# DEVELOPMENT AND OPERATION OF NATIONAL CMAQ-BASED $PM_{2.5}$ FORECAST SYSTEM FOR FIRE MANAGEMENT

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## 1. INTRODUCTION

The BlueSky smoke modeling framework is a tool developed by the U.S. Department of Agriculture-Forest Service (USFS) for modeling the cumulative impacts of $PM_{2.5}$ emitted from multiple fires (Larkin et al., 2007). The BlueSky Framework (BSF) uses the Lagrangian CALPUFF model (Scire et al., 2000) to calculate local-scale transport and dispersion of smoke produced by wildfires and prescribed burns. While this approach is appropriate at a local scale in the vicinity of individual fires, it is computationally burdensome to use a Lagrangian model to track smoke from fires on a national scale, or to carry over predicted smoke concentrations from previous simulations into the current and future-day predictions.

The BlueSky Framework has been recently upgraded and redesigned. Among the high-level development goals in improving the BlueSky Framework version 3 (BSF3) was to build a reliable, operational system that provides national forecasts of emissions and smoke. To fulfill this goal, we designed and implemented the BlueSky National Smoke Modeling System, or BlueSky National. BlueSky National is an operational $PM_{2.5}$ forecasting system for the United States based on the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model, Version 5 (MM5) (Grell et al., 1994) and the Community Multiscale Air Quality (CMAQ) model (U.S. Environmental Protection Agency, 1998; National Exposure Research Laboratory, 1999). The BlueSky National system provides a low-resolution (36 km) national forecast of ground-level $PM_{2.5}$ concentrations caused by anthropogenic, biogenic, and fire emissions. BlueSky National also models carryover smoke from previous days' emissions and other sources to provide a more realistic national $PM_{2.5}$ background. These national forecasts will be used by the various Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS) to improve their regional high-resolution CALPUFF simulations.

This paper describes the details of the Bluesky National Smoke Modeling System. A retrospective simulation is performed to demonstrate the BlueSky National system.

## 2. SMOKE MODELING FRAMEWORK

### 2.1 Modeling System Overview

BlueSky National is based on BlueSky Framework version 3, MM5 version 3.7, and CMAQ version 4.5.1 (March 17, 2006 release). Forecasts from the North American Mesoscale (NAM) model are used to provide initial and boundary conditions for the MM5 simulations. Hourly meteorological data from MM5 is prepared for use in CMAQ with the Community Multiscale Air Quality Model Meteorology-Chemistry Interface Processor (MCIP) version 3.1. Non-fire emissions are based on the 2002 National Emission Inventory (NEI) version 3 (U.S. Environmental Protection Agency, 2006) projected to the current year, and average meteorological conditions for the current month. Emissions from fires are developed by the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) and BSF3 (Raffuse et al., 2006). The overall process is illustrated in Figure 1.

The modeling domain is the 36-km national Regional Planning Organization (RPO) grid, which covers the continental United States and much of southern Canada and northern Mexico. MM5 modeling is performed on a 29-layer vertical grid. Vertical resolution is 50 to 75 m in the boundary layer, and gradually stretches to coarser resolution up to the model top (approximately 20 km). CMAQ uses a 17-layer grid, which maps exactly to the MM5 vertical grid in the lowest 250 m, then averages every two MM5 layers up to the model top.

BlueSky National provides 72-hr forecasts of $PM_{2.5}$ concentrations caused by anthropogenic, biogenic, and fire emissions. Daily simulations are initialized off predicted concentration fields from the previous day, thereby providing national

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background $PM_{2.5}$ concentrations that include carryover from previous days' emissions.

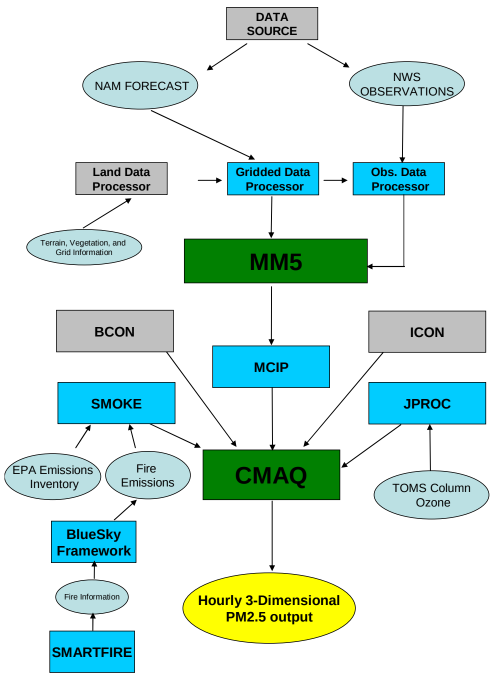


Fig. 1. Overview of data and processes involved in the BlueSky National Smoke Modeling System.

## 2.2 Emissions Modeling

A new tool, SMARTFIRE, was developed to provide burn-area predictions for the BlueSky Framework. SMARTFIRE integrates and reconciles human-recorded wildfire incident data from Incident Status Summary (ICS-209) reports with satellite-detected fire data. This merging provides a more comprehensive and spatially accurate data set than either tool alone, while minimizing double reports. The method also provides a more realistic temporal profile of area burned.

Burn-area predictions from SMARTFIRE are fed into the BlueSky Framework, which runs a fuel-loading model, a fire consumption model, and an emission model to develop a prediction for $PM_{2.5}$ emissions caused by fires. These emissions are merged with day-specific biogenic and non-fire anthropogenic emissions to produce the final merged emissions input files for CMAQ.

Emission files for biogenic and non-fire anthropogenic sources are developed off-line using version 2.3 of the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Coats, 1996; Houyoux and Vukovich, 1999; Houyoux et al., 2000; Houyoux and Adelman, 2001). Emission estimates from the 2002 NEI are processed through SMOKE and projected to the current year using growth factors generated by the U.S. Environmental Protection Agency's Economic Growth Analysis System version 4.0 (E.H. Pechan & Associates, 2001). Average meteorological conditions for the current month are used in the preparation of emissions data for sources that are temperature-dependent, such as on-road mobile sources and biogenic sources.

## 2.3 Fire Tracer Species

A series of aerosol tracers have been implemented in CMAQ to separately track the evolution of primary $PM_{2.5}$ generated from wildfires, agricultural burns, and prescribed burns within BlueSky National (Table 1). Separate variables are also created to differentiate between $PM_{2.5}$ generated from the current day's run, and carryover $PM_{2.5}$ from the previous day's run. Primary $PM_{2.5}$ emissions from fires are assigned to unique tracer variables within SMOKE and are emitted into the CMAQ grid only through the special aerosol tracer variables. These fire aerosols are chemically inert but are subject to transport, dispersion, and deposition. Primary $PM_{2.5}$ emissions from non-fire anthropogenic sources are processed through SMOKE, chemically speciated, and introduced into CMAQ in the standard way. They are carried through CMAQ via the standard $PM_{2.5}$ species and are subject to secondary formation and destruction processes.

Table 1. Aerosol species introduced into CMAQ to track fires in the national smoke modeling system.

| Tracer ID | Species Name |
|---|---|
| F1 | Wild fires (today's run) |
| F2 | Wild fires (yesterday's run) |
| F3 | Prescribed fires (today's run) |
| F4 | Prescribed fires (yesterday's run) |
| F5 | Agricultural fires (today's run) |
| F6 | Agricultural fires (yesterday's run) |
| F7 | Planned prescribed fires |
| F8 | Planned agricultural fires |

The standard version of CMAQ supports the inclusion of chemically inert tracers, but they are assumed to be in the *gaseous* phase. Tracers are carried through the modeling system in volume-based units (ppm), dry deposition of tracers is described by a gas-phase deposition velocity, and wet deposition and scavenging are based on Henry's Law of Equilibrium. Several modifications to the standard CMAQ source code were necessary to properly model the new $PM_{2.5}$ tracer species. These modifications are described below.

Because CMAQ assumes that inert tracers are gases, it also expects emission rates for inert tracers to be in units of moles/s, which are subsequently converted to ppm within CMAQ. However, the emissions processing software generates emission rates for aerosols in units of grams per second. To inject the proper aerosol tracer mass into the model, it was necessary to convert the emission rates to moles/s using the tracer molecular weight. Since the $PM_{2.5}$ aerosols produced from fires are primarily carbonaceous in nature, we assumed that the molecular weight of the aerosol tracers was that of carbon (12 g/mol).

Dry deposition for CMAQ tracers by default is determined by the gas-phase deposition velocity, which ordinarily is calculated by MCIP and provided to CMAQ through an MCIP file. Dry deposition velocity is not valid for aerosol tracers. Aerosol dry deposition is complex—an entire physics module (aero_depv) is devoted to this process. Though it was outside the scope of the effort to develop a full aerosol tracer deposition model, aerosol deposition parameters calculated for the native CMAQ aerosol species can be used to estimate deposition for the aerosol tracer species. The RDDEPV.F routine in CMAQ was modified to use the dry deposition velocity for accumulation mode (J-mode) aerosol calculated by the aerosol dry deposition module.

Tracer scavenging and wet deposition in CMAQ is based on Henry's Law of Equilibrium for gases, which is clearly not applicable for aerosol scavenging and wet deposition. The SCAVWDEP.F routine in CMAQ was modified to use calculations that are consistent with those used for aerosols in the accumulation-mode.

### 2.4 Operational Implementation

The operational BlueSky National Smoke Modeling System will be executed three times daily. The first execution initializes off the 1800 UTC NAM run during the afternoon and evening hours of the previous day. This "early bird" run uses fire emissions information generated only from preliminary (i.e., unverified) satellite-derived fire-location data to provide a preliminary early morning $PM_{2.5}$ forecast. The second run initializes off the 0000 UTC NAM run of the current forecast day, and executes during the overnight hours. This run still uses fire emissions generated from preliminary satellite-derived fire-location data, but the data are augmented with information from ICS-209 reports, which are made available by 2300 MDT. The third and final run is based on the same meteorological data as the previous run, but incorporates the best estimate of fire emissions generated from finalized (i.e., human-verified) satellite-derived fire-location data augmented with ICS-209 reports. Output from this final run will be archived for use in future research applications.

## 3. DEMONSTRATION

During the last week of June 2005, numerous wildfires were burning in the western United States. Among these were several clusters of fires located north and east of Las Vegas, Nevada, near the confluence of the Nevada, Utah, and Arizona state boundaries (Figure 2). Smoke from these fires impacted the air quality in Las Vegas and Salt Lake City (SLC) during this time period. The abundance of fires combined with the potential to impact air quality in major metropolitan areas makes this time period an interesting test case to demonstrate BlueSky National. Thus, a full test simulation was run from June 27, 2005, at 1200 UTC, through July 1 at 0000 UTC.

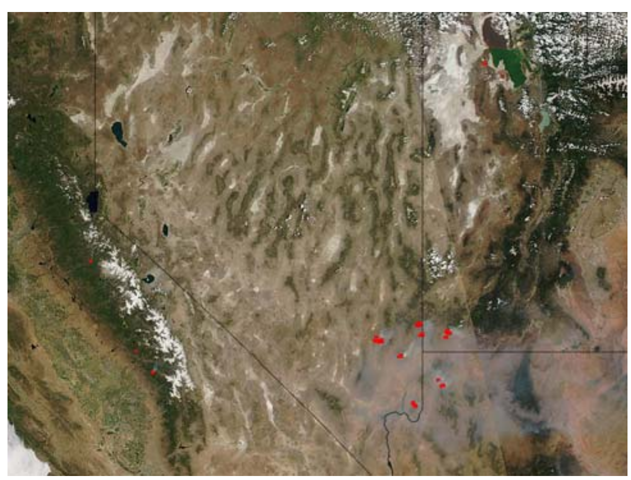

Fig. 2. MODIS-Aqua satellite image from June 29, 2005. Red markers indicate satellite-detected "hot spots", indicating fire locations.

On June 26 through the morning of June 28, southwesterly flow at the surface and aloft advected wildfire smoke northeast toward SLC.

Elevated levels (15 to 45 µg/m$^3$) of $PM_{2.5}$ were observed at several monitoring stations in the SLC area during this time period, including the Hawthorne site (Figure 3) located in SLC. High $PM_{2.5}$ concentrations in this region occur infrequently during the summer months. A HYSPLIT trajectory analysis confirmed that the air passing through SLC at this time originated from the fire complexes to the southwest. Note that $PM_{2.5}$ concentrations remained low (less than 10 µg/m$^3$) in Las Vegas, despite its proximity to the fires.

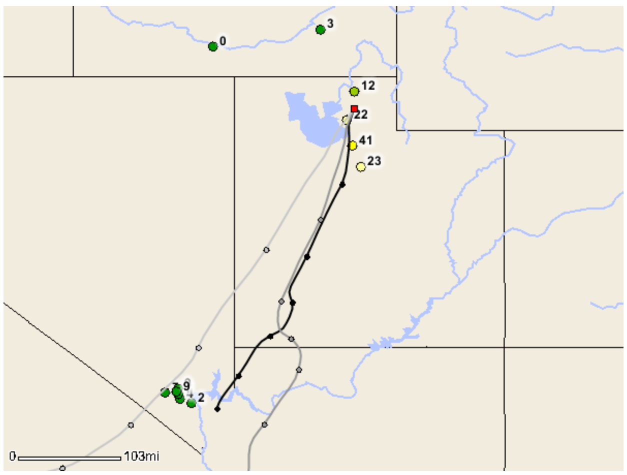


Fig. 3. Observed $PM_{2.5}$ concentrations and 36-hr HYSPLIT backward trajectories on June 28, 2005, at 0800 UTC. Trajectories originate at 250 m, 500 m, and 1000 m.

Spatial distributions of predicted ground-level fire $PM_{2.5}$ from June 27 and 28 show a distinct plume that originates from the fire complexes and stretches northeast across Utah and into southwest Wyoming. Figure 4 shows a snapshot of the predicted smoke plume at 0800 UTC on June 28 as it passes through SLC. BlueSky National predicted a ground-level fire impact of 7 to 8 µg/m$^3$ in the SLC area at the same time that elevated concentrations were observed. Figure 5 shows predicted $PM_{2.5}$ concentrations caused by anthropogenic and wildfire sources at the Hawthorne site, along with the observed total $PM_{2.5}$ concentrations during the modeling episode. Recall that CMAQ within BlueSky National is configured to separately track $PM_{2.5}$ emitted by fires from $PM_{2.5}$ resulting from anthropogenic activities. The observations show a 10-hr period starting June 27 at 1900 PST during which $PM_{2.5}$ concentrations were at or above 15 µg/m$^3$. During the same time period, predicted wildfire $PM_{2.5}$ concentrations are nonzero. Once the smoke plume passed though SLC, observed $PM_{2.5}$ fell below 10 µg/m$^3$ for the remainder of the modeling period, while predicted fire $PM_{2.5}$ dropped to and remained zero. BlueSky National captures the timing, as well as the transient nature of the smoke plume passing through SLC. However, the model underestimates the peak magnitude of the impact at Hawthorne, as the observed peak was 42 µg/m$^3$ while the predicted peak (fire plus anthropogenic) was 12.2 µg/m$^3$.

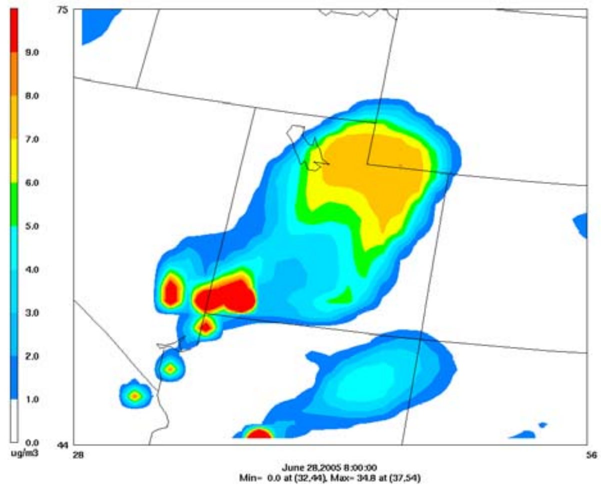


Fig. 4. Simulated ground level $PM_{2.5}$ concentration due to fires on June 28, 2005 at 0800 UTC.

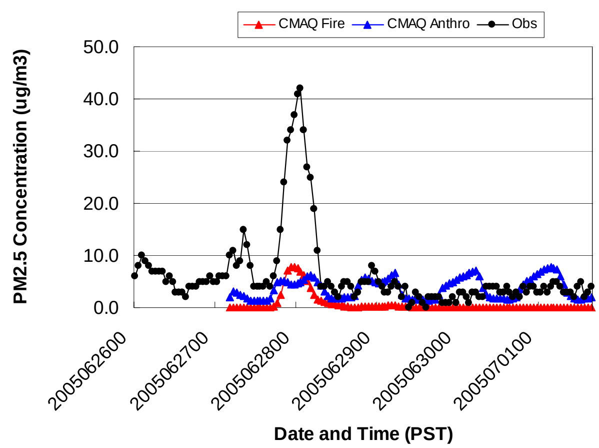


Fig. 5. Observed total $PM_{2.5}$ and predicted ground-level wildfire and anthropogenic $PM_{2.5}$ concentrations from June 26 through July 1, 2005, at Hawthorne, located in SLC.

BlueSky National predicted little or no fire $PM_{2.5}$ over the Las Vegas area. Though it is unknown how much of the observed $PM_{2.5}$ at this time was due to smoke, based on concentrations observed in subsequent days, it is reasonable to assume a minimal fire impact during this time. Therefore BlueSky National correctly predicted a minimal fire impact on Las Vegas.

During the afternoon and evening on June 28, the regional-scale wind flow shifted from southwesterly to westerly. This change in wind flow shifted the wildfire smoke plume away from SLC on June 29, and observed $PM_{2.5}$ levels dropped accordingly (Figure 6). Satellite imagery from June 29 shows a smoke plume originating from the fires and stretching eastward across northern Arizona and southern Utah, well south of SLC (Figure 2). BlueSky National also showed a plume of ground-level $PM_{2.5}$ over the same region at the same time (Figure 7). The modeled plume extends more northward into Utah than the satellite indicates, but the fire impact remains well south of SLC, as observed.

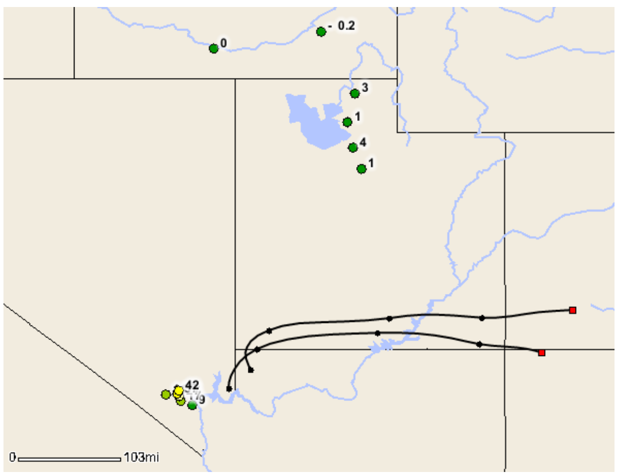


Fig. 6. Observed $PM_{2.5}$ concentrations and 24-hr HYSPLIT forward trajectories on June 29, 2005, at 1600 UTC. Trajectories originate on June 28 at 1600 UTC at 500 m agl from two of the observed fire complexes.

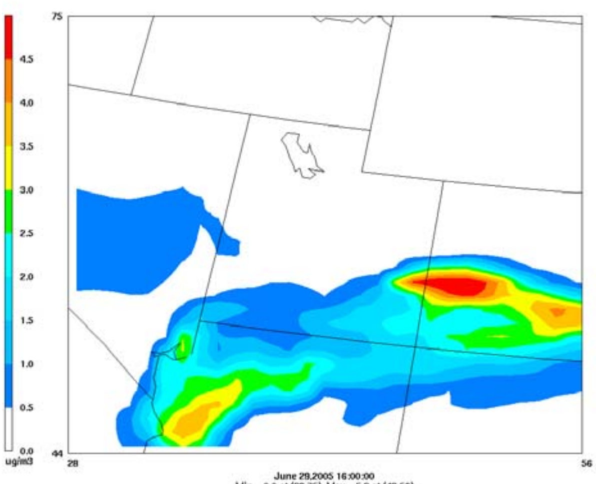


Fig. 7. Simulated ground level $PM_{2.5}$ concentration caused by fires on June 29, 2005, at 1600 UTC.

Unlike the previous day, BlueSky National incorrectly predicted a minimal fire $PM_{2.5}$ impact in Las Vegas. The satellite images show smoke persisting over Las Vegas and much of southern Nevada, and observed $PM_{2.5}$ concentrations at some Las Vegas monitoring sites exceeded 35 $\mu g/m^3$ for much of June 29; however, the western edge of the predicted smoke $PM_{2.5}$ plume remained just east of Las Vegas. On June 30, a day with weak regional surface wind flows, observed $PM_{2.5}$ concentrations remained high (peak 1-hr concentration of 85 $\mu g/m^3$). And though BlueSky National predicted a peak fire $PM_{2.5}$ concentration of 55 $\mu g/m^3$ in southern Nevada, most of the predicted $PM_{2.5}$ still remained east of Las Vegas.

## 4. DISCUSSION

The BlueSky National Smoke Modeling System has been described, and a test case was performed to demonstrate its performance and capabilities. The test case involved modeling $PM_{2.5}$ emissions from several wildfires in the western United States in June 2005. Smoke from these wildfires impacted SLC, which was 250 to 300 miles downwind of the fires, and Las Vegas, which was just 50 miles west of fires in southern Nevada. Satellite imagery, hourly $PM_{2.5}$ observations, and HYSPLIT trajectory analyses were used to evaluate model performance.

SLC was impacted on one day by a transient smoke plume transported from the fires by southwest winds. BlueSky National accurately depicted the timing of the smoke impact at SLC, even though the model underpredicted peak concentrations. As the smoke plume passed through SLC and the regional wind flow shifted, BlueSky National accurately depicted the shifted smoke plume and no longer predicted an impact on SLC.

Model performance was not as good near the fires themselves. During days when southwest winds were stronger, BlueSky National accurately predicted a minimal impact on $PM_{2.5}$ concentrations in Las Vegas as smoke was advected downwind. But on days when regional wind flows were light, BlueSky National did not predict a fire $PM_{2.5}$ impact on Las Vegas, while satellite imagery and hourly observations both indicated that smoke from the nearby fires was indeed impacting Las Vegas. Our findings are consistent with a previous evaluation of the original BlueSky Framework (Raffuse et al., 2006), in which model performance degraded near fires.

The real power of BlueSky National is its ability to combine both fire and anthropogenic (primary and secondary) contributions of $PM_{2.5}$ and carry those predictions into future-day simulations. This system will provide national background $PM_{2.5}$ concentration fields that individual FCAMMS will use in their own regional high-resolution BSF3 runs. The result will be more accurate depictions of smoke impacts from wildfires and prescribed burns, and an improved smoke prediction tool for use by decision makes.

## 5. ACKNOWLEDGMENTS

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