DEASCO$_3$ PROJECT UPDATES TO THE FIRE PLUME RISE METHODOLOGY TO MODEL SMOKE DISPERSION

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Introduction

For the Joint Fire Science Program (JFSP) Deterministic and Empirical Assessment of Smoke's Contribution to Ozone (DEASCO$_3$[1]) project, a photochemical grid model (PGM) was applied to estimate the contribution of emissions from three types of fires to ozone concentrations: Wildfires (WF), Prescribed Burns (Rx), and Agricultural Burning (Ag). The Comprehensive Air Quality Model with Extensions (CAMx[2]) PGM was applied for a continental U.S. domain and two modeling years: 2002 and 2008. The 2002 CAMx PGM modeling database was developed by the Western Regional Air Partnership (WRAP[3]) and used for regional haze planning. For the 2008 fire ozone modeling, the CAMx modeling database that was developed as part of the West-wide Jump-start Air Quality Modeling Study (WestJumpAQMS[4]) was used. The DEASCO$_3$ project's new 2008 fire emissions are described in the "DEASCO$_3$ 2008 Emissions Inventory Methodology" report.[5] As part of the DEASCO$_3$ project, the fire plume rise methodology was updated from what was used in the 2002 WRAP study, which is described in this document.

2002 WRAP Fire Plume Rise Approach

The plume rise methodology used for the WRAP 2002 fire emissions is described in the "2002 Fire Emission Inventory for the WRAP Region – Phase II" report (WRAP 2002 EI).[6] In the WRAP plume rise methodology, three parameters are defined to provide the release heights of fire smoke emissions as hourly inputs to the PGM: (1) height above ground of plume top (P_{top});

[1] http://deasco3.wraptools.org/

[2] http://www.camx.com/

[3] http://www.wrapair.org/forums/aqmf/index.html

[4] http://www.wrapair2.org/WestJumpAQMS.aspx

[5] Air Sciences Inc. 2013. "DEASCO$_3$ 2008 Emissions Inventory Methodology." Prepared for the Joint Fire Sciences Program. Project No. 178. September 2013. http://wraptools.org/pdf/ei_methodology_20130930.pdf.

[6] Air Sciences Inc. 2005. "2002 Fire Emission Inventory for the WRAP Region—Phase II." Prepared for the Western Governors' Association/Western Regional Air Partnership. Project No. 178. July 22, 2005. Available at: http://www.wrapair.org/forums/fejf/tasks/FEJFtask7PhaseII.html.

(2) height above ground of plume bottom (P_{bot}); and (3) the fraction of emissions emitted near the ground (Lay1f). Each daily fire event is assigned a "plume class" that, combined with the hour of the day, is used with look-up tables to calculate the input parameters accounting for the fact that fire plume rise and emissions are higher in the day and lower at night.

PGM Configuration

The 2002 WRAP fire plume rise approach was originally implemented using the Community Multi-scale Air Quality (CMAQ[7]) modeling system for the year 2002. The WRAP 2002 CMAQ application used three-dimensional (3-D) emission inputs that readily accommodated the vertical distribution of fire emissions produced by the WRAP plume rise methodology, but resulted in very large emission input files.

For the DEASCO$_3$ project, CAMx PGM emission inputs consisted of two-dimensional (2-D) gridded emissions released in the lowest layer (Layer 1) of the model and a point source emission input file comprised of locations of stacks and their parameters with hourly plume rise calculated internal to the model. Although the 2-D gridded surface emission input file readily accommodates the Layer 1 fraction of the WRAP fire emissions, the elevated fire emissions between P_{bot} and P_{top} (1-Lay1f) were treated using point source inputs with stack locations in a center of a grid cell and stack heights at the center of a vertical layer where fire emissions needed to be injected between P_{bot} and P_{top}. This resulted in many point source inputs to treat fire emissions.

2008 DEASCO$_3$ Fire Plume Rise Update

The DEASCO$_3$ study used the WRAP fire emissions and plume rise approach for the 2002 modeling. Preliminary 2008 modeling used the Fire Inventory from the National Center for Atmospheric Research (FINN[8]) with plume rise calculated using the WRAP methodology. However, for the 2008 PGM modeling using the 2008 DEASCO$_3$ fire emissions inventory, the WRAP plume rise method was updated, with a focus on two parts:

- Assigning a fire to a plume class "bin"
- Defining how the fraction of fire emissions emitted near the ground (Lay1f) is emitted not just in the lowest layer of the PGM as in the WRAP methodology, but also how it is distributed between the ground (Layer 1) and P_{bot}

[7] http://www.cmascenter.org/cmaq/
[8] http://bai.acd.ucar.edu/Data/fire/

Plume Class Assignment

In the 2002 WRAP plume rise approach, fires were assigned to plume class bins based on acres normalized to the pre-burn fuel loading defined for each fire (virtual acres). This method was modified to consider actual fuel consumed and the intensity of the fire (see Equation 1). By using the actual flaming-phase fuel consumed, the Flaming Phase Consumption Index (FPCI) looks at the *actual* heat released instead of the *potential* heat released. In addition, dividing by the square root of the acres burned attempts to capture the intensity of the burn: 1,000,000 British Thermal Units (BTUs) released over 100,000 acres is not equivalent, in terms of plume rise, to the same amount of heat released over 10,000 acres.

Equation 1. FPCI Calculation Used to Determine Plume Height Bins

$$FPCI = {}^{Flaming\ Phase\ Consumption}\Big/_{\sqrt{acres}}$$

FPCI was calculated for every fire in the $DEASCO_3$ modeling domain, and bins were calibrated with help from the distribution found in the WRAP 2002 EI (see Table 1), keeping in mind that the total coverage of (especially small) fires was greater in 2008.

Table 1. Plume Height Bins Calculated Using FPCI and Fire Activity in the WRAP Region

Plume Class	**1**	**2**	**3**	**4**	**5**	
FPCI	***0-75***	***75-300***	***300-675***	***675-1,250***	***>1,250***	**Total**
Fire Days, $DEASCO_3$ 2008	48,725	9,912	1,167	366	96	60,266
Bin Frequency, $DEASCO_3$ 2008	81%	17%	1.9%	0.61%	0.16%	
Bin Frequency, WRAP 2002	62%	33%	4.5%	0.2%	0.02%	

Lay1f Emissions Vertical Distribution

In the WRAP plume rise methodology, the Lay1f fire emissions were released in the lowest layer of the PGM, which was approximately 40-meters (m) thick in the WRAP 2002 modeling. Since the WRAP 2002 PGM modeling, PGMs have used higher vertical resolution near the surface, and the WRAP plume rise methodology was modified to release the Lay1f fire emissions in the lowest 2-3 layers that were, in total, approximately 40-m thick. However, this resulted in discontinuous fire emission injections in the vertical layers between the Lay1f emissions released near the ground and the emissions released between P_{bot} and P_{top} (1-Lay1f). The WRAP approach also does not necessarily account for the effects that meteorological conditions have on the release heights of the Lay1f fire emissions, although it does impose a diurnal variation with higher plume rise estimates in the day than night.

The vertical distribution of the Lay1f fire emissions in the fire plume processor was modified for the $DEASCO_3$ 2008 PGM modeling by including the gridded hourly meteorological data from the Weather Research Forecast (WRF) model. The Lay1f fire emissions were then injected in vertical layers between the surface and the maximum of P_{bot} and the WRF-estimated hourly Planetary Boundary Layer (PBL) height in the grid cell containing the fire emissions:

- Lay1f fire emissions = Surface to Max(P_{bot}, PBL)

Vertical Distribution of Elevated P_{bot} to P_{top} Fire Emissions (1-Lay1f)

In the WRAP fire plume rise methodology, the non-surface fire emissions were released in the vertical layers spanning the heights between P_{bot} and P_{top} above ground level (AGL). In the revised fire plume methodology for $DEASCO_3$, the elevated fire emissions (1-Lay1f) were released in layers between P_{bot} and the maximum of P_{top} and the WRF-estimated PBL height for the hour and grid cell of the fire.

- 1-Lay1f fire emissions = P_{bot} to Max(P_{top}, PBL)

Thus, in the case where the plume bottom is greater than the PBL height (P_{bot} > PBL), the Lay1f fire emissions are emitted from the surface to P_{bot} and the elevated (1-Lay1f) fire emissions are emitted in layers from P_{bot} to P_{top}. In the case where the PBL height is between P_{bot} and P_{top}, then both the Lay1f and the 1-Lay1f emissions are emitted in layers spanning P_{bot} and the PBL height, with the Lay1f emissions also emitted between the ground and P_{bot}. If the PBL height is above P_{top}, then the Lay1f emissions are emitted from the ground to the PBL height and the 1-Lay1f emissions are emitted between P_{bot} to the PBL height.

Fire Emissions Speciation

The fire emissions processor also speciates the fire Volatile Organic Compound (VOC) emissions into the VOCs used in the CB05 chemical mechanism used by CAMx and CMAQ. VOC speciation profiles vary by 10 biomass types given in Table 2. The biomass-specific VOC speciation profiles were from Akagi et al.[9]

Table 2. Biomass Categories Used in the $DEASCO_3$ 2008 Fire Emissions Processing

Biomass Type	Biomass Name
1	Tropical Forest

[9] Akagi, S. K., R. J. Yokelson, C. Wiedinmyer, M. J. Alvarado, J. S. Reid, T. Karl, J. D. Crounse, and P. O. Wennberg. 2011. "Emission factors for open and domestic biomass burning for use in atmospheric models." *Atmos. Chem. Phys.*, 11, 4039-4072. doi:10.5194/acp-11-4039-2011.

2	Savanna
3	Crop Residue
4	Pasture Maintenance
5	Boreal Forest
6	Temperate Forest
7	Extratropical Forest
8	Peatland
9	Chaparral
0	Non-Fuel Area (emissions should be zero)

Updated Fire Emission Inputs in CAMx

As noted above, CAMx modeling of the WRAP 2002 fire emissions used point sources with stack heights in the center of a vertical layer to inject the emissions into the proper vertical layers. Thus, if a fire in a specific grid cell and hour spans 5 vertical layers, then there are five fire point sources in that grid cell and hour. This results in hundreds of thousands of point source inputs to treat the vertical distribution of fire emissions. The CAMx model was updated so that it could accept a point source with hourly P_{bot} and P_{top} in a grid cell and then allocate the emissions to the proper vertical layers internally to the model. With this approach, a fire in a grid cell is represented by two point sources: one corresponding to the Lay1f emissions and the other corresponding to the 1-Lay1f emissions.

Example Fire Plume Rise Modeling Results

For the WestJumpAQMS, preliminary PGM modeling of the 2008 period was performed with the FINN fire emission estimates processed using the WRAP plume rise methodology. When the $DEASCO_3$ 2008 fire emissions inventory was ready, final WestJumpAQMS PGM simulations were performed using the 2008 $DEASCO_3$ fires and the new plume rise approach as described above. Two plume rise approaches for two very different situations are described as follows: agricultural burning of grasslands in Flint Hills, Kansas, and wildfires in northern California.

Agricultural Burning in Flint Hills, Kansas

Almost every April, the grasslands in Flint Hills, Kansas are burned so that more grass grows back, resulting in larger and more valuable cattle. Figure 1 displays the $DEASCO_3$ and FINN fire NO_X (oxides of nitrogen) emissions from the Flint Hills area on April 6, 2008. Note that FINN NO_X emissions almost double those from $DEASCO_3$ on this day.

Figure 2 shows the diurnal variation in the plume rise for the grid cell with the maximum NO_X emissions (78, 49) from the Flint Hills fire on April 6, 2008, using the $DEASCO_3$ and WRAP (FINN) plume rise methodologies. The GMT time scale is used in Figure 2, which shows that maximum plume rise is achieved around hour 21 or 22 (3 or 4 p.m. LST). The maximum plume rise in the $DEASCO_3$ plume rise approach is Layer 5, which is approximately 2,500 m AGL. However, the maximum plume rise of the FINN fires using the WRAP plume rise methodology is Layer 20, which is approximately 6,000 m AGL. A plume rise of 6,000 m AGL seems too high for a grassland fire, whereas the $DEASCO_3$ maximum plume rise height of 2,500 m AGL seems more likely. The WRAP approach distributed emissions within Layer 1 (Lay1f) and between P_{bot} and P_{top}, producing plume rise with a discontinuity in the vertical layers that doesn't seem realistic. The updated $DEASCO_3$ plume rise algorithm appears to be more realistic with continuous plume rise.

Figure 1. Flint Hills Fire NO_X Emissions on April 6, 2008, Estimated by $DEASCO_3$ (Left) and FINN (Right)

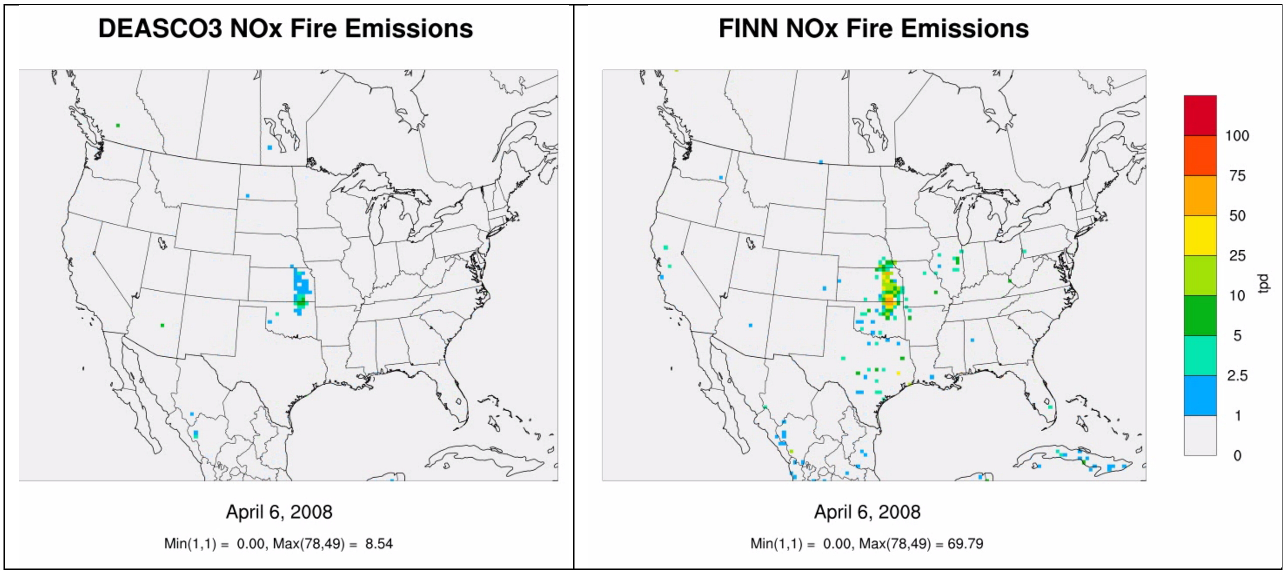
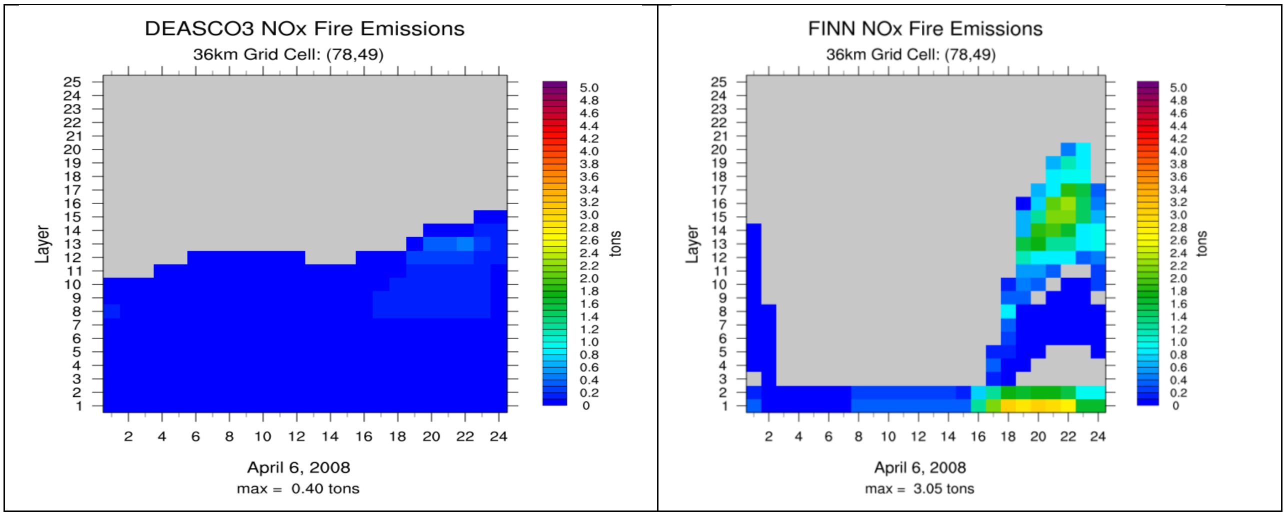


Figure 2. Diurnal Variation in Plume Rise for Grid Cell with Maximum NO_X Emissions from Flint Hills, Kansas on April 6, 2008, Using $DEASCO_3$ (Left) and FINN (Right) Methodologies



Northern California Wildfires

Figure 3 displays the $DEASCO_3$ and FINN fire NO_X emissions from a northern California wildfire on July 9, 2008. One of the biggest wildfires in 2008 occurred when convective cells with dry lightning passed over northern California on June 21, 2008, starting numerous fires—many of which lasted for over a month.

Figure 4 shows the diurnal variation in the plume rise for the grid cell with the highest NO_X emissions (16, 72) from a northern California wildfire on July 9, 2008, using the $DEASCO_3$ and WRAP (FINN) plume rise methodologies. As shown earlier in Figure 2, the WRAP plume rise approach has an unrealistic discontinuity in the vertical plume rise between the Lay1f surface and (1-Lay1f) elevated fire emissions, while the $DEASCO_3$ approach produces a more continuous plume rise. The WRAP approach also allocates more fire emissions to the lowest layers than the $DEASCO_3$ approach. Both approaches produce a plume rise up to Layer 21, (approximately 6,000 m AGL), which seems realistic at the maximum emissions location for a major wildfire. In Figure 4, it appears that the fire emissions are greater going up in the vertical layers, peaking at the top of the plume. But this is because the vertical layers get thicker with height, so the seemingly higher emissions are just the use of thicker layers aloft. The fire emissions are distributed uniformly between P_{bot} and P_{top} based on spatial coverage of the layer heights, so there is more mass in the layers as they get thicker.

Figure 3. Northern California Fire NO_X Emissions on July 9, 2008, Estimated by $DEASCO_3$ (Left) and FINN (Right)

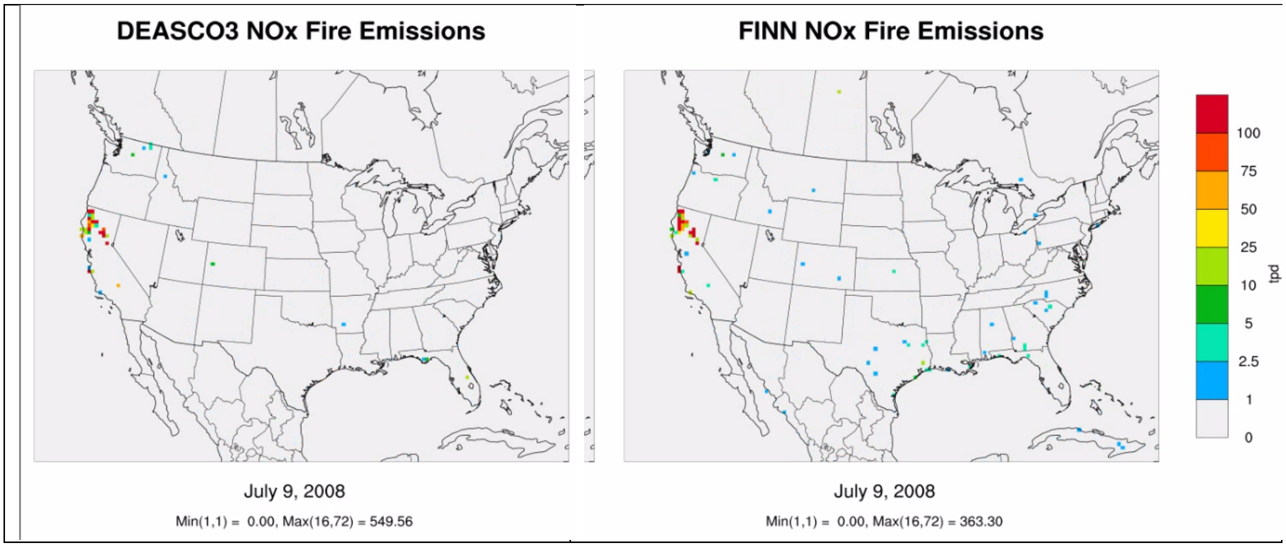


Figure 4. Diurnal Variation in Plume Rise for Grid Cell with Maximum NO_X Emissions from Northern California Wildfires on July 9, 2008, Using $DEASCO_3$ (Left) and FINN (Right) Methodologies