that was generated on the previous day and transported away from the Flint Hills region.

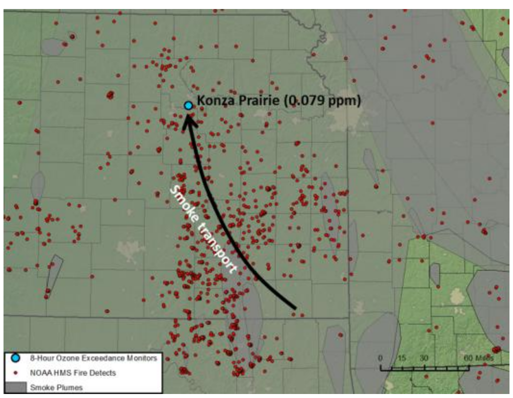

Fig. 5. Summary of conditions on April 13, 2011. Black arrow denotes smoke transport by southeasterly winds.

With the exception of KNI-Topeka, both observed and modeled ozone concentrations at all monitors increased on April 13 from the previous day (Table 3). At monitors other than Konza Prairie, however, the modeled ozone impacts due to Flint Hills fires were no more than 2 ppb. The regional ozone enhancement on this day was likely due to a combination of ozone and precursor emissions from fires that burned the previous day, and photochemical production that would have occurred even without Flint Hills fire emissions.

The model predicted an ozone enhancement of 30 ppb at the Konza Prairie monitor due to the Flint Hills fires. Because the base case simulation overpredicted the 8-hr ozone concentration at Konza Prairie by 13 ppb (not shown), the modeled ozone impact from the Flint Hills fires was likely overestimated as well. However, the 8-hr ozone concentration at the Konza Prairie monitor exceeded the 8-hr ozone NAAQS by only 4 ppb, so a small ozone enhancement from smoke would have been sufficient to cause a violation of the 8-hr ozone standard of 75 ppb.

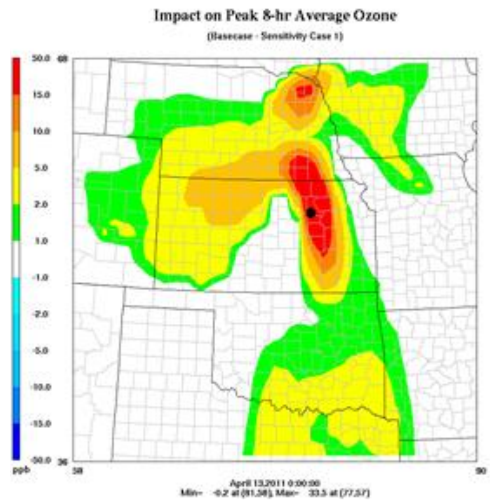

Fig. 6. Ozone difference plot representing modeled ozone concentrations directly caused by fires in the Flint Hills region on April 13. Black dots represent approximate locations of impacted monitors.

Table 3. Modeled impact of Flint Hills fires on 8-hr average ozone concentrations at the Kansas air monitors on April 13, 2011. Bold values indicate data at the impacted monitors.

Site	Peak 8-hr Average Ozone Concentration (ppm)			
	Observed	Base Case (all fires)	Without Flint Hills Fires	Impact of Flint Hills Fires
Mine Creek	0.071	0.070	0.070	0.000
Wichita Health Department	0.069	0.069	0.068	0.001
Sedgwick	0.075	0.065	0.064	0.001
KNI-Topeka	0.070	0.075	0.073	0.002
Peck	0.073	0.069	0.068	0.001
Konza Prairie	**0.079**	**0.092**	**0.062**	**0.030**

4. CONCLUSION AND DISCUSSION

In support of an exceptional event demonstration, we applied a model-based analysis to show that the NAAQS exceedances for 8-hr ozone in eastern Kansas during April, 2011 would not have occurred “but for” the Flint Hills fires. We performed CMAQ model simulations with and without emissions from Flint Hills fires using the BlueSky Gateway air quality modeling system. To support this effort, we developed a unique emissions inventory for the Flint Hills fires using local county-level fire and fuels data, a refined spatial allocation approach, and the BlueSky Smoke Modeling Framework. Smoke plumes generated in CMAQ using data from the Flint Hills fires matched observed smoke plumes reasonably well. The modeled impacts on peak 8-hr average ozone on the exceedance days ranged from 5 to 30 ppb at the Kansas monitoring locations, and up to 49 ppb within the modeling domain.

To mitigate impacts from prescribed fires in the Kansas Flint Hills region, KDHE has developed and adopted a smoke management plan (Kansas Department of Health and Environment, 2010). An important component of this plan is providing stakeholders with tools to help them make burn/no-burn decisions based on meteorological conditions that affect smoke transport and dispersion. STI developed a prescribed burn decision support system for KDHE that provides land managers with daily smoke forecasts and localized guidance on when and where to burn to avoid adverse air quality impacts on downwind cities. This tool can be accessed through the KDHE Flint Hills smoke management website at http://www.ksfire.org, and will be operational during the upcoming 2014 fire season.

5. REFERENCES

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