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# Refining fire emissions for air quality modeling with remotely sensed fire counts: A wildfire case study

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## Abstract

This paper examines the use of Moderate Resolution Imaging Spectroradiometer (MODIS) observed active fire data (pixel counts) to refine the National Emissions Inventory (NEI) fire emission estimates for major wildfire events. This study was motivated by the extremely limited information available for many years of the United States Environmental Protection Agency (US EPA) NEI about the specific location and timing of major fire events. The MODIS fire data provide twice-daily snapshots of the locations and breadth of fires, which can be helpful for identifying major wildfires that typically persist for a minimum of several days. A major wildfire in Mallory Swamp, FL, is used here as a case study to test a reallocation approach for temporally and spatially distributing the state-level fire emissions based on the MODIS fire data. Community Multiscale Air Quality (CMAQ) model simulations using these reallocated emissions are then compared with another simulation based on the original NEI fire emissions. We compare total carbon (TC) predictions from these CMAQ simulations against observations from the Inter-agency Monitoring of Protected Visual Environments (IMPROVE) surface network. Comparisons at three IMPROVE sites demonstrate substantial improvements in the temporal variability and overall correlation for TC predictions when the MODIS fire data is used to refine the fire emission estimates. These results suggest that if limited information is available about the spatial and temporal extent of a major wildfire fire, remotely sensed fire data can be a useful surrogate for developing the fire emissions estimates for air quality modeling purposes.
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*Keywords:* Biomass burning; Wildfire; Pixel; Emissions reallocation; Spectroradiometer; Satellite; MODIS

## 1. Introduction

Major wildland fire events can be an important source of airborne fine particulate matter (PM) (PM with aerodynamic diameter $\leqslant 2.5\,\mu m$, hereafter referred to as $PM_{2.5}$) emissions in the form of elemental carbon (EC) and organic carbon (OC). This study was motivated by the extremely limited information available for many years of the United States Environmental Protection Agency (US EPA) National Emissions Inventory (NEI) about the specific location and timing of major fire events, and the cost of assimilating this information is often

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prohibitive. As a specific example, the 2001 National Emission Inventory (NEI) biomass-burning related emissions estimates (US Environmental Protection Agency, 2004) are spatially resolved to 48 states in the Conterminous United States (CONUS) and temporally resolved to monthly time-scales. In the 2001 NEI, emissions are distributed evenly across the entire month, and over each state based on the forested land type. In this paper, we test a relatively inexpensive, and an easily adaptive technique using satellite-based fire data that can help characterize fire emissions when spatio-temporal information is limited about major fire events.

There are several other satellite-based methods that estimate biomass burning emissions for air quality applications. For example, Kondragunta and Zhang (2006) have developed a satellite-based algorithm that uses satellite-derived fuel loading and fuel moisture databases. Also, Wiedinmyer et al. (2006) have proposed an alternative approach using satellite drivers and ground-based information to develop a North American fire inventory and fire emissions model for multiple years. The method introduced in this paper differs from these other techniques in that we are not developing a new emissions model. Rather, we are using satellite information as a surrogate to refine the spatial and temporal characterization of biomass burning in an existing emission inventory.

To test and demonstrate the utility of this approach, a major wildfire event in May 2001 was selected as a case study. The fire event occurred during May 2001 in Lafayette County, FL, and was popularly known as the "Mallory-Swamp fire". The wildfire event was started by lightning activity on 12 May in the big bend region of Florida north of the Suwannee River. The fire burned for many days with the largest number of acres consumed on 24–25 May. After the fire was contained at the end of May, it smoldered into June. The total spatial extent as reported by the Florida Department of Forestry was 57,200 acres (http://www.fl-dof.com/wildfire/stats_significant_fires.html). In the year 2001 NEI, Florida biomass burning contributed approximately 60% of the CONUS-wide total fire-related $PM_{2.5}$ emissions for the month of May. This was selected as the case study because of the major contributions of this fire event to $PM_{2.5}$ emissions and because the limited NEI 2001 information could therefore contribute substantially to poor model performance for carbonaceous $PM_{2.5}$ predictions.

For the May 2001 case study, we develop air quality modeling simulations using the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006) with the standard NEI 2001 inventory, and with a revised version where the fire emissions have been reallocated spatially and temporally. To reallocate the emissions, remotely sensed fire activity data are used to redistribute the state-level NEI biomass burning emissions to more accurately characterize the fire emissions. We will demonstrate with this case study how this relatively simple approach can be a useful approach for improving air quality model predictions when extremely limited information is available about the emissions from major wildfire events.

## 2. Observed data description

### 2.1. The Moderate Resolution Imaging Spectroradiometer (MODIS) rapid response (RR) product

To characterize the location and temporal variability in major fires, we will use an active fire detection product developed by the University of Maryland (UMD), Department of Geography, (Justice et al., 2002) that is based on National Aeronautics and Space Administration's (NASA) MODIS collection-4 data. Collection-4 data sets are formally validated and uncertainties are properly identified and made ready for scientific publications (NASA Goddard DAAC, 2003). The MODIS instrument was first launched aboard the polar orbiting Terra satellite and began collecting data during February 2000.

The UMD RR active fire pixel count data are based on an absolute detection criterion for the strong fires using brightness temperature information from the MODIS sensor at 4 μm ($T_{b4}$) wavelength and at 11 μm ($T_{b11}$) wavelength (Justice et al., 2002). This method bases fire detection on either of the two conditions:

$$T_{b4} > 360\,\mathrm{K}\ \ (330\,\mathrm{K\ at\ night}), \tag{1}$$

$$\begin{aligned} &T_{b4} > 330\,\mathrm{K}\ \ (315\,\mathrm{K\ at\ night}), \quad \text{and} \\ &T_{b4} - T_{b11} > 25\,\mathrm{K}\ \ (10\,\mathrm{K\ at\ night}). \end{aligned} \tag{2}$$

If neither is satisfied, then a relative fire detection algorithm is applied where the fire is distinguished from the background values as follows:

$$T_{\mathrm{b4}} > \left(\overline{T_{\mathrm{b4}}}\right) + 3\sigma_{T_{\mathrm{b4}}}, \quad \text{and}$$
$$T_{\mathrm{b4}} - T_{\mathrm{b11}} > (T_{\mathrm{b4}} - T_{\mathrm{b11}})_{\mathrm{median}} + 3\sigma_{T_{\mathrm{b4}}-T_{\mathrm{b11}}}, \qquad (3)$$

where $\sigma$ is standard deviation of brightness temperature in degree K, and $\overline{T_{\mathrm{b4}}}$ is the mean brightness temperature for cloud-, water-, and fire-free grid having the candidate fire-pixel at its center (Justice et al., 2002). False detections due to sun-glint are rejected using the MODIS 250-m red and near infrared channel if reflectance is greater than 30% and lies within 40° of the specular reflection position. Each fire detection represents the center of a 1 km pixel flagged as containing one or more actively burning fires within that pixel. For any given scene the minimum detectable fire size is a function of many different variables (scan angle, biome, solar zenith angle, land surface temperature, cloud cover, amount of smoke and wind direction, etc.) so a precise value will vary slightly with these conditions. The probability of fire detection is enhanced during cloud free conditions at (or near) nadir and when the scene is free of heavy smoke and sun-glint. Pixel sizes are $\sim$1 km$^2$ at nadir (exact vertical point on surface of earth drawn from satellite) and are larger at the eastern and western edges of the scan due to the MODIS bow-tie effect (Gomez-Landesa et al., 2004). The MODIS RR fire count data are available for day- and nighttime passes over the CONUS.

We used the fire pixel latitude, longitude, acquisition date, time, pixel count, and the pixel-level confidence (0–100%) data to generate a total fire pixel count for each CMAQ grid. The detected fire pixel confidence is actually a geometric mean of five sub-confidences derived by applying a ramp function (Giglio et al., 2003b) to (i) day- and nighttime temperature threshold of the candidate pixel, (ii) two standardized variables involving $T_{\mathrm{b4}}$, the temperature difference between $T_{\mathrm{b4}}$ and $T_{\mathrm{b11}}$ and its departure from non-fire background temperature, and respective standard deviations. Details about this contextual fire detection pixel confidence that is applied to the MODIS RR product can be found in Giglio et al. (2003a, b). We have considered only fire pixels with data confidence greater than or equal to 70%. This cut-off criterion is chosen so that we use only fire counts that bear nominal and high confidence levels as defined in Justice et al. (2002).

Terra is a sun-synchronous satellite; hence, it views the same earth scene during a fixed time of the day. Two retrievals are made over the CONUS each day, one in the 0300 UTC-0800 UTC time window and the other during the daytime 1500–2000 UTC window during which the satellite passes over the CONUS. For this sensitivity study, the time of the resulting fire pixel counts is estimated to be 0600 and 1800 UTC for all locations in the CONUS. The total fire pixel counts from the UMD RR dataset are binned over each CMAQ grid cell. To generate hourly emissions field from the accumulated maps obtained for 0600 and 1800 UTC linear temporal interpolation is used. This linear interpolation necessary for application to hourly emissions introduces uncertainties for fires of short duration; however, it is more reasonable for major wildfire cases such as this Mallory Swamp (MS) fire case study, where the fire duration spans several days. The method used to reallocate the emissions inventory using these satellite fire pixel counts is described in Section 3.

### *2.2. The Inter-agency Monitoring of Protected Visual Environments (IMPROVE) TC data*

Typically, IMPROVE monitors are located in rural areas and are designed to characterize long-term trends in visibility and visibility degrading aerosols mostly at National Parks and Wilderness (Class I) areas. They collect 24-h integrated samples every third day (midnight to midnight, local time) and a majority of them are located in the western United States. To assess the impact on model performance from reallocating the emissions based on fire pixel count data from the MS fire in Florida during May 2001, the following IMPROVE sites were used: Chassahowitzka National Wildlife Refuge (CHAS), Okefenokee National Wildlife Refuge (OKEF), and Everglades National Park (EVER). Site CHAS is located about 134 km south-southwest of the MS fire at an elevation of 2 m above mean sea-level (MSL), site OKEF is located 128 km northeast of the MS-fire at an elevation of 48 m above MSL, and the site EVER is located about 550 km south of the MS fire with an elevation of 1.25 m above MSL. These three sites (shown as white circles in Fig. 1d) reported a more or less complete set of monthly data and the station elevations are nominal so that the concentrations from IMPROVE sensor are directly compared with the CMAQ TC surface level predictions.

Although the CMAQ and IMPROVE algorithms speciate total aerosol carbon into OC and EC

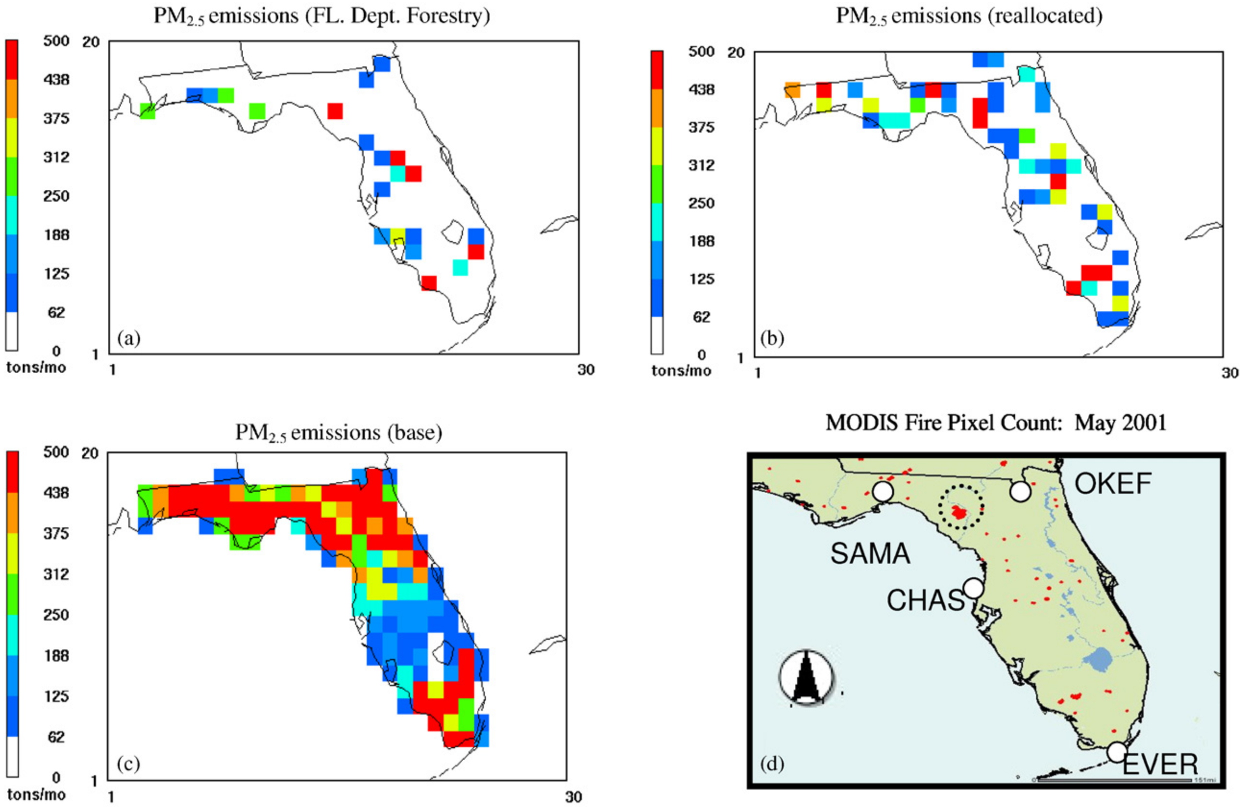

Fig. 1. (a) Spatial plot for $PM_{2.5}$ emission rates (tons/mo.) derived using the fire event inventory obtained from the Florida department of forestry, (b) Same as in 1(a) except the rates are computed after reallocating the NEI emissions using MODIS fire pixel-count data, (c) Same as in 1(a) except emissions obtained directly from the NEI (base case), (d) Accumulated fire pixel count map for the month of May 2001 obtained from MODIS rapid response web site (Image courtesy of MODIS Rapid Response Project at NASA/GSFC), the small white circles shown inside the image denote the location of the four IMPROVE sites in the Florida region out of which 3 sites are used for comparison; Mallory-swamp fire is shown inside the dotted circle.

aerosols, we compare total carbon (TC, or OC + EC) as an indicator of model performance. Several problems have been identified in the use of evolved gas analysis to distinguish OC from the EC (NARSTO Assessment, 2004), but adequate precision and collocated comparability can be achieved for measurements of TC. Thus, we consider TC as a more robust indicator of model performance than OC and EC alone.

## 3. Air quality model

### 3.1. General description of the air quality model

The US EPA Models-3 CMAQ model (Byun and Ching, 1999; Byun and Schere, 2006) version 4.4 is used for these model sensitivity studies. The CMAQ modeling domain covers the contiguous United States and portions of Canada and Northern Mexico. The CMAQ model simulations were performed using the Carbon Bond IV (CB4) chemical mechanism (Gery et al., 1989). The CMAQ aerosol predictions are based on a modal aerosol model (Binkowski and Roselle, 2003) and the ISORROPIA thermodynamic equilibrium model (Nenes et al., 1998). Chemical lateral boundary conditions for the CMAQ domain were based on a global simulation with the GEOS-CHEM model (Bey et al., 2001). Evaluation results for an annual simulation have been reported (Eder and Yu, 2006; Phillips and Finkelstein, 2006; Gilliland et al., 2006).

The meteorological inputs to CMAQ are based on the Penn State/NCAR Mesoscale Model or MM5 (Grell et al., 1994) version 3.6.1. Both the MM5 and CMAQ simulations were conducted with 36 × 36 km horizontal grid dimensions for the entire year of 2001. The Meteorology-Chemistry Interface Program (MCIP) version 2.2 is used to collapse the

MM5 vertical layers to 14 sigma layers from the surface to 100 mb, with the first layer being 36 m thick. An evaluation of the meteorological simulation used here can be found in Gilliam et al. (2006).

### 3.2. Emissions characterization

The base emissions used in this study were those used for the base 2001 year scenario from the Clean Air Interstate Rule (CAIR), with average year fires replaced with year specific fire information (US Environmental Protection Agency, 2004). Emissions were generated using the MOBILE6 module (US Environmental Protection Agency, 2003) for mobile source emissions, and the BEIS3.12 model for Biogenic Emissions (2005) (http://www.epa.gov/asmdnerl/biogen.html). Emissions from other sources were based on the US EPA NEI for 2001, which relies on state reported values. Full documentation for the 2001 NEI as developed for the CAIR is available at http://www.epa.gov/air/interstateairquality/technical.html#NODA. The seasonality distribution of the ammonia emissions is further discussed in Gilliland et al. (2006).

MODIS-derived fire pixels have been used in this study to improve the fire-related NEI emissions by redistributing the NEI fluxes based on the fire pixels. Once the fire pixels have been binned into respective CMAQ grid-cells, we reallocated 90% of the NEI monthly prescribed burns and wildfire emissions for each state and month using the spatial and temporal distribution of the MODIS-derived fire pixel count. The remaining 10% of the emissions were left intact to account for fires missed by the MODIS platform because satellite-determined fires are detected at an efficiency of less than 100%. According to Hao et al. (2004) (web-reference: http://www.wrapair.org/forums/fejf/documents/biomassburning_fire/agenda/040505/T1-B2_Hao.pdf), MODIS-derived data account for at least 90% of the burned area due to biomass burning fires larger than 6 km$^2$. Since the biomass burning base emissions do not account for the spatial variation within a state, this reallocation can have emissions moved from one part of the state to another with the magnitude of emissions reallocation being a function of the MODIS fire pixel counts. Ninety percent of the state's monthly emissions in the NEI from these sectors were multiplied by the fraction of pixel count for each grid cell over the monthly pixel count for the state. Next, the spatially reallocated emissions were distributed temporally using the ratio of the pixel count per day and pixel count per month for each grid cell.

CMAQ ready gridded emissions were created from the reallocated NEI emissions using the SMOKE modeling system. The PM$_{2.5}$ speciation profiles used in generating the reallocated emissions can be found at: http://www.epa.gov/ttn/chief/emch/speciation. Figure 1(a) shows the spatial plot of PM$_{2.5}$ obtained after using the FL. Department of Forestry data, Figure 1(b) shows the PM$_{2.5}$ emissions rate obtained after reallocating the NEI using MODIS based fire pixel count data, Figure 1(c) is same as Figure 1(b) but for the base case emissions used from the NEI, and Figure 1(d) shows the accumulated map of the MODIS fire pixel count showing locations of various fires that occurred during the month of May 2001 in the state of Florida. The MS fire had maximum intensity during 24–25 May period (based on the MODIS fire counts data: see Fig. 2) thereby rendering it a large source of carbonaceous aerosols that were injected into the atmosphere and transported to large extents due to the existing flow patterns. On 24 May the south-easterly winds are believed to have transported aerosols from the MS fire site to the vicinity of the CHAS site, and on 25 May when the wind direction reversed, aerosols were transported northeastward to locations near to OKEF site. The EVER site was located in a relatively fire-free region and is believed

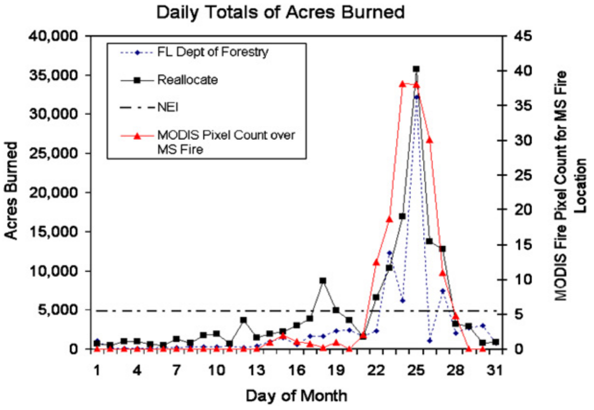

Fig. 2. Shows the time-series of the area burnt (acres) obtained from three different sources: (i) MODIS fire-count based acreage (solid line), (ii) Florida department of forestry data (dotted line), (iii) the base case NEI area burnt (dot-dash line), and (iv) MODIS fire count data (red solid line). Note that the base case burnt area remains constant at 5000 acres throughout the month, whereas the burnt area derived using the Florida Department of Forestry and MODIS based reallocated NEI show peaks that match well with the fire count data.

to have been negligibly impacted directly due to the large MS fire in north Florida. As a result the reallocated component of emissions over the EVER site is quite small. These three IMPROVE sites are also shown in Fig. 1(d) as white circles. Each site provides about 10 samples of "ground truth" TC data with which the CMAQ TC predictions are compared and analyzed.

The peak MODIS fire pixel count for the CMAQ grid cell containing the MS fire located in Lafayette County, FL (shown inside a dark dotted circle in Fig. 1d) is 38 during the 24–26 May period. The MS fire case represents a major biomass burning fire event where refinement of fire-related emissions should improve CMAQ TC predictions. The satellite derived fire pixel-count based redistribution of the monthly emission rates show increased concentrated emission sources where major biomass burning fire events were detected by the MODIS RR system and show lowered emission rates at all other non-fire grid cells.

Fig. 2 shows the comparison of acreage burned data derived from three different sources, (i) the NEI, (ii) the MODIS-based reallocated emissions, and (iii) from the burned area data obtained from the Florida Department of Forestry (Bill Barnard, MACTEC Engineering, Inc., pers. comm.). MODIS fire count daily time-series is also shown along with this plot. It is noted from this figure that the Florida Department of Forestry supplied area burned data has a very similar time profile as that of the MODIS reallocated emissions derived area burned data. The peak during 24–26 May period corresponds well with the MODIS pixel count which is also a direct indicator of the MS fire activity in the state because of its size and temporal extent. In Fig. 2 note that the NEI base emissions derived acreage is of a constant magnitude (5000 acres) for the state of Florida for the entire month of May 2001. This magnitude does not change with time. However, the peaks in the reallocated emissions derived- and FL department of forestry data derived burned area coincide with the intensity of the MS fire.

## 4. Model sensitivity results: impact on TC

CMAQ simulations were performed for May 2001 using the base NEI and the version including redistributed biomass burning fire emissions described in the previous section. Here, we assess the impact of the emissions refinement on the CMAQ TC predictions in areas surrounding the two major fire events. Fig. 3 shows the base case TC predictions for 24 May (Fig. 3c), and 25 May (Fig. 3d), and reallocated emissions case for 24 May (Fig. 3e) and 25 May (Fig. 3f), respectively, when the MS fire was at its peak intensity. Comparing Figs. 3(c, d) with 3(e, f), respectively, it is noted that emissions reallocation has re-distributed the TC concentration from state-wide extent to a more localized fashion and, due to reallocation, source strength over the MS fire area is increased substantially resulting in distinct aerosol mass loading and subsequent transportation due to wind out of the fire region (cf. Figs. 3c and e; 3d and f). In order to make sure that the transport of layer 1 carbonaceous aerosols predicted by CMAQ is in the proper direction the 1745 UTC Geostationary Operational Environmental Satellite (GOES-8) derived visible images showing the smoke trails on these 2 days of interest are given. Comparing Fig. 3(a) with Fig. 3(e), and Fig. 3(b) with Fig. 3(f) we note that there is generally a fair agreement on the flow direction, however, the CMAQ carbonaceous plume shown here is from layer 1 data and the satellite image is a gross signature obtained from all the layers.

The percentage contribution of observed OC to observed $PM_{2.5}$ mass at the CHAS, OKEF and EVER sites are 12.8%, 18.5% and 14.7%, respectively, whereas the relatively small contribution from EC to observed $PM_{2.5}$ mass are of the order 3.2%, 2.6% and 3.4%, respectively. In order to illustrate the effect of emissions reallocation on the predicted TC concentration, the time-series plots of TC concentrations at the three Florida IMRPOVE sites (CHAS, OKEF and EVER) are shown in Figs. 4. Fig. 4(a)–(c) shows the time-series plots of TC concentration for IMPROVE monitor at the CHAS, OKEF and EVER sites, respectively, shown along with the CMAQ predicted TC data once using base case emissions and another time using the reallocated emissions. Fig. 4(a) shows a very good agreement of reallocated TC predicted for the 36 km grid cell with the IMPROVE observations at the CHAS site for all days during the month except for day 11 and 12 when there were two short-lived fire pixels detected by MODIS. Fig. 4(b) shows the time-series of the TC data obtained from the model with the TC data obtained from the OKEF site which is mostly influenced by the MS fire on day 25 due to the shift in the wind direction (see the location of OKEF site from Fig. 1d, and flow direction from Fig. 3(b). Fig. 4(c) shows the same

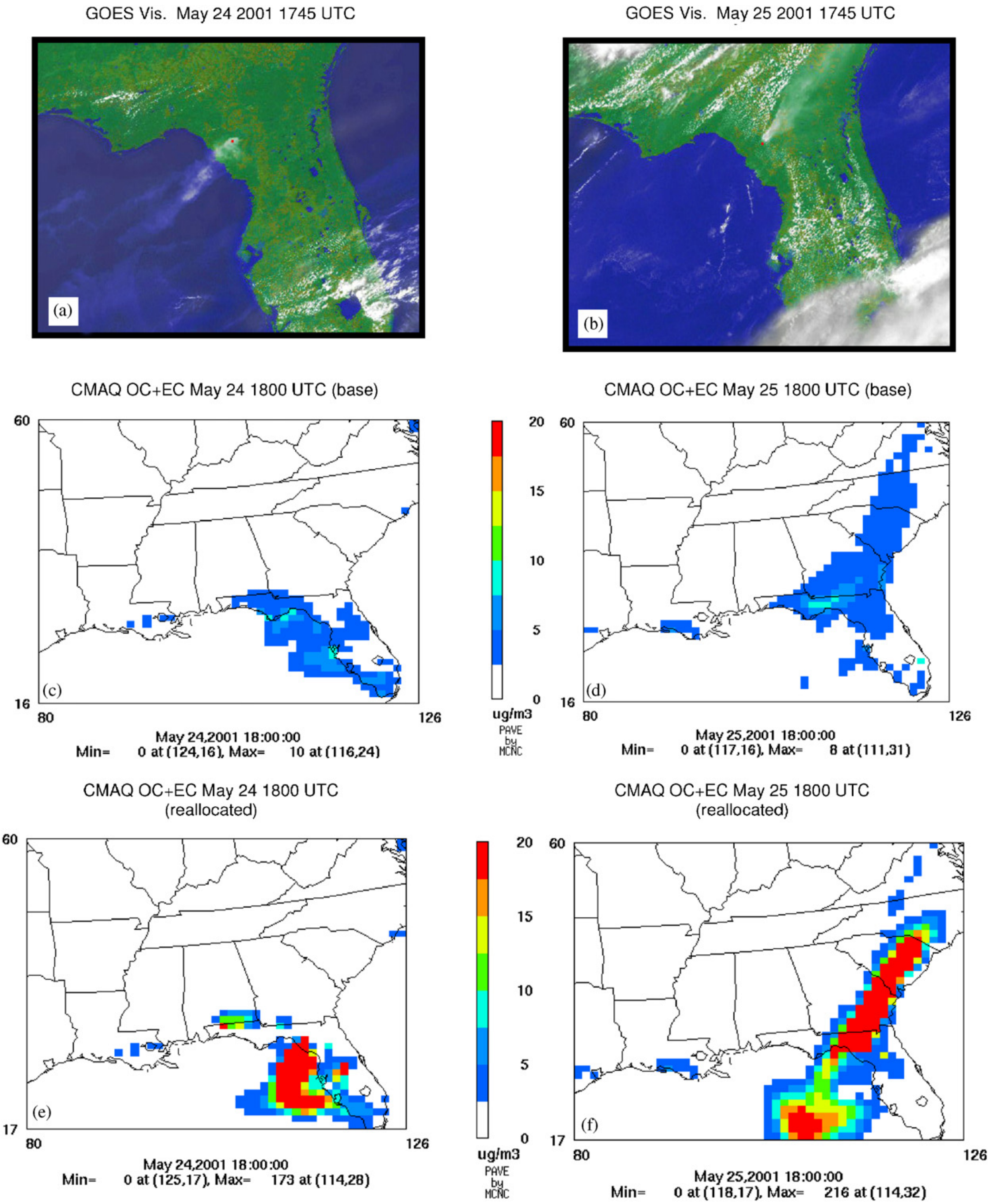

Fig. 3. (a) Shows the Geostationary Operational Environmental Satellite (GOES-8) visible channel clouds at 1745 UTC on 24 May 2001 with a background color map showing classification of surface types in Florida. Note the transport of pollutants from the Mallory swamp (shown as red dots) fire in the south-westerly direction, (b) Same as in 3(a) but for 25 May 2001 (note the reversal of northeasterly flow pattern to south-westerly flow), (c) Total carbon concentration predicted by CMAQ using base case emissions at 1800 UTC on 24 May 2001, (d) same as in 3(c) but for 25 May 2001, (e) same as in 3(c) but after using reallocated emissions for 24 May, (f) same as in 3(e) but for 25 May 2001.

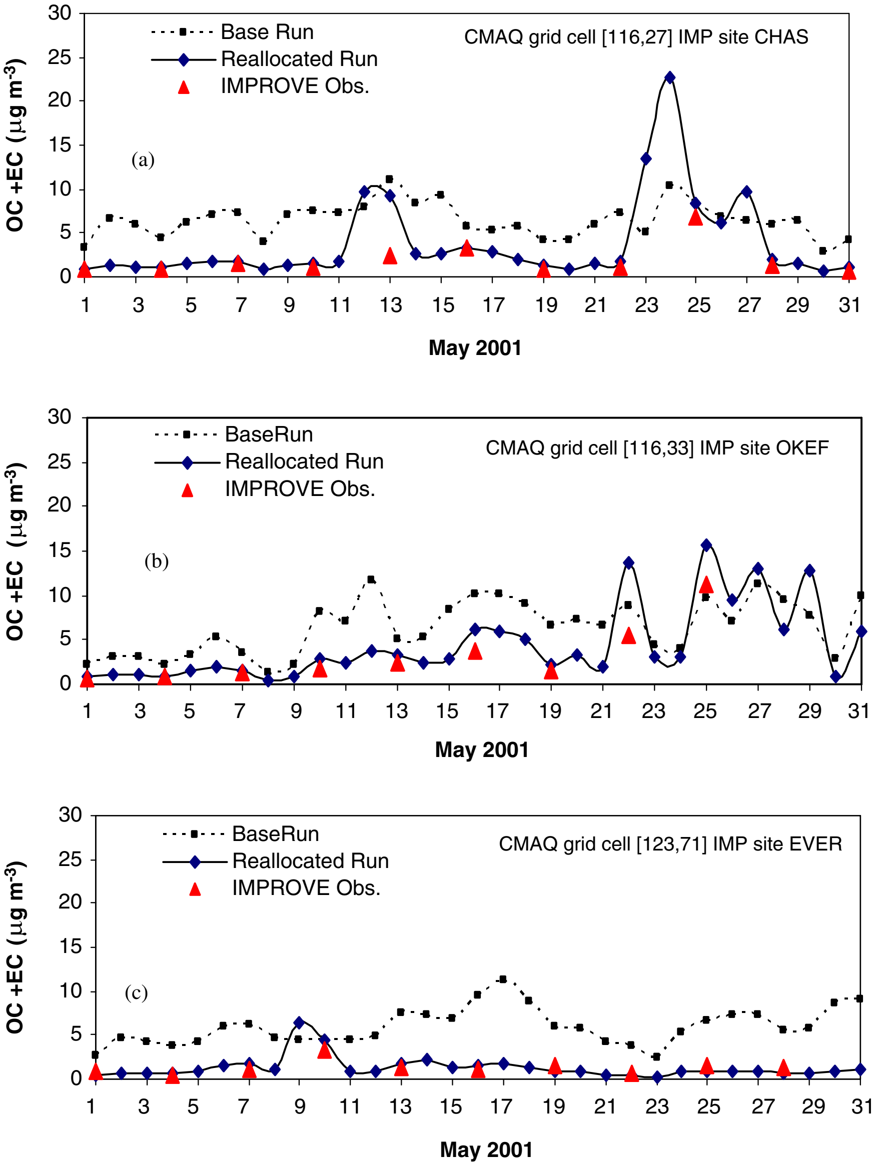

Fig. 4. Time-series of total carbon (OC + EC) concentrations measured at the (a) CHAS, (b) OKEF, and (c) EVER sites in Florida during May 2001. The IMPROVE data (red triangles) obtained every third day are shown along with the daily average total carbon CMAQ predictions at the corresponding 36 km grid, once using the base case emissions from the NEI (shown as dotted lines) and another time using the MODIS based reallocated emissions (shown as solid line).

profile for the EVER site that was not affected by the MS fire activity. We see a very good correspondence between the observed and model predicted TC data using reallocated emissions. In general, we find that the base case NEI resulted in larger predicted values of TC even if there was no fire activity in vicinity of the site, whereas the reallocated emissions enable TC predictions which expectedly follow the MODIS derived fire activity pattern detected near respective IMPROVE sites.

To assess potential improvements in TC predictions due to emissions reallocation, we compare the modeled TC and IMPROVE observed TC data from the three FL sites. With the 30 daily values from the month of May, Figs. 5(a) and (b) show the scatter between IMPROVE and model predicted base case EC, OC data with an $R^2$-value improving

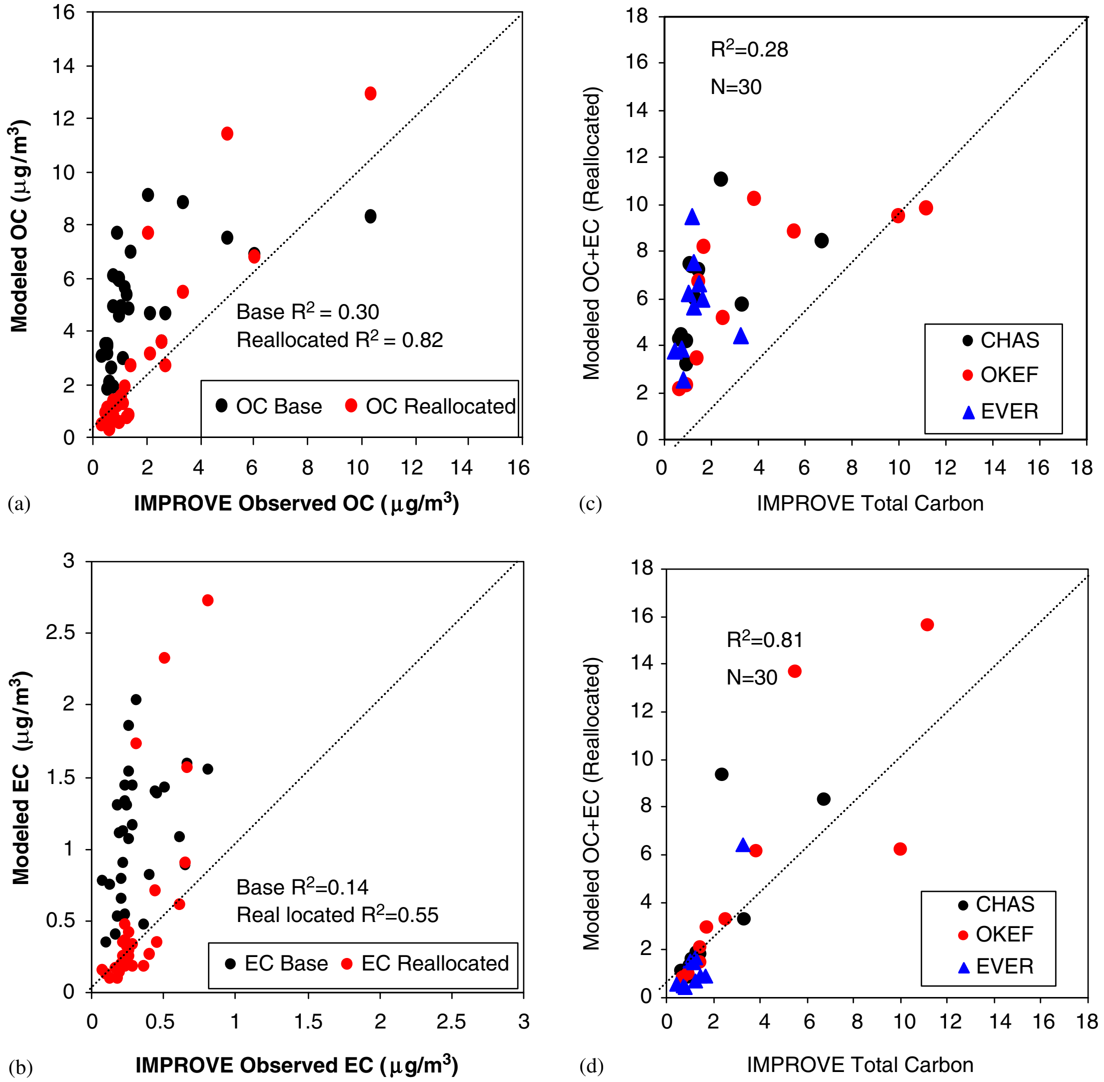

Fig. 5. (a) Scatter plot for the IMPROVE measured OC data from CHAS, OKEF, and EVER combined with CMAQ predicted OC data for May 2001, the diagonal line correspond to 1:1 values, and also shows the $R^2$-value for each fit; (b) same as 5(a) but for elemental (black) carbon; (c) scatter plot for the IMPROVE (CHAS, OKEF, and EVER sites) observed total carbon data obtained every third day versus the base case total carbon concentrations (in $\mu g\,m^{-3}$) predicted using CMAQ model during the month of May 2001 using base case emissions, (d) same as in 5(c) but CMAQ predicted total carbon data predicted every third day using the MODIS fire count based reallocated emissions data.

from 0.31 for base case OC data to 0.82, and for EC, $R^2$ improved from 0.14 to 0.5. Fig. 5 also shows a significant improvement in the correlation coefficient ($R^2 = 0.81$) when the emissions reallocated case model predicted TC values are plotted with IMPROVE TC data (cf. Fig. 5(c) for base case and 5(d) for reallocated emissions case). Separate analyses of the EC and OC model results reveal that the improved model performance for TC is due to reductions in both EC and OC on days unaffected by the MS fire.

## 5. Summary

State-reported biomass burning fire emissions in the current 2001 US EPA NEI only provide information at the state level and monthly basis for many states, resulting in spatial and temporal distributions of biomass burning fire emissions that are very coarse. In this study, MODIS-derived fire pixel count data were used to test a simple reallocation approach to redistribute and refine biomass burning emissions at a finer spatial and temporal resolution. The approach has inherent uncertainties for shorter duration fires, but appears to be a suitable method for refining emissions from major wildfire events when limited information is available about the extent and timing of the fire episode. To test the method for a major wildfire event, the Florida Mallory Swamp wildfire in May 2001 was selected as a case study. CMAQ simulations were performed using the original NEI 2001 base inventory and the resulting reallocated fire emissions inventory. This provided a modeling comparison of the original base biomass burning $PM_{2.5}$ emissions with the reallocated $PM_{2.5}$ emissions that were distributed based on the MODIS fire data with more detailed spatio-temporal information.

$PM_{2.5}$ emission rates derived using the Florida Department of Forestry data are found to match very well in space and time with the emission rates computed using the MODIS-based reallocated NEI emissions, whereas the NEI base case emissions alone are noted to be constant with time as previously described. This suggests that satellite fire count data could be used directly to obtain reallocated emissions for regions where there is pronounced wildfire activity.

Model results were compared against TC aerosol (OC + EC) data obtained from three IMPROVE monitoring sites to assess whether the reallocation of fire emissions contributed to an improvement in model performance. The results suggest that the reallocation procedure can help improve the predictions of temporal variability in TC aerosol concentrations. We have seen a large improvement in CMAQ predicted TC concentration data after using the reallocated emissions, because the modeled field is found to follow closely to the actual flow pattern (also observed by another satellite) with enhanced concentration arising due to the source being localized effectively over the actual fire region. In general, there is substantial improvement in the correlation coefficient between the modeled and observed TC data after emissions are reallocated ($R^2$ is found to change from 0.28 to 0.81 after use of the reallocated emissions).

With the increased availability of fire count products from two MODIS instruments (2003 and onward) aboard two different polar satellites (Terra and Aqua, each having morning and afternoon coverage of the CONUS), we expect a better sampling of biomass burning fires. These data could be processed along with the satellite observation products such as the GOES Aerosol and Smoke Products (GASP). These hybrid products might improve temporal sampling and resolution.

The next generation of wildfire emission estimation is incorporating more process-based emission models, such as the United States Department of Agriculture Forest Service's BlueSky system that links computer models of fuel consumption and emissions, fire, weather, and smoke dispersion into one system for predicting the cumulative impacts of smoke from wildfire, prescribed fire, and agricultural fire (Blue-Sky Website, 2005). Better records are now being kept on the spatial and temporal characteristics of the fire events on Federal lands. As newer emission inventories include these advancements, remote sensing products may be better suited as data for evaluation of the spatial and temporal estimates of biomass burning fire emissions from these models and to potentially fill-in information gaps on major fires. Also, as existing inventories are adapted for other time periods, approaches such as the one introduced in this paper can be useful for more accurately representing emissions related to fire activity for air quality modeling.

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## References

Bey, I., Jacob, D.J., Yantosca, R.M., Logan, J.A., Field, B.D., Fiore, A.M., Li, Q., Liu, H.Y., Mickley, L.J., Schultz, M.G., 2001. Global modeling of tropospheric chemistry with assimilated meteorology: model description and evaluation. Journal of Geophysical Research 106 (D19), 23073–23096.

Binkowski, F.S., Roselle, S.J., 2003. Models-3 Community Multiscale Air Quality (CMAQ) model aerosol component 1. Model description. Journal of Geophysical Research 108 (D6), 4183.

Byun, D.W., Ching, J.K.S., 1999. Science algorithms of the EPA Models-3 Community Multiscale Air Quality Model (CMAQ) modeling system. EPA/600/R-99/030, US.

Byun, D.W., Schere, K.L., 2006. Review of the governing equations, computational algorithm, and other components of the models-3 Community Multiscale Air Quality (CMAQ) Modeling System. Applied Mechanical Reviews 59, 51–77.

Eder, B., Yu, S., 2006. A performance evaluation of the 2004 release of Models-3 CMAQ. Atmospheric Environment 40, 4811–4824.

Gery, M.W., Whitten, G.Z., Killus, J.P., Dodge, M.C., 1989. A photochemical mechanism for urban and regional scale computer modeling. Journal of Geophysical Research 94, 12925.

Giglio, L., Descloitres, J., Justice, C.O., Kaufman, Y., 2003a. An enhanced contextual fire detection algorithm for MODIS. Remote Sensing Environment 87, 273–282.

Giglio, L., Kendall, J.D., Mack, R., 2003b. A multi-year active fire dataset for the tropics derived from the TRMM VIRS. International Journal of Remote Sensing 24 (22), 4505–4525.

Gilliam, R., Hogrefe, C., Rao, S.T., 2006. New methods for evaluating meteorological models used in air quality applications. Atmospheric Environment 40, 5073–5086.

Gilliland, A.B., Roselle, S.R., Pinder, R., Dennis, R.L., 2006. Seasonal $NH_3$ emissions for an annual 2001 CMAQ simulation: inverse model estimation and evaluation. Atmospheric Environment 40, 4986–4998.

Gomez-Landesa, E., Rango, A., Bleiweiss, M., 2004. An algorithm to address the Modis Bowtie effect. Canadian Journal of Remote Sensing 30 (4), 644–650.

Grell, G., Dudhia, A.J., Stauffer, D., 1994. A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note, TN-398 + STR, National Center for Atmospheric Research, Boulder, CO, 138pp.

Hao, W.M., Nordgren, B.L., Salmon, J.M., Freeborn, P.H., 2004. 〈http://www.wrapair.org/forums/fejf/documents/biomassburning_fire/agenda/040505/T1-B2_Hao.pdf〉.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morissette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F., Kaufman, Y., 2002. The MODIS fire products. Remote Sensing Environment 83, 244–262.

Kondragunta, S., Zhang, X., 2006. Satellite derived PM2.5 emissions from prescribed and wildfires. In: Proceedings from the 15th International Emission Inventory Conference "Reinventing Inventories—New Ideas in New Orleans", 16–18 May 2006, New Orleans, LA, USA.

NARSTO Assessment, 2004. Particulate Matter Science for Policy Makers. Cambridge University Press, New York, p. 177.

Nenes, A., Pandis, S.N., Pilinis, C., 1998. ISORROPIA: a new thermodynamic equilibrium model for multiphase multicomponent inorganic aerosols. Aquatic Geochemistry 4, 123–152.

Phillips, S., Finkelstein, P., 2006. Comparison evaluation of two leading photochemical air quality models for particulate matter. Atmospheric Environment 40, 4999–5009.

US Environmental Protection Agency, 2003. User's guide to MOBILE6.1 and MOBILE6.2; EPA Office of Air and Radiation, EPA420-R-03-010, Assessment and Standards Division, Office of Transportation and Air Quality, US Environmental Protection Agency, 262pp.

US Environmental Protection Agency, 2004. Technical Support Documents for the Final Clean Air Interstate Rule: Fire Temporal Documentation. Prepared for US EPA by B. Battye. Available online at 〈www.epa.gov/air/interstateairquality/pdfs/Fire_Temporal_Documentation.pdf〉.

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

### *Web References*

Biogenic Emissions, 2005. 〈http://www.epa.gov/asmdnerl/biogen.html〉.

Blue-Sky Website, 2005. 〈http://www.fs.fed.us/bluesky〉.

Florida Department of Forestry: 〈http://www.fl-dof.com/wildfire/stats_significant_fires.html〉.

NASA Goddard DAAC, 2003. MODIS data versioning website: 〈http://www.daac.gsfc.nasa.gov/MODIS/Terra/data_versioning.shtml〉.

Speciation website: 〈http://www.epa.gov/ttn/chief/emch/speciation〉.