Sensitivity of air quality simulation to smoke plume rise

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Abstract. Plume rise is the height smoke plumes can reach. This information is needed by air quality models such as the Community Multiscale Air Quality (CMAQ) model to simulate physical and chemical processes of point-source fire emissions. This study seeks to understand the importance of plume rise to CMAQ air quality simulation of prescribed burning to plume rise. CMAQ simulations are compared between fire emissions as area and point sources. For point source, Daysmoke is used to calculate plume rise. A burn day in Florida is examined. The results indicate significant sensitivity of simulated $PM_{2.5}$ (particulate matter with a size smaller than 2.5 µm) concentrations to plume rise. The air quality effects, measured by $PM_{2.5}$ concentrations at the burning area, are more significant by specifying fire emissions as an area source. The implication of the results for the uncertainty in evaluating the contribution of prescribed burning to regional air pollution is discussed.

Keywords: prescribed burning, air quality, plume rise, CMAQ simulation, sensitivity analysis.

1 INTRODUCTION

Prescribed burning is a forest management technique [1]. Prescribed burning temporarily reduces damage from wildfire by removing a portion of the accumulating dead fuels (such as duff and logs on the forest floor) and reducing the stature of the developing understory when burning conditions are not severe. Prescribed burning also serves as a surrogate for the historical fires by recycling nutrients and restoring/sustaining ecosystem health.

However, prescribed burning can lead to adverse consequence of air quality degradation [2-4]. Smog, regional haze, and visibility impairment are the major air quality concerns of the U.S. Environmental Protection Agency (EPA). Prescribed burning can contribute to all these air quality problems by releasing large amounts of $PM_{2.5}$ and PM_{10} (particulate matter with a size not greater than 2.5 and 10µm, respectively), NO_2 and volatile organic compounds (VOC), which are either direct contributor or precursors of O_3. Prescribed burning also emits CO, SO_2, which together with PM, NO_2, and O_3 are the criteria air pollutants subject to the U.S. National Ambient Air Quality Standards (NAAQS) [5]. EPA has issued the Interim Air Quality Policy on Wildland and Prescribed Fire to protect public health and welfare by mitigating the impacts of air pollutant emissions from wildland fires on air quality [6].

Air quality modeling tools such as the EPA Community Multiscale Air Quality (CMAQ) model [7] and emission processing models such as the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) [8] include different types of emission sources. Emissions from prescribed burning have been traditionally considered as an area source. Area source emissions are annual amounts (or converted to daily averages) from counties, and are distributed only at the lowest model level. However, prescribed burning occurs as individual events geographically with hourly and daily variability, and smoke from prescribed burning

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may be ejected to levels a few kilometers above the ground. Point source is another emission source in SMOKE, whose emissions are daily or hourly amounts from individual locations like power plants, and are partitioned to multiple vertical levels. Emissions from prescribed burning therefore are more likely to be a point source.

One important issue for point-source emissions is plume rise, that is, the height smoke plumes can reach. Plume rise information is needed in SMOKE and is crucial for evaluating the air quality effects of prescribed burning. Emissions, if injected into higher elevations, are likely to be transported out of the burn area by prevailing winds, meaning relative smaller local ground concentrations and therefore reduced chances for exceeding the NAAQS standards, which are measured by ground concentration. SMOKE is equipped with the Briggs scheme [9] for calculating plume rise. This scheme was originally developed for stacks of power plants. Many efforts have been made to develop plume rise schemes for fires. For example, Achtemeier [10] developed Daysmoke for burning of sugarcane.

The purpose of this study is to understand sensitivity of air quality effect simulation of prescribed burns. The approach is to compare CMAQ simulations between area and point emissions. A case of prescribed burns in Florida, a state with the most extensive prescribed burning among the southern U.S. states [11], is examined. Methods are described in the Section 2. Results and discussion are provided in Section 3. Conclusions are given in the final section.

2 METHODS

2.1 Air quality and meteorological models

CMAQ (v4.4) and SMOKE (v2.1) were used. The SMOKE inputs included $PM_{2.5}$, PM_{10}, SO_2, CO, NOx, NH_3, and VOC. The Carbon Bond-IV (CB-IV) chemical mechanism was used to simulate gas-phase chemistry in CMAQ. In this model, the particle-size distribution is represented as the superposition of three lognormal sub-distributions. $PM_{2.5}$ is represented by two interacting sub-distributions (or modes) of the nuclei or Aiken (i) mode and the accumulation (j) mode.

The National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) [12] was used for providing meteorological conditions for emission calculation and SMOKE and CMAQ simulations. The MM5 model was configured with the Kain-Fritsch [13] convective parameterization, the Medium Range Forecast (MRF) boundary layer scheme [14], the simple ice microphysics scheme and a 5-layer soil model for the land surface scheme. The MM5 outputs were processed through the Meteorology-Chemistry Interface Processor (MCIP) v2.2 for use of SMOKE and CMAQ.

2.2 Plume rise schemes

Daysmoke was used to calculate smoke plume rise. Daysmoke is a dynamical model to simulate movement and deposition of smoke particles. It was first developed for burn of sugar cane [10], and recently modified for applications to burns of various forest ecosystems. Daysmoke describes three processes of particle movement (Fig. 1), that is, moving up with a plume, dropping out of plume, and irregular movements due to turbulence. Each process is described with a sub-model. The first process is simulated by the Entrainment Turret Model. The plume is assumed to be a succession of rising turrets. The rate of rise of each turret is a function of its initial temperature, vertical velocity, effective diameter, and entrainment. The second process is simulated by the Detraining particle trajectory model. Movement within the plume is described by the horizontal and vertical wind velocity within the plume, turbulent horizontal and vertical velocity within the plume, and particle terminal velocity. Detrainment occurs when stochastic plume turbulence places particles beyond plume boundaries, plume rise rate falls below a threshold vertical velocity, or absolute value of large eddy velocity exceeds plume rise rate. The third process is simulated by a large eddy parameterization. Eddies are two-dimensional and oriented normal to the axis of the mean layer flow. Eddy size and strength are proportional to depth of the planetary boundary-layer (PBL). Eddy growth and dissipation are time-dependent and are independent of growth rates of neighboring eddies. Eddy structure is vertical. Eddies are transported by the mean wind in the PBL. In addition, the plume rise and vertical profiles are calculated with relative emissions production model. Particles passing a "wall" a few miles downwind from a burning are counted for each hour during the burning period. A percent of particle number at each layer at each hour relative to the total particle number is assigned to SMOKE/CMAQ simulations.

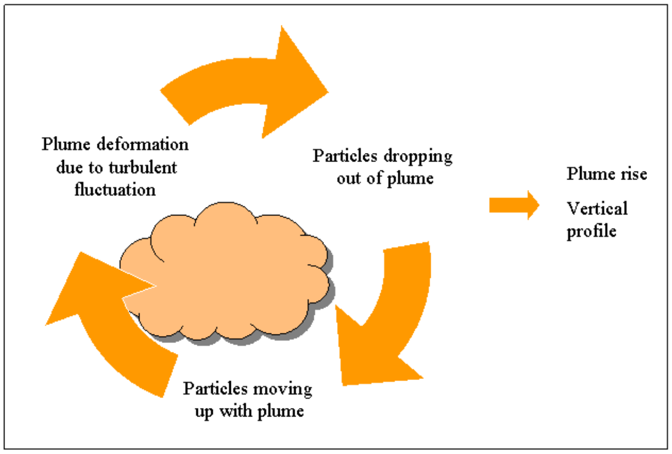

Fig. 1. Physical processes in Daysmoke.

SMOKE (v2.1) is equipped with the Briggs's scheme, which was originally developed to calculate plume rise of power plant stacks. Plume rise is determined by buoyancy flux, exit speed, wind speed, atmospheric static stability, turbulence activity, etc. Two techniques, Layer Fraction Method (LFM) and Cutoff Method (CM), are available in SMOKE for specifying vertical distribution of emissions. In LFM, the plume is distributed into the vertical layers that the plume intersects based on the pressure in each layer. This method is used when a chemical model has fine vertical resolution. CM is mainly used when a chemical model has coarse vertical resolution. The calculated plume rise is compared with a user-defined cutoff value. Sources below this cutoff value are treated as single-layer point sources, and sources above this cutoff value are considered elevated point sources. LFM was used for smoke vertical distribution specification in the experiment simulation.

In comparison with Briggs scheme which was developed for power plant stack, Daysmoke is a dynamic model which integrates over time. In addition, Daysmoke provides both plume rise and vertical profiles, while Briggs scheme only provides plume rise.

2.3 Simulations

CMAQ simulations were conducted for the prescribed burns in Florida on March 6, 2002. Florida has been operating probably a most complete prescribed burning management plan in southeastern United States. This region comprises one of the most productive forested areas in the country with approximately 200 million acres (81 million ha) or 40% of the Nation's forests despite only 24% of the U.S. land area [15]. Furthermore, southern forests are dynamic ecosystems characterized by rapid growth and hence rapid deposition of fuels within a favorable climate, and the high fire-return rate of every 3-5 years [16]. Therefore, prescribed burning has been extensively used, treating 6 to 8 million acres (2–3 million ha) of forest and agricultural lands each year [1]. Fires have been found to be an important contributor to regional PM and ozone levels [17], raising concern that air quality issues could begin to limit the use of prescribed fire as a management tool.

The model domain covers Florida with a 95×47 horizontal grid and a grid spacing of 12 km. The MM5 vertical component of the grid was divided into irregular 41 layers, providing maximum resolution near the surface (minimum vertical grid spacing is 10 m). Initial and six hourly boundary conditions were provided by the National Centers for Environmental Prediction (NCEP) reanalysis data. The CMAQ vertical component of the grid was divided into 21 layers.

Two simulations, denoted as Simu-Area and Simu-Daysmoke, were conducted. Fire emissions are specified as an area source in Simu-Area, and a point source in Simu-Daysmoke. Plume rise in Simu-Daysmoke is calculated with Daysmoke. To include fire emissions as a point source, fire emission files in SMOKE were created. A fire was identified by its latitude and longitude position in an emission file in the Inventory Data Analyzer (IDA) format. All fire properties (height, diameter, exit temperature, exit velocity, and flow rate) were included in this file. Day- or hour-specific emissions of various chemical species were stored in separate files in the Emissions Modeling System'95 (EMS-95) format.

In addition, a third simulation denoted as Simu-Briggs was conducted for comparison purpose. It is the same as Simu-Daysmoke expect that plume rise is calculated using Briggs scheme.

2.4 Fire data and emission estimation

Prescribed fire data were obtained from the Florida Division of Forestry (FDF). Through the Division's Fire Management Information System [18], FDF records in a central database information regarding the size, location, date/time (of ignition and completion) and purpose for all silvicultural, agricultural and land-clearing prescribed burns.

A fuel loading was assigned to each burn using the burn's location and size and the FDF's 30 meter resolution fuels map. As part of the Division's Wildland Fire Risk Assessment (http://www.fl-dof.com/wildfire/wf_fras.html) vegetative fuels were characterized into one of 13 fire behavior prediction fuel models described in [19]. Using the burn's location to define the center point of a square with an area equivalent to that of the burn, a weighted average of the fuel loading from each 30 meter pixel within the burn area was calculated. The portion of this total fuel load consumed by the fire is determined using the single parameter regression equations of CONSUME 3.0 [20]. Fire emissions were calculated by multiplying the consumed fuel by an emission factor appropriate for the fuel type and ignition plan [21]. These total emission values were transformed into hourly values using equations provided in [22].

3 RESULTS AND DISCUSSION

3.1 Burns

On the simulation date of March 6, 180 prescribed burns occurred with the total burned area of nearly 20,000 acres, the largest single-day burned area in 2002 (Fig. 2). Nineteen of them had a size greater than 1.0 km, which accounted for only about 10.5% of total burns in number, but about 80 % in burned area.

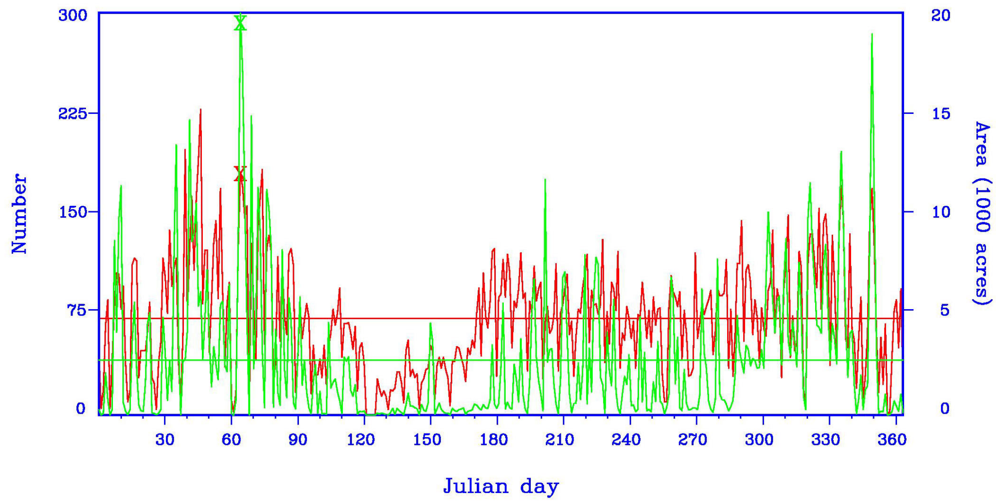

Fig. 2. Number (red) and total area (green) of daily prescribed burns in Florida during 2002. The simulation day of March 6 (Julian day 65) is marked by cross sign. The horizontal lines represent annual averages.

Besides March 6, burn data for entire year of 2002 was also analyzed to estimate the contribution of prescribed burning to regional air pollution in regard to the EPA standard. Burns had large seasonal variability. They were more active during the middle winter and early spring (the first Julian 90 days or January through March) and the second half of the year (after day 180) in 2002. On average, there were 72 burns per day (Table 1). The largest daily burn number was 228. The total burned area was about 2700 acres per day. The larger burns (greater than 1.0 km in size) was about 2.5 per day, which account for about 4.4% of total burns in number, but about 65 % in burned area.

Table 1. Distribution of burns with size.

	Size (km)	<0.1	0.1-0.25	0.25-0.5	0.5-1	1-2.5	>2.5	Total
March 6	Number	60	55	29	18	17	2	180
	Number %	33.3	30.0	16.1	10.0	9.4	1.1	
	Area %	0.4	2.1	5.5	12.1	52.7	27.2	
2002 average	Number	40.9	17.1	7.3	5.5	2.3	0.2	72.0
	Number %	57.9	23.7	10.1	5.9	3.1	0.3	
	Area %	1.9	3.8	9.1	20.2	45.0	20.0	

Accurate fire activity data is a fundamental prerequisite for air quality simulation of wildland fires [11]. Satellite remote sensing (RS) has emerged as a useful technique for wildfire detection (e.g., [23-26]. RS detention of prescribed fires in the South, however, remains a challenge because of the limitations related to fire size, forest crown, and clouds.

RS detection of fire information is not a research issue for this study. Nevertheless, it is interesting to note that, as suggested by the Florida burn data, for some advanced RS techniques such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) [27, 28], size might be no longer a limitation for those prescribed burns that are the major contributor to regional air pollutions. MODIS has a resolution of 1 km for surface temperature and 0.25 km for land vegetation detection. If all 2002 Florida prescribed had burned under forest crown- and cloud-free conditions, about 65% (95%) of total burned areas would have been detected by using MODIS surface temperature (land vegetation) measurements.

3.2 Weather conditions

A high pressure system dominated the Southeast on the simulation day. Florida was in the southern sector of the system. Figure 3 shows wind vector on the ground simulated with MM5. Northeasterly airflows came from the Atlantic coast. They turned to westwards and northwards in the northern Florid and southern Georgia.

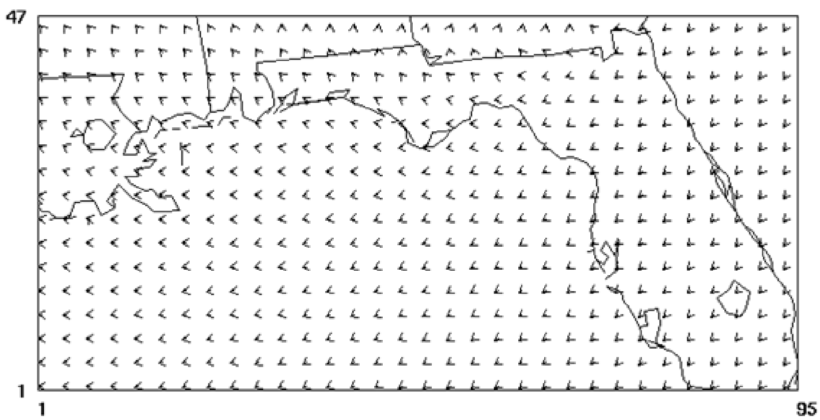

Fig. 3. Ground wind vector at the beginning of simulation.

3.3 Daysmoke plume rise

Figure 4 shows smoke vertical profile. The MM5-simulated meteorological elements (air temperature, winds, humidity, etc.) averaged over 72 grid points within the major burn region in the northern Florida were used. Plume rise calculated with Daysmoke gradually increases from about 180 m at 1000 Eastern Standard Time (EST, same hereafter) to nearly 1 km at 1300, and then gradually decreases. Substantial amounts of smoke particles are found within two or more layers in the upper portion of the plume until 1700.

In comparison with Daysmoke, plume rise calculated with Briggs scheme is lower (near the ground) at 1000 and about the same in the next two hours; but it becomes about two times as high at 1300 and continues to increase up to about 6.5 km. Furthermore, the plume rise remains at a highest value in the afternoon hours. In addition, smoke particles are distributed almost entirely within a single layer at all hours (except at 1200), as indicated by a percentage value of nearly100.

3.4 CMAQ simulation

Figure 5 shows the geographic distribution of the ground-layer $PM_{2.5}$ at 1400 when the largest values during the simulation period are found. Smoke particles spread over the northwestern Florida. But there is significant spatial variability. The values of 100 μg m^{-3} or larger are found along the Florida borders with Georgia and Alabama.

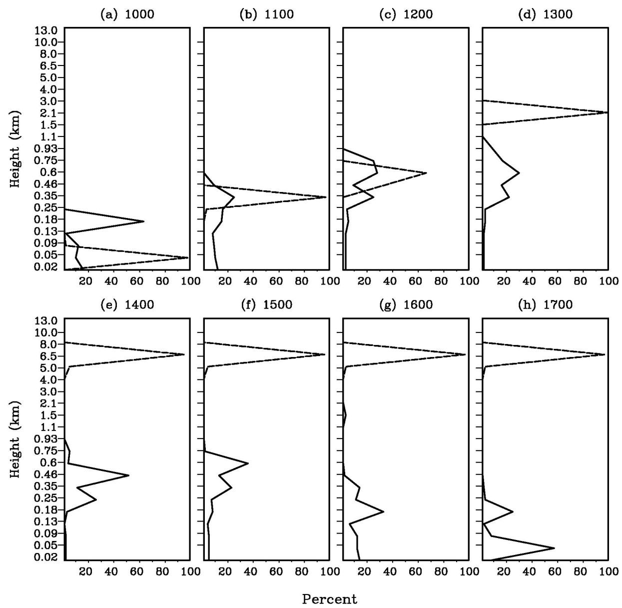

Fig. 4. Vertical distribution of smoke particles (in %) with height at the hours from 1000 throughout 1700. Real and dashed lines represent the estimates using Daysmoke and Briggs scheme, respectively.

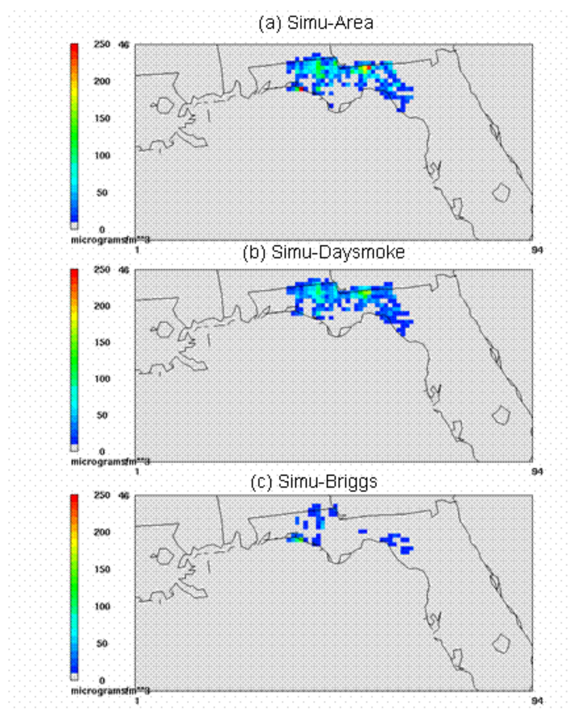

Fig. 5. Spatial distribution of ground $PM_{2.5}$ concentration ($\mu g\ m^{-3}$). Panels (a-c) are for three simulations.

The ground $PM_{2.5}$ concentrations are the largest with Simu-Aera. The values over 200 μg m^{-3} are found near the Florida-Georgia border and the Gulf coast. The maximum value is 300 μg m^{-3}. Simu-Daysmoke also produces large $PM_{2.5}$ concentrations in the two areas along the Florida borders with Georgia and Alabama. The maximum value is 164 μg m^{-3}. Simu-Briggs produces much smaller $PM_{2.5}$ concentrations in most areas in spite of a maximum value is 142 μg m^{-3}.

Figure 6 shows the time-altitude cross section of $PM_{2.5}$ concentrations averaged over the 72 grid points over the area with large concentrations near the Florida-Georgia border. For Simu-Aera, Smoke particles appear as early as 1000 and the concentrations increase gradually to about 90 μg m^{-3} on the ground until 1400. The height of the smoke area with $PM_{2.5}$ concentrations larger than 20 μg m^{-3} increases from 0.75 to about 1.3 km during the period. The concentrations reduce gradually with height. The temporal evolution and vertical distribution of $PM_{2.5}$ concentrations in Simu-Daysmoke are similar to those in Simu-Area except a smaller amount of about 70 μg m^{-3} on the ground at 1400. The peak of $PM_{2.5}$ concentrations in Simu-Briggs also appears shortly after the noon, but the magnitude is only over 30 μg m^{-3} found about 2 km above the ground.

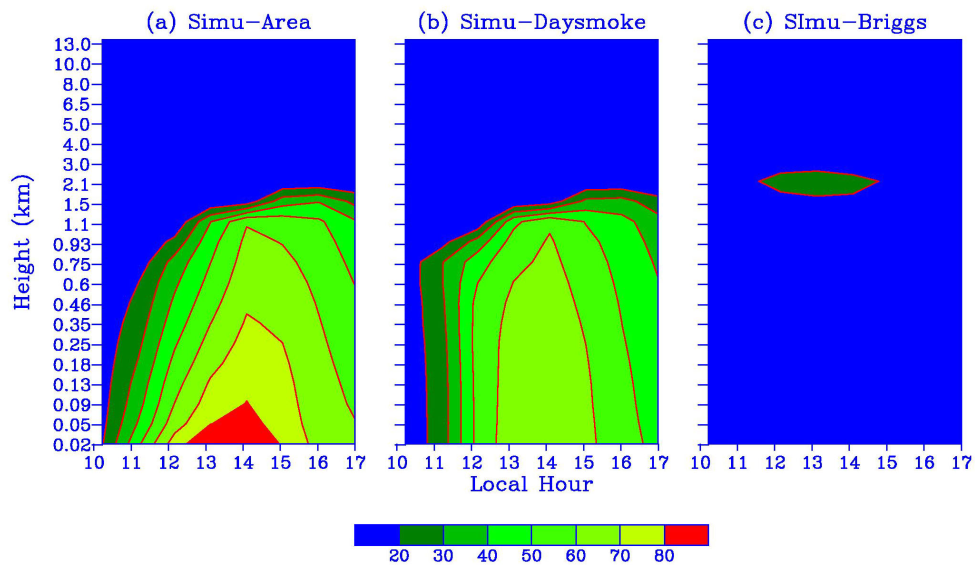

Fig. 6. Time-height cross section of $PM_{2.5}$ concentration (μg m^{-3}). Panels (a-c) are results for three simulations.

3.5 Discussion

The results shown above indicate large sensitivity of CAMQ simulation to plume rise for the examined Florida prescribed burning case. The ground $PM_{2.5}$ concentrations with area emissions (zero plume rise) are larger than those with point emissions. This sensitivity to plume rise could have important implications for assessing the air quality effects of prescribed burning case using CMAQ. With area emissions, more smoke particles are trapped near the ground in the simulation, leading to more severe air quality effects in the burning area.

The NAAQS for daily mean ground $PM_{2.5}$ was recently reduced from 65 to 35 μg m^{-3}. It is essential to estimate the magnitude of $PM_{2.5}$ concentrations from prescribed burning in order to understand the possible impacts of the tightening regulation on prescribed burning management. The daily mean ground $PM_{2.5}$ standard at each population orientated monitor within an area is measured using the average over the annual 98^{th} percentile (approximately seven days of the most pollution conditions in a year) during a three-year period. The simulation conducted in this study is only for one day and, thus, it is impossible to use the results for a complete and strict assessment of the contribution of prescribed burning to local air quality with respect to the NAAQS standard. Nevertheless, a rough estimate can be made using the results in combination with the annual burn data of 2002.

The procedure for such an estimate is as follows: (1) Estimation of daily average of $PM_{2.5}$ near the largest burn on the simulation day of March 6, which occurred at 30.5°N, 84°W with a burned area about 6 km^2. It is assumed from Fig. 6 that the major smoke episode lasted for about half a day during which $PM_{2.5}$ concentrations first gradually increased from zero to a maximum around 1400, and then gradually decreased to a very small amount in the late evening. As seen in the figure, the maximum ground-layer $PM_{2.5}$ concentrations over the 72 grid-point area is about 90 (70) $\mu g\ m^{-3}$ for Simu-Area (Simu-Daysmoke). Thus, the average over the smoke period is estimated to be approximately 45 (35) $\mu g\ m^{-3}$ and the average over the entire day is close to 22.5 (17.5) $\mu g\ m^{-3}$. (2) Estimation of the 98^{th} percentile average. It is found that, within the 72 grid-point area, burns with the comparable size happened on six other days during 2002. Thus, the $PM_{2.5}$ concentration for March 6 would roughly represent the 98^{th} percentile average of 2002. (3) Estimation of the average over a three-year period. We assume little interannual variability in prescribed burning activities. So the annual average is close to a three-year average.

The final estimate is 22.5 $\mu g\ m^{-3}$ for the largest prescribed burning in Florida for area emissions or 17.5 $\mu g\ m^{-3}$ for point emissions using Daysmoke for plume rise calculation. The ratios of the estimates to the NAAQS value are about to 2/3 and 1/2, respectively, for the specific case examined here. The differences in the ratio indicate large uncertainty in estimating the contribution of prescribed burning to regional and local air pollutions as the EPA $PM_{2.5}$ standard is concerned. It is emphasized again that the estimate is very rough with the result of only one-day simulation.

In comparison with Daysmoke, the ground $PM_{2.5}$ concentrations using Briggs scheme to calculate plume rise are much smaller. A large portion of smoke particles is ejected into high elevations due to large plume rise values. It is likely that these values are unrealistically large because they are well above the planetary boundary layer. This may be related to the different features between fire smoke plumes and power plant stacks. Fire plumes usually have larger initial temperature contrast with the ambient atmosphere and therefore larger buoyant flux. This leads to larger plume rise value based on Briggs scheme. On the other hand, fire smoke plumes usually are much large in size. Thus, their interactions with the ambient atmosphere through entrainment are more significant. This would suppress the upward motion and therefore lead to small plume rise. The interactions are involved in Daysmoke but not in Briggs scheme.

4 SUMMARY

Simulations with CMAQ have been conducted for the Florida prescribed burns on March 6, 2002, and sensitivity to plume rise has been examined by comparing area and point emissions. The results indicate large sensitivity of $PM_{2.5}$ concentration simulation to specification of plume rise, which could be different due to the specification of different emission types. The ground $PM_{2.5}$ concentration is larger for area source than point source. For the case examined here, the air quality effects at the burning area are overestimated by specifying fire emission as an area source. They are underestimated, on the other hand, when using Briggs scheme to calculate plume rise.

The Florida burning data of 2000 together with the CMAQ simulation results have been used to understand the uncertainty in evaluating the contribution of prescribed burning to regional air pollution with respect to the NAAQS standard and the potential of satellite remote sensing in detecting prescribed burns. The prescribed burning examined in this study could produce ground $PM_{2.5}$ concentrations that account for about two thirds for area source and half for point source of the NAAQS daily standard value according to a rough estimation.

The Florida burning data of 2000 have also been used to evaluate the potential capacity of satellite remote sensing technique in detecting prescribed burning information. The technique such as MODIS is able to detect the large Florida prescribed burns that have major contributions to regional air quality as long as burn size is the only limiting factor. With the development of the solutions to other factors such as forest crown and clouds, remote sensing would be a useful tool in providing much needed multiple-year high-resolution fire information for simulating the regional air quality effects of prescribed burning.

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