

We thank the two reviewers for their insightful comments on our manuscript. Our responses to each of the reviewer's comments are provided below in italics.

Reviewer #1:

The manuscript presents a study comparing three plume rise parameterizations on their ability to capture observed injection heights, and how they differ in their impacts on air quality and photochemistry on the short and long range. This study represents good contributions to the field and it's within the scope of ACP. I think the paper needs more work before it's ready for publication based on the comments below.

My main comments are the following:

- The section evaluating injection heights is very short and could be greatly improved in many ways, including the addition of more cases that are more representative of the really extreme conditions that happened during this period. Also, the only injection height data used is that from MISR capturing fresh plumes. This does not capture the peak of fire activity that usually happens on the afternoon. For this I recommend including data from CALIPSO. While the chances for CALIPSO to capture fresh smoke are much lower, this event was so massive that most CALIPSO overpasses captured some section of the smoke emitted on a previous day. Thus an analysis could be done for the regional smoke heights rather than for smoke from individual fires, complementing that from MISR. The analysis should move a bit beyond a few study cases and try to capture the whole extend of the fire

Thank you for the comments. We have compared the model simulations with the CALIPSO in our previous paper Li et al. (2021, GRL). The simulated vertical distribution of the smoke matched the observation near the wildfire source region and downwind area. In this paper, we have now added more comparisons with CALIPSO, in sections 2.4.1, 3.1, and relevant references.

In section 2.4.1, the following was added:

“CALIPSO is an Earth Science observation mission that was launched on 28 April 2006 and flies in a nominal orbital altitude of 705 km and an inclination of 98 degrees as part of a constellation of Earth-observing satellites. CALIPSO's lidar instrument, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), provides high-resolution vertical profiles of aerosol and cloud attenuated backscatter signals at 532 nm and 1064 nm (Winker et al., 2007). The footprint of the lidar beam has a 100 m cross-section with an overpass around 1:30 p.m. local time. Level 1 attenuated backscatter profiles at 532 nm are used to calculate the plume height in this study following Amiridis et al. (2010).”

In Section 3.1, we added the discussion and a figure about CMAQ plume height compared to CALISPO:

“The vertical profiles of CMAQ simulated PM_{2.5} are also compared to the CALIPSO aerosol vertical profile. The CALIPSO overpass occurs around 1:30 p.m. local time, closer to the peak fire behaviour in the afternoon than the MISR observations. The CALIPSO smoke injection heights are directly calculated from Level 1 attenuated backscatter profiles at 532 nm following Amiridis et al. (2010). There are several steps involved in this process. First, GBBEPx FRP data were used to locate the fire location along the CALIPSO swath. Then, a slope method (Pal et al., 1992) is applied to each profile to smooth out the original Level 1 532 nm attenuated backscatter

coefficient profiles at each fire point. Next, we calculate the steep gradient in the attenuated backscatter profiles. The height of the minimum gradient value is selected as the smoke injection height. Figure 4 shows the comparison between the CALIPSO plume height results and the estimated plume heights from the three plume rise schemes for west coast fires. In most cases, the plume heights from the three schemes are close to each other, especially for the cases with plume tops under 4 km. For strong fires with plume tops higher than 4 km, S12 seems to be more skillful than B69 and F07. It successfully simulates the high plume top observed by CALIPSO, whereas B69 and F07 tend to underestimate the plume heights.

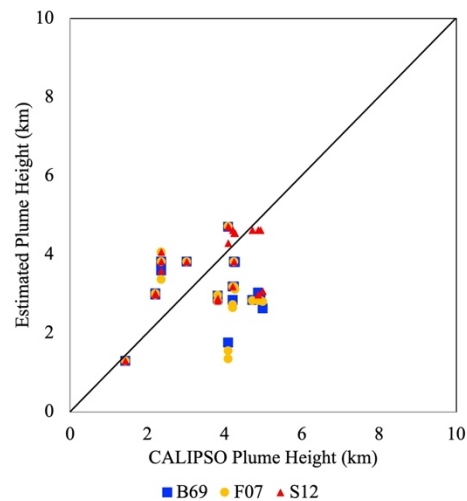


Figure 4: Comparisons of plume top heights from three simulations: B69 (blue rectangle), F07 (orange dot), and S12 (red triangle), against aerosol height observations from the CALIPSO for west coast fires.”

The following papers are added to the reference:

Amiridis, V., Giannakaki, E., Balis, D. S., Gerasopoulos, E., Pytharoulis, I., Zanis, P., Kazadzis, S., Melas, D., and Zerefos, C.: Smoke injection heights from agricultural burning in Eastern Europe as seen by CALIPSO, *Atmos. Chem. Phys.*, 10, 11567–11576, <https://doi.org/10.5194/acp-10-11567-2010>, 2010.

Pal, S. R., Steinbrecht, W., and Carswell, A. I.: Automated method for lidar determination of cloud base height and vertical extent, *Appl. Opt.*, 31, 1488–1494, 1992.

Winker, D. M., Hunt, W. H., and McGill, M. J. Initial performance assessment of CALIOP, *Geophys. Res. Lett.*, 34, L19803, [doi:10.1029/2007GL030135](https://doi.org/10.1029/2007GL030135), 2007.

- The article could be improved by being more thorough in its literature review and using reference to better backup some statements. See some examples in the comments by line below

Thanks for the comments. We have added these references (see the details in our responses to “Comments by line”).

- Some sections of the results were very qualitative on its description, where I think a better job on being quantitative and using statistical metrics could have been done. More details in the comments below.

Thank you. Please see the detailed responses below in the “Comments by line”.

Comments by line:

Intro. There have been multiple studies evaluating some of these plume injection height schemes beyond the Ye et al. (2021), so these previous findings need to be summarized. Some that come to mind can be found below, also look for work from Joe Wilkins. This literature review also can be used to motivate this study (i.e., what hasn't been done). Some uniqueness I see from these work include the comparison of these 3 schemes and the type of event studied (record-breaking wildfire season)

-Mallia, D., Kochanski, A., Urbanski, S. & Lin, J. Optimizing Smoke and Plume Rise Modeling Approaches at Local Scales. *Atmosphere* 9, 166 (2018).

- Wilmot, T. Y., Mallia, D. V., Hallar, A. G., and Lin, J. C.: Wildfire plumes in the Western US are reaching greater heights and injecting more aerosols aloft as wildfire activity intensifies, *Scientific Reports*, 12, 12400, 10.1038/s41598-022-16607-3, 2022.

-Sessions, W. R., Fuelberg, H. E., Kahn, R. A. & Winker, D. M. An investigation of methods for injecting emissions from boreal wildfires using WRF-Chem during ARCTAS. *Atmos. Chem. Phys.* 11, 5719–5744 (2011).

-Roy, A. et al. Effects of Biomass Burning Emissions on Air Quality Over the Continental USA: A Three-Year Comprehensive Evaluation Accounting for Sensitivities Due to Boundary Conditions and Plume Rise Height. in *Energy, Environment, and Sustainability* 245–278 (Springer Singapore, 2017). doi:10.1007/978-981-10-7332-8_12

Thanks for the comments. All of the above papers are added to the paper. The following lines have been added to the paper:

“Wilmot et al. (2022) produced a decadal-scale wildfire plume rise climatology for the U.S. west coast and Canada and found trends toward enhanced plume heights, and the surface smoke injection to the free troposphere, which suggest a growing impact of wildfires on air quality and regional climate.” added to line 54.

“Previous studies have found that the smoke injection height plays a vital role in smoke dispersion, as wind speed and direction generally vary with altitude (e.g., Mallia et al., 2018; Vernon et al., 2018;).” added to line 58.

“Sessions et al. (2011) tested the Freitas plume rise scheme with Weather Research and Forecasting and Chemistry (WRF-Chem) model and found that differences in injection heights produce different transport pathways. Roy et al. (2017) compared the simulated plume heights from two different approaches, Western Regional Air Partnership’s (WRAP) plume model and

the Freitas plume model. Results show that the Freitas plume model got a better diurnal variation of the plume rise height. Mallia et al. (2018) tested different ways to distribute the fire emissions vertically for prescribed fires. Results indicated that plume height plays a critical role in determining how smoke distributes downwind of the fire.” added to line 74.

76. Add a reference to support these statements

Thanks for the comment. The reference has been added.

“A series of large wildfires fuelled by accumulated biomass, heatwaves, and dry winds, burned more than 10 million acres (National Interagency Fire Center, 2020).”

National Interagency Fire Center. 2020 National Large Incident Year-to-Date Report (PDF). Geographic Area Coordination Center (Report). December 21, 2020.

95-104. This paragraph is lacking any referencing, please add. Also, the notion that primary organic aerosol is also quite dynamic needs to be included as well.

Thanks for the comment. The following papers have been added to section 2.1 as references:

Koppmann, R., von Czapiewski, K., and Reid, J. S.: A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds, Atmos. Chem. Phys. Discuss., 5, 10455–10516, <https://doi.org/10.5194/acpd-5-10455-2005>, 2005.

Schlosser, J. S., Braun, R. A., Bradley, T., Dadashazar, H., MacDonald, A. B., Aldhaif, A. A., Aghdam, M. A., Mardi, A. H., Xian, P., and Sorooshian, A.: Analysis of aerosol composition data for western United States wildfires between 2005 and 2015: Dust emissions, chloride depletion, and most enhanced aerosol constituents, J. Geophys. Res.-Atmos, 122, 8951–8966, <https://doi.org/10.1002/2017JD026547>, 2017.

Seinfeld, J.H. and Pandis, S.N., Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, 3rd edition, John Wiley & Sons, Hoboken, 2016.

In section 2.1 primary aerosol refer to the aerosols emitted from fires, and secondary aerosol refers to the aerosols generated after emitted. Line 117 has been changed to:

“Wildfire emissions include primary aerosols (direct emission) and large amounts of gases that can be oxidized to form secondary aerosols (generated after emission).”

Section 2.2. A description of how model smoke injection height is derived is missing. Please be specific, e.g., what variable and what threshold is used, how is it mapped to the MISR pixels (location and time). Also include info on how AOD is derived and mapped to VIIRS.

Thanks for the comments. More details of the three plume rise schemes are shown in section 2.3.

For B69 scheme, we added the equation:

“It uses a set of semi-empirical formulas to estimate plume injection height (H_p) in different atmospheric stability states (i.e., neutral, stable, and unstable). Heat flux (B), horizontal wind speed (U), static stability (S), and friction velocity (x^) are used to estimate the plume injection height:*

$$H_p = \begin{cases} 1.33 \times BU^{-1}x^{*-2}, & \text{neutral} \\ 2.6 \times (BU^{-1}S^{-1})^{\frac{1}{3}}, & \text{stable} \\ 30 \times (BU^{-1})^{\frac{3}{5}}, & \text{unstable} \end{cases} \quad (1)$$

Previous studies found that FRP is about 10-20% of the total fire heat (Wooster et al., 2005; Freeborn et al., 2008). In this study, we derive the heat flux from FRP provided by the GBBEPx dataset multiplied by a factor of 10 following Val Martin et al. (2012).”

For F07 we added more information:

“It takes in fire information, including fire area and heat flux, as well as atmospheric profile information, including temperature, moisture, density, and wind velocity. The plume top height is defined as the altitude at which the plume is neutrally buoyant, and is approximated as a vertical velocity < 1 m/s.”

For S12 we added the equation:

“It utilizes FRP, PBL height (H_{PBL}), and the Brunt-Vaisala frequency in the free troposphere (BV_{FT}) to estimate the plume injection height from wildfires:

$$H_p = \alpha H_{PBL} + \beta \left(\frac{FRP}{FRP_0} \right)^\gamma \exp \left(-\frac{\delta BV_{FT}^2}{BV_0^2} \right) \quad (2)$$

Where FRP_0 is the reference fire radiative power which equals 10^6 W, BV_0 is the reference Brunt-Vaisala frequency which equals $2.5 \times 10^{-4} \text{ s}^{-2}$, and $\alpha, \beta, \gamma, \delta$ are constants.”

The simulated plume height is mapped to MISR pixels using the nearest neighbor approach. The CMAQ model calculates AOD, which is compared to VIIRS AOD (Figure 6). We interpolated the model AOD to VIIRS pixels that passed quality control based on the nearest point method. The following lines are added to the paper:

“The simulated plume heights were interpolated to the MISR observation MISR pixels using the nearest neighbour approach.” added to line 286.

“The CMAQ predicted AOD was interpolated to the VIIRS pixels that passed quality control using the nearest neighbor approach.” added to line 412.

Section 2.3. There are some details missing from the explanations of the injection schemes that could be useful to understand results. For instance, how is the plume distributed once the injection is computed? Is there a height of the bottom of the plume computed as well or how is it assumed? Is there a fraction of emission placed at the surface (so called “smoldering” emissions as stated in Freitas 2007)? If so, what % for each scheme? Due any of the parameterization consider different parameters for different fuels? Is the FRP used from GBBEPx a daily value? If so, is it applied as constant throughout the day or a given diurnal cycle is specified?

Thanks for the comments. The plume is distributed between 0.5-1.5 times the plume injection height (default setting in CMAQ). In this study, we did not separate smoldering from flaming.

For the plume rise calculation, we did not consider different parameters for different fuels. But for emission and FRP, the GBBEPx applied different emission factors to different land use types (Zhang et al., 2012, 2019). The FRP used from GBBEPx is a daily value. When used in the model we gave the FRP a climatological diurnal cycle from the Western Regional Air Partnership (WRAP) work.

*The following lines have been added to the paper in line 161:
“A climatological diurnal cycle from the Western Regional Air Partnership (WRAP) work was applied to the daily GBBEPx emission to derive hourly model-ready emission input.”*

*The following lines have been added to the paper in line 236:
“After getting the estimated plume injection height from the three schemes, the fire emissions were distributed between 0.5-1.5 times plume injection height (default setting in CMAQ).”*

The main focus of this study is to evaluate the impact of different plume injection heights on the near source and downwind air quality. For more information about the plume rise scheme or fire emission, please see the related references.

161-162. Please expand a bit more on why the factor of 10 is applied.

Thanks for the comments. The following lines and additional references have been added to the paper line 181:

“Previous studies found that FRP is about 10-20% of the total fire heat (Wooster et al., 2005; Freeborn et al., 2008). In this study, we derive the heat flux from FRP provided by the GBBEPx dataset multiplied by a factor of 10 following Val Martin et al. (2012).”

167-168. Please add references for this sentence

Thanks for the comments. We added the references here and in paper line 198:

“The Freitas scheme is the default plume rise scheme in WRF-Chem and has been widely used in many studies (e.g., Sessions et al., 2011; Val Martin et al., 2012; Roy et al., 2017; Mallia et al., 2018).”

Section 2.4. VIIRS AOD data was not described. Please include any quality flags applied

Thanks for the comments. The description for VIIRS AOD have been added to section 2.4.3:

“2.4.3 VIIRS AOD data

The simulated AOD results are compared to the VIIRS Enterprise AOD from Suomi-NPP. The VIIRS Enterprise Aerosol Algorithm retrieves AOD at the 750-m pixel level for the nominal wavelength of 550 nm using radiances from 11 VIIRS channels (412, 445, 488, 555, 672, 746, 865, 1240, 1378, 1610, and 2250 nm). The AOD is calculated separately for land and ocean using a lookup table of pre-computed values for several atmospheric parameters to simplify radiative transfer calculations.”

180. MISR injection heights have the limitation that MISR overpass is in the morning while peak fire behavior (and thus deeper injections) tends to be in the afternoon. This has been highlighted in previous work (paper below for instance). Since this is the only dataset used for evaluation in this work, this needs to be mentioned and taken into consideration when discussing results and deriving conclusions.

Kahn, R. A. et al. Wildfire smoke injection heights: Two perspectives from space. *Geophys. Res. Lett.* 35, (2008).

Thanks for the comment. We add more comparison with CALIPSO which pass in the early afternoon at ~ 1:30 p.m. local time. The following discussion have been added to section 3.1:

“The vertical profiles of CMAQ simulated PM_{2.5} are also compared to the CALIPSO aerosol vertical profile. The CALIPSO overpass occurs around 1:30 p.m. local time, closer to the peak fire behaviour in the afternoon than the MISR observations. The CALIPSO smoke injection heights are directly calculated from Level 1 attenuated backscatter profiles at 532 nm following Amiridis et al. (2010). There are several steps involved in this process. First, GBBEPx FRP data were used to locate the fire location along the CALIPSO swath. Then, a slope method (Pal et al., 1992) is applied to each profile to smooth out the original Level 1 532 nm attenuated backscatter coefficient profiles at each fire point. Next, we calculate the steep gradient in the attenuated backscatter profiles. The height of the minimum gradient value is selected as the smoke injection height. Figure 4 shows the comparison between the CALIPSO plume height results and the estimated plume heights from the three plume rise schemes for west coast fires. In most cases, the plume heights from the three schemes are close to each other, especially for the cases with plume tops under 4 km. For strong fires with plume tops higher than 4 km, S12 seems to be more skillful than B69 and F07. It successfully simulates the high plume top observed by CALIPSO, whereas B69 and F07 tend to underestimate the plume heights.”

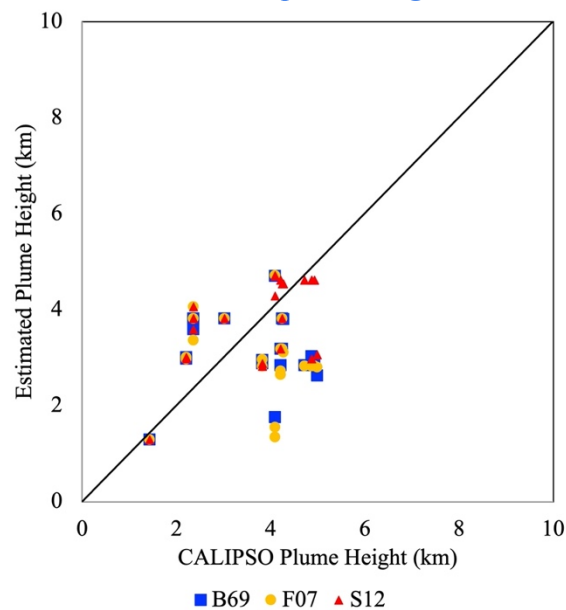


Figure 4: Comparisons of plume top heights from three simulations: B69 (blue rectangle), F07 (orange dot), and S12 (red triangle), against aerosol height observations from the CALIPSO for west coast fires.”

Figure 3. Having a visible image (MODIS Terra) including hotspots would help to visualize each scene.

Thanks for the comment. MODIS Terra visible images have been added to Figure 3.

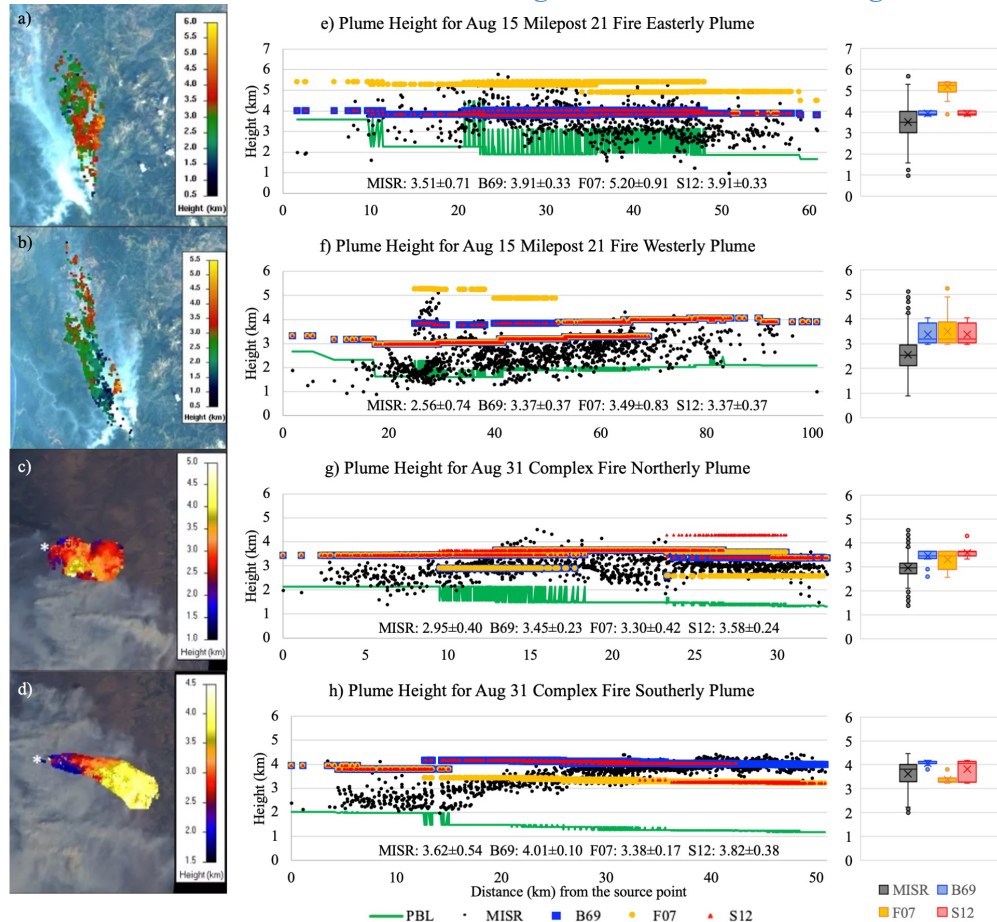


Figure 3: MISR plume heights superposed on the MODIS Terra visible images (a-d) and the comparisons of the observed plume height with the simulated plume heights (e-h) for the August 15th Milepost 21 fire easterly plume (a, e), westerly plume (b, f), August 31st Complex fire northerly plume (c, g), and southerly plume (d, h).*

**Source: MISR Active Aerosol Plume-Height (AAP) Project / R.A. Kahn, K.J. Noyes, J. Limbacher (NASA Goddard Space Flight Center), A. Nastan (JPL-Caltech), J. Tackett, J-P. Vernier (NASA Langley Research Center)*

Figure 3. It would also help to have the model boundary layer height as reference to assess boundary layer injections versus into the free-troposphere. Given the range shown by MISR, I would assume it's estimates contains a mixture of boundary layer smoke and injections. But the model doesn't show this variability, so it would be nice to understand why *PBL heights have been added to Figure 3 (see above).*

Figure 3. Are these heights capturing mostly freshly emitted smoke or is here any recirculated smoke from the same or other fires?

Thanks for the comment. They are freshly emitted smoke. More information about the MISR observation of the 2020 fires can be found here:

<https://appliedsciences.nasa.gov/our-impact/news/nasa-researchers-analyze-properties-and-dispersion-smoke-plumes-august-complex>

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The main focus of this study is to evaluate the impact of plume injection heights on the near source and downwind air quality. More details about the MISR plume observation go beyond the scope of this paper.

Figure 3. I find that evaluating only for 2 snapshots capturing 2 fires during August is a bit insufficient. There are likely many more opportunities during this 2 month period, especially during September where fires in the whole western US were exploding.

Thanks for the comment. The MISR data is from MISR Active Aerosol Plume-Height (AAP) Project. We only found the information for two August fires. However, we added more comparisons and discussions with CALIPSO in section 3.1. See the response above.

Figure 3. Also think in better ways of presenting the data, maybe aggregate MISR to the model resolution to avoid having so many repeated values for the model?

Thanks for the comment. We think it is easier for the reader to understand if we aggregate the model results into the observation space (MISR grid).

Figure 3. The model resolves the increase of height with distance, so you can do analysis to assess why is this happening. This is a bit counterintuitive as one would expect to earlier plume (i.e., further away) be emitted a lower altitudes. Or are the conditions such that the plume is just rising with time?

Thanks for the comments. The main focus of this study is to evaluate the impact of plume injection heights on the near source and downwind air quality rather than the plume rise. This level of detail goes beyond the scope of this paper.

191-202. Please be more quantitative. Higher by how much? Show some statistics

Thanks for the comment. We have added more quantitative discussion:

“For the Milepost 21 Fire, the plume heights simulated by B69 and S12 are similar but 25% and 3% lower than that by F07 for the easterly and westerly plume. In the case of the August Complex Fire northerly plume, the plume heights simulated by S12 are 4% and 8% higher than that by B69 and F07, respectively. For the southerly plume, the plume heights simulated by B69 are 16% and 5% higher than that by F07 and S12.”

206-207 Maybe do statistical testing on the mean o backup this statement?

Thanks for the comment. Box and whisker charts are added to Figure 3 to show more statistical results. Line 298 have been changed to:

“According to the box and whisker chart shown in the right panel of Figure 3, the simulated plume heights are all within the range of MISR observation. Overall, the simulated plume heights with all three schemes are reasonably comparable to the MISR observations.”

208-213. Need to better backup these statements. For instance, what were the stability conditions the model used for these fires. Also note Briggs not always shows higher injections.

Thanks for the comment. We decide to delete this discussion.

Figure 4. It would be nice to explore if these trends are also found on observations such at those from IMPROVE sites

Thanks for the comment. We did not compare to IMPROVE sites for the following reasons. First, Figure 5 (original figure 4) shows the results of the column $PM_{2.5}$ rather than the surface $PM_{2.5}$ as we want to include the aerosol change both at the surface and in the plume aloft, while IMPROVE only measures the surface $PM_{2.5}$ concentration. Secondly, figure 5 shows the aerosol change due to the emission from biomass burning (the impact of other $PM_{2.5}$ sources was removed by subtracting the results of NoFire run). It is the difference between the two CMAQ simulations with and without fires, so we cannot compare it to the IMPROVE observation, which also include the $PM_{2.5}$ emitted from other sources. In addition, IMPROVE does not have observations for ammonium separately.

Figure 5. It would be good to have a panel showing the average profile for one of the schemes to use it as a reference.

Thanks for the comment. However, there is already a lot of information in Figure 6 (original figure 5). We don't want to make the figure too complicated. So, we did not add the average profile. But we add a difference ratio plot at the bottom (Figures 6 o and p), which can be used as a reference.

Section 3.3. While VIIRS AOD is included, it doesn't seem to be used in the analysis. Satellite AOD tends to saturate around 5 so retrievals for the very fresh plumes are likely missing. If the model was not screened by these missing values then this likely explain why the model is overpredicting AOD on the locations of the fires. Ones you move away a bit from the fires the bias flip, with models tending to underpredict AOD. This discussion needs to happen before analysis is done comparing model runs.

Thanks for the comment. We updated Figure 7 (original figure 6). When compared to the VIIRS, we applied the same saturation level, which is 5, to CMAQ results. When comparing the models, we removed the saturation level.

New Figure 7:

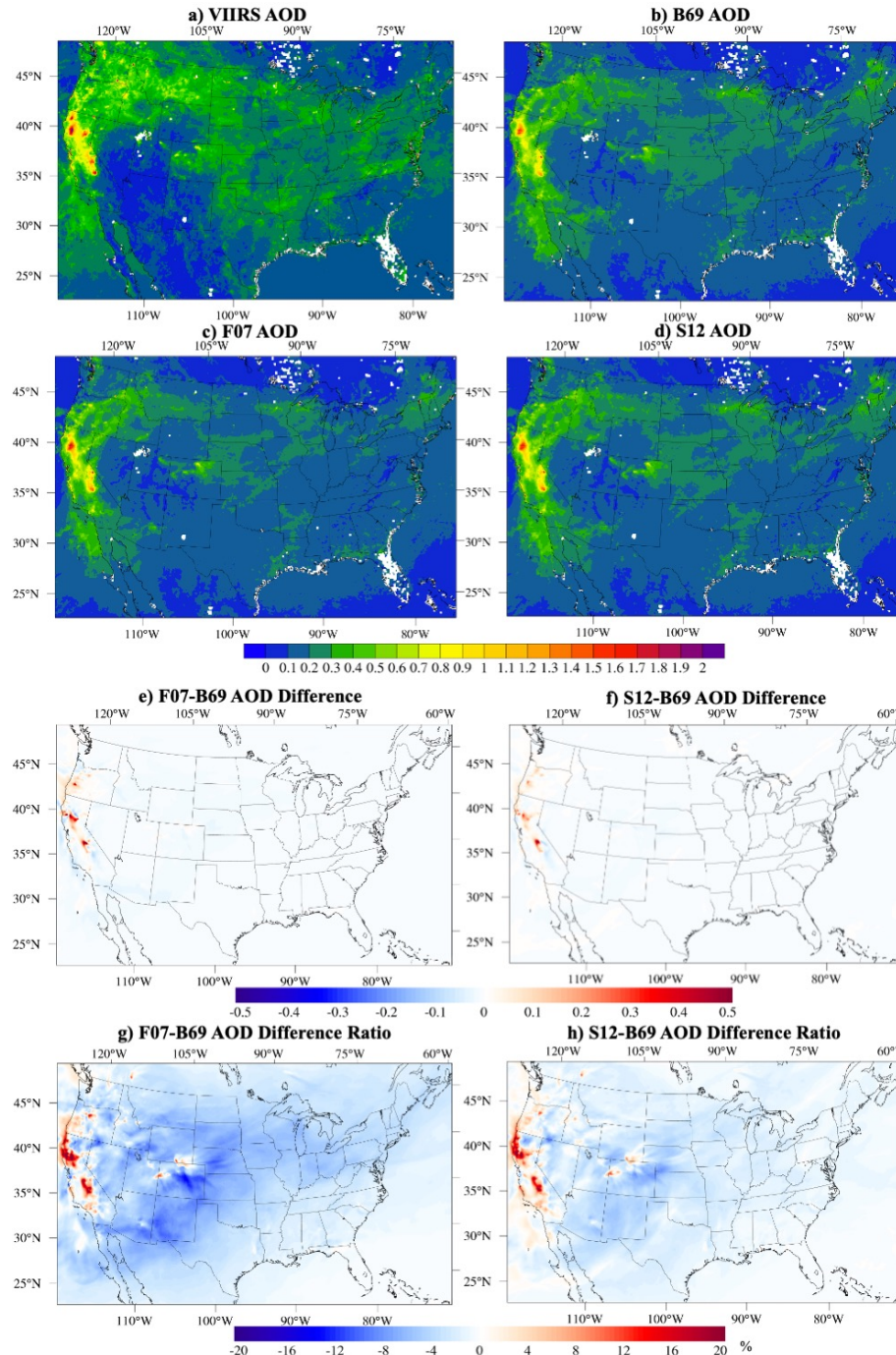


Figure 7: Two-month average AOD from VIIRS (a), B69 run (b), F07 run (c), and S12 run (d); the average AOD differences between F07 and B69 (e), and between S12 and B69 (f) from August 1st, 2020 to September 30th, 2020; and the average AOD difference ratio between F07 and B69 (g), and between S12 and B69 (h) during the same period.

The following lines have been added to line 411:

“Figure 7a shows the two-month averaged AOD from VIIRS compared with model simulations (Figures 7b-d). The CMAQ predicted AOD was interpolated to the VIIRS pixels that passed quality control using the nearest neighbor approach. When comparing the CMAQ AOD to VIIRS AOD

(Figures 7b-d), we applied VIIRS AOD saturation level (5) to CMAQ AOD results. In the west coast high peak region, all three runs capture the observed AOD high peak near the San Francisco region, but the simulated AOD peak is lower than VIIRS observed. The average AOD from VIIRS observation is higher than 2. However, among the three CMAQ runs, only F07 simulated an average AOD higher than 2. In the downwind region, all three CMAQ runs reproduce the general downwind transport pattern, but the simulated smoke affected region (AOD>0.5) is smaller than the observations.

Figures 7e-h show the AOD differences and the difference ratio (percentage of the difference relative to B69) between the different plume rise scheme simulations. When comparing different model simulations, the AOD saturation level is removed.”

295. Reference Figure 6 to make it clear you are comparing to that figure
We deleted this discussion related to NO₂.

310. Changes of 70% are described, but the color-scale of Fig 8 saturates at 30%. Exploring a scale that’s not linear (like Fig 5) might work better.

Thanks for the comment. The color-scale of Figure 9 (original figure 8) is changed:

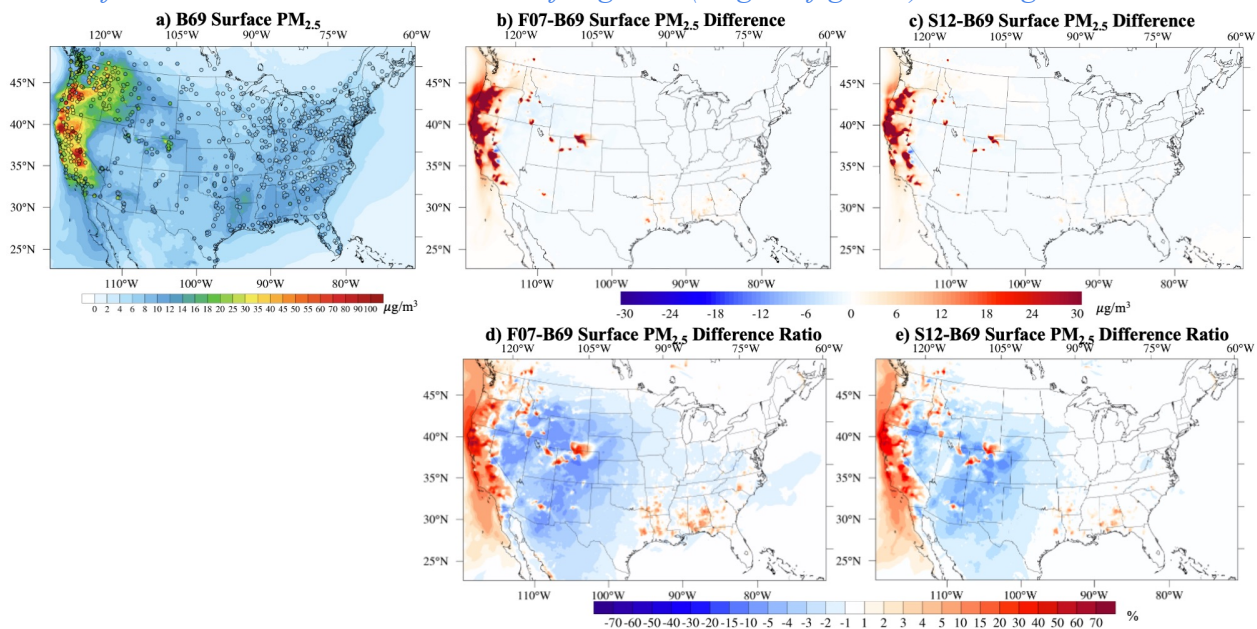


Figure 9: Simulated and observed surface PM_{2.5} from August 1st, 2020, to September 30th, 2020: a) average surface PM_{2.5} simulated with B69 overlaid by AirNow observations; b) difference in averaged surface PM_{2.5} between F07 and B69; c) difference between S12 and B69; d) and e) same as b) and c), but for the differences in percentage (%) between F07 and B69, and between S12 and B69, respectively.

Figure 8. It would be nice to have a surface PM_{2.5} map for one of the simulations as a reference to better interpret the differences.

Thanks for the comment. The surface PM_{2.5} map is added to Figure 9 (see above).

Figure 8. How much of these differences are due to differences in injection height versus assumptions of fraction of emissions placed at surface levels vs injected?

All of the differences are due to the differences in injection heights. The only difference between the B69, F07, and S12 runs is the calculated fire injection heights. All three runs use the same emission and emission distribution algorithm.

319-331. While 35 $\mu\text{m}/\text{m}^3$ is the standard, this divides the "Moderate" from "Unhealthy for sensitive groups" categories. However, it would be nice to see how the models in predicting the more extreme categories ("Unhealthy", "Very unhealthy", "Hazardous".) where more authorities might take more stringent measures

Thanks for the comment. The results for "Unhealthy" and "Very unhealthy" are now included in Figure 10.

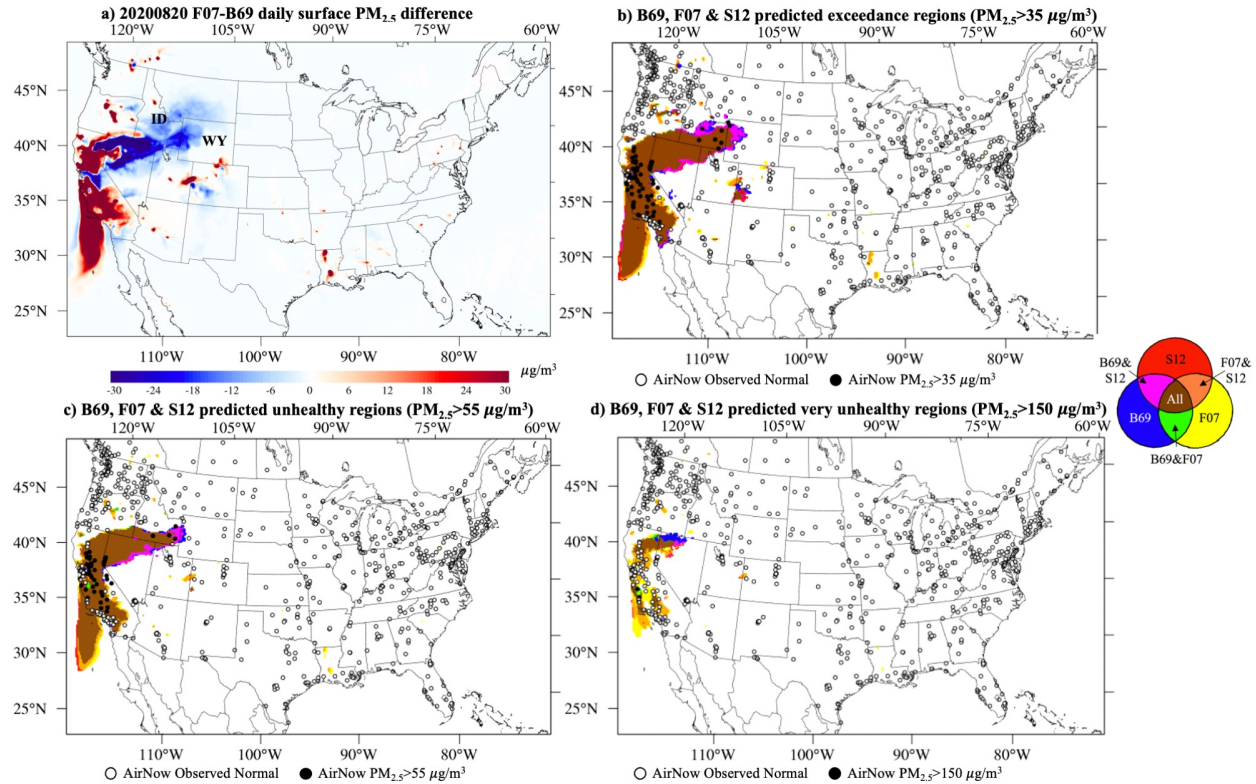


Figure 10: Predicted surface PM_{2.5} concentrations above unhealthy levels by the S12, F07, and B69 runs for August 20th, 2020: a) The daily mean surface PM_{2.5} difference between F07 and B69 runs; b) simulated PM_{2.5} exceedance regions by B69, F07, and S12 overlaid by AirNow observed exceedance ($\text{PM}_{2.5} > 35$ $\mu\text{g}/\text{m}^3$); c) same to b) but for US EPA defined unhealthy regions ($\text{PM}_{2.5} > 55$ $\mu\text{g}/\text{m}^3$); d) same to b) but for US EPA defined very unhealthy region ($\text{PM}_{2.5} > 150$ $\mu\text{g}/\text{m}^3$). The brown color represents the region where the runs with all three schemes simulate PM_{2.5} exceedances; the blue (red/yellow) color represents the region where only B69 (S12/F07) simulates the PM_{2.5} exceedance; the green represents the region where both the B69 and F07 simulate the PM_{2.5} exceedance; the magenta color represents the region where both the B69 and S12 simulate the PM_{2.5} exceedance; the orange represents the region where both F07 and S12 simulate the PM_{2.5} exceedance.

The discussion in line 564 have been changed to:

“The simulated PM_{2.5} exceedance regions ($\text{PM}_{2.5} > 35$ $\mu\text{g}/\text{m}^3$, defined by NAAQS, same level with US EPA defined unhealthy for sensitive groups), unhealthy region ($\text{PM}_{2.5} > 55$ $\mu\text{g}/\text{m}^3$, defined by

US EPA), and very unhealthy region ($PM_{2.5} > 150 \mu\text{g}/\text{m}^3$, defined by US EPA) by different plume rise schemes overlaid by AirNow observed exceedance for the same day are shown in Figures 10b, c, and d. According to Figure 10b and c, on August 20th, 2020, B69 and S12 simulated more $PM_{2.5}$ exceedance and a larger unhealthy region in the downwind regions (Wyoming (WY) and Idaho (ID), magenta and blue region), whereas F07 and S12 simulated more exceedance and a larger unhealthy region in the southeastern U.S. (yellow and orange region), where prescribed fires were the major biomass burning sources. In WY and ID, where F07 did not simulate the $PM_{2.5}$ exceedance whereas B69 and S12 did, the difference between F07 and B69 reached $15 \mu\text{g}/\text{m}^3$ (Figure 10a). Furthermore, B69 and S12 simulate some very unhealthy regions in Nevada, whereas F07 simulates more very unhealthy regions in central and south California.”

319-331. This analysis is based on one day. A way to generalize this analysis could be to show a map or difference maps of the number of days the models predict exceedances.

Thanks for the comment. We have added a new figure (Figure 11) to show the total number of exceedance days and the difference in the number of exceedances between different:

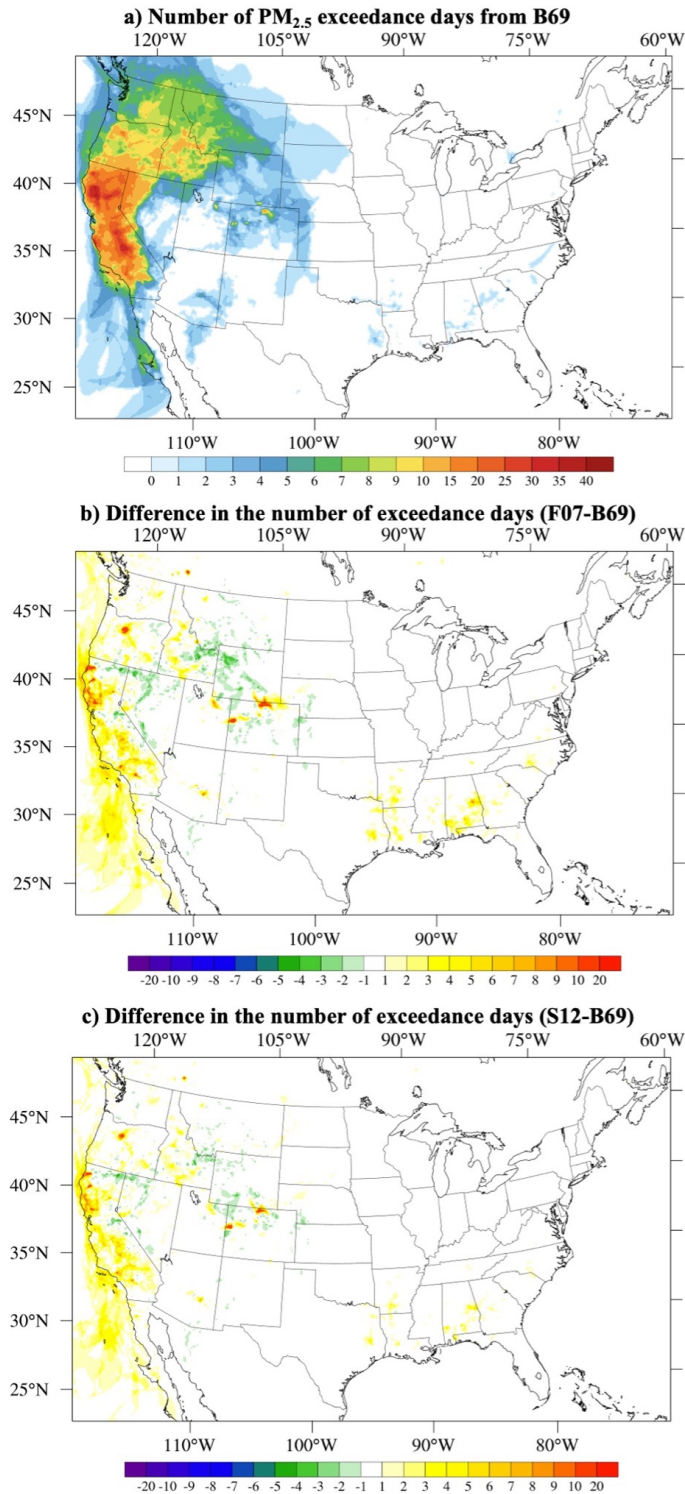


Figure 11: The CMAQ B69 predicted total number of PM_{2.5} exceedance days during Aug-Sep, 2020 (a); the difference in the number of predicted exceedance days between B69 and F07 (b), and between B69 and S12 (c).

The following discussions have been added to the paper in line 634:

“The total number of predicted exceedance days from the B69 simulation and the differences between B69, F07, and S12 are shown in Figure 11. All the states in the western coast and mountain region experienced at least one day of PM_{2.5} exceedance (Figure 11a). Most of the region in northern California experienced more than 20 exceedance days, with a maximum of more than 35 days. F07 and S12 simulate more exceedance days on the west coast near the source region and in the southeast. The difference in the exceedance days could be as large as 20 days in northern California. B69 simulates more exceedance days in downwind regions such as Nevada, Idaho, Montana, and Wyoming. The difference could reach 4 days in the downwind regions.”

Minor Edits

191: ACP won't allow links, convert it to a reference

Thanks for the comment. The link is deleted and added to the data availability part.

321-325. A lot of this text is already in Fig 9 caption so no need to repeat.

Thanks for the comment. They are deleted.

Reviewer #2:

This paper used an offline CMAQ model with three different plume rise schemes to discuss the impact of injection plume height on local and downwind aerosols' chemical composition as well as the photochemical processes. The paper clearly explains the basic settings of the CMAQ model and the different input parameters in three plume models.

This work has compared the predicted AOD among three plume models to illustrate their different prediction performance in the source and downwind area, while a detailed comparison between VIIRS observed AOD and modeled AOD is expected to further validate the model prediction accuracy. This work has made the comparison of PM exceedance regions between the model prediction and the AirNow observation on Aug 20, 2020. The result shows good consistency.

The analysis of the plume models' impacts on photochemistry mainly focuses on the photolysis of NO₂. We expect more observation evidence on NO₂ concentration to validate the model prediction. The relationship between NO₂ concentration or photolysis rate and other species concentration which have adverse effects on human health (e.g., ozone) needs to be further established.

General comments:

Introduction:

Authors explained the different parameters used in three schemes for plume height estimates. We expect the authors to explain how the later-published schemes of plume height simulation improve the modeling accuracy, in general. Also, what is the limitation of each model.

Thanks for the comment. More details of the three plume rise schemes are shown in section 2.3.

For B69 scheme, we add the equation:

"It uses a set of semi-empirical formulas to estimate plume injection height (H_p) in different atmospheric stability states (i.e., neutral, stable, and unstable). Heat flux (B), horizontal wind speed (U), static stability (S), and friction velocity (x^) are used to estimate the plume injection height:*

$$H_p = \begin{cases} 1.33 \times BU^{-1}x^{*-2}, & \text{neutral} \\ 2.6 \times (BU^{-1}S^{-1})^{\frac{1}{3}}, & \text{stable} \\ 30 \times (BU^{-1})^{\frac{3}{5}}, & \text{unstable} \end{cases} \quad (1)$$

Previous studies found that FRP is about 10-20% of the total fire heat (Wooster et al., 2005; Freeborn et al., 2008). In this study, we derive the heat flux from FRP provided by the GBBEPx dataset multiplied by a factor of 10 following Val Martin et al. (2012). "

For F07 we add more information:

"It takes in fire information, including fire area and heat flux, as well as atmospheric profile information, including temperature, moisture, density, and wind velocity. The plume top height is defined as the altitude at which the plume is neutrally buoyant, and is approximated as a vertical velocity < 1 m/s."

For S12 we add the equation:

"It utilizes FRP, PBL height (H_{PBL}), and the Brunt-Vaisala frequency in the free troposphere (BV_{FT}) to estimate the plume injection height from wildfires:

$$H_p = \alpha H_{PBL} + \beta \left(\frac{FRP}{FRP_0} \right)^\gamma \exp \left(-\frac{\delta BV_{FT}^2}{BV_0^2} \right) \quad (2)$$

Where FRP_0 is the reference fire radiative power which equals 10^6 W, BV_0 is the reference Brunt-Vaisala frequency which equals $2.5 \times 10^{-4} \text{ s}^{-2}$, and α , β , γ , δ are constants.”

All three schemes are widely used schemes, but using different methods to calculate the plume height. We don't want to say which one is the best, or which one is the worst in this paper. Also, the main focus is the plume height impact on downwind air quality, not plume rise schemes. More details about these schemes are beyond the scope of this paper.

Method:

The CMAQ model domain has a spatial resolution of $12 \text{ km} \times 12 \text{ km}$. The scale of an wildfires in the western US is normally smaller than the spatial resolution of the defined CMAQ domain (Biomass burning emission is a 0.1 degree product). Please provide the dimension information (or related information) of the studied fire to explain the choice of domain resolution.

Thanks for the comment. We use the same horizontal and vertical resolution as NOAA's operational National Air Quality Forecasting Capability (NAQFC). The results of this paper and the following studies will be used to improve NAQFC. The following lines have been added to line 151:

“(the same horizontal and vertical resolution as NOAA's operational National Air Quality Forecasting Capability)”

In section 2.1 Experiment Design, authors have mentioned the reaction pathway from VOCs to SOA. However, in the result analysis part, section 3.2, the contribution of SOA in the total OM has not been mentioned. The portion of OM in the total $PM_{2.5}$ seems to be completely regarded as the primary emission. Combining primary OA and SOA together may introduce errors in the further discussion on particle/gas transport issue.

This is a good point and we have clarified it in Section 3.2 (first paragraph):

“In this section, we investigate the impact of plume injection height on different $PM_{2.5}$ chemical components. Figure 5 shows the distribution of simulated $PM_{2.5}$ components from both direct emissions and secondary formation (the impact of other $PM_{2.5}$ sources was removed by subtracting the results of NoFire run) from B69, F07, and S12 in three different regions.”

Primary and secondary aerosols have different sources (primary aerosols refer to the aerosols emitted by the fire, secondary aerosols refer to the aerosol generated after emitted), but could be the same species, just like the organic carbon, sulfate, ammonium, and nitrate in figure 2. In CMAQV5.3.1, primary and secondary aerosols are blended to do the reaction and dispersion. It is hard to separate secondary aerosols from primary aerosols in the output. However, we don't think it will affect our discussion, as the main focus is the overall impact (combining primary and secondary aerosols) of plume rise on air quality.

Results:

Figure 5 plots the specific chemical component of $PM_{2.5}$ against the distance (km) from the source point. Is this distance along certain smoke transport pathway? If so, which specific pathway you chose to sample the modeled concentration of different species.

Thanks for the comment. Figure 5 (Now it is Figure 6) shows the zonal mean results (average for each latitude), not along certain smoke transport pathways.

Line 378 has been changed to clarify it:

“Figure 6 shows the difference in the zonal mean (average for each latitude) concentrations of six major PM_{2.5} species”

Specific comments:

Line 48: PM_{2.5} definition: Particle’s aerodynamic diameter is less than 2.5 μm

Thanks for the comment. Line 49 has been changed to:

“O’Neil et al. (2021) discuss the regional health impacts of the 2017 Northern California wildfires and estimated 83 excess deaths from exposure to PM_{2.5} (i.e., particles having aerodynamic diameter less than 2.5 μm), of which 47% of the deaths were attributable to wildfire smoke during the smoke episode.”

Line 48: “47%” in mass or other types of measure?

Thanks for the comment. It is 47% of the estimated excess deaths. Line 49 has been changed to:

“O’Neil et al. (2021) discuss the regional health impacts of the 2017 Northern California wildfires and estimated 83 excess deaths from exposure to PM_{2.5} (i.e., particles having aerodynamic diameter is less than 2.5 μm), of which 47% of the deaths were attributable to wildfire smoke during the smoke episode.”

Line 62: “Irregular large point sources”. What does this terminology mean? The boundary of the source is irregular? Then why is a point source?

Thanks for the comment. In CMAQ, fire is treated as an irregular point source emission, as the occurrence and location of the emission are not regular or fixed. Line 66 have been changed to make it clear:

“...the Briggs scheme was not designed for irregular occurrence large point source emissions, such as forest fires...”

Line 78: the unit of “3720”. Daily, hourly cases?

Thanks for the comment. The NAAQS defined PM_{2.5} exceedance based on daily PM_{2.5}. Line 92 has been changed to make it clear:

“From late August to early October 2020, the West Coast wildfires contributed 23% of surface PM_{2.5} pollution nationwide and caused 3,720 observed PM_{2.5} exceedances (daily PM_{2.5}>35 μg/m³ based on National Ambient Air Quality Standards; Li et al., 2021). “

Line 156: What’s the result of this reason?

Thanks for the comment. Line 244 has been changed to:

“The main focus of this study is to evaluate the impact of different plume injection heights on the near source and downwind air quality, and the two-month average state is more important to our results and future health studies.”

Line 209: Define “ABL” before using it
This paragraph is deleted.

Line 225: Is “OM” here the same as organic carbon you defined in section 2.1, which only refers to primary organic carbon?

Thanks for the comments. In section 2.1 primary aerosol refer to the aerosols emitted from fires, and secondary aerosol refers to the aerosols generated after emitted. They can be the same species. As in Figure 2, there are Sulfate, Nitrate, and Ammonium in both primary and secondary aerosols (same as the organic carbons). Primary and secondary aerosols are not different species, but different sources. In section 2.1, organic carbon does not only refer to primary organic carbon. OM is organic matter, it is different from organic carbon in that it includes all the elements (hydrogen, oxygen, nitrogen, etc) that are components of organic compounds, not just carbon. OC is included in OM. In CMAQ, OM is used to calculate the total PM_{2.5}. Therefore, we use OM instead of OC in the discussion in section 3.

We added a note to Figure 2 to make it clear:

“+Note: The CMAQ model separates organic carbon (OC) and non-carbon elements (O, H, etc) in organic matter (OM).”

Line 226: Clarify that the composition of PM_{2.5} in this section is surface PM_{2.5}, or PM_{2.5} under PBL, or column PM_{2.5}. Line 232 mentioned “surface PM_{2.5}”, and the conclusion of this section is “integrated over all vertical layer”.

Thanks for the comment. Sorry, it is a typo. Not surface PM_{2.5}. It should be PM_{2.5} integrated over all vertical layers. The word “surface” is deleted.

Figure 4: The negative sign before the longitude is unnecessary
Thanks for the comment. We decide to keep it.

Line 249: Unify the representation of longitude: either 115° W or -115° throughout the paper
Thanks for the comment. We have changed it to “in the west of 115° W”.

Figure 6: The comparisons between VIIRS AOD and modeled results may be needed to demonstrate the prediction accuracy of different plume models.

Thanks for the comments. More discussions about the comparisons between VIIRS AOD and model results have been added to the paper section 3.3:

“Figure 7a shows the two-month averaged AOD from VIIRS compared with model simulations (Figures 7b-d). The CMAQ predicted AOD was interpolated to the VIIRS pixels that passed quality control using the nearest neighbor approach. When comparing the CMAQ AOD to VIIRS AOD (Figures 7b-d), we applied VIIRS AOD saturation level (5) to CMAQ AOD results. In the west coast high peak region, all three runs capture the observed AOD high peak near the San Francisco region, but the simulated AOD peak is lower than VIIRS observed. The average AOD

from VIIRS observation is higher than 2. However, among the three CMAQ runs, only F07 simulated an average AOD higher than 2. In the downwind region, all three CMAQ runs reproduce the general downwind transport pattern, but the simulated smoke affected region (AOD>0.5) is smaller than the observations.”

Line 286: Thicker smoke in this study doesn't necessarily mean higher AOD. Thicker smoke somehow may be attributed to a diluted plume because of the different plume height modeled by different schemes. A basic assumption in this study is the primary biomass burning emissions among three models are similar (or identical).

Here thicker smoke refers to a higher concentration of total column PM_{2.5}. Aerosol optical depth (AOD) is a quantitative estimate of the amount of aerosol present in the atmosphere. Since all three runs use the same emission, the aerosol type should be similar, a higher AOD can indicate higher smoke concentrations.

Typos or other improvement suggestions:

Line 25: lower case “western”

We decided to keep “Western United States”. It's a proper noun. Proper nouns should be capitalized.

Line 46: two “annual”

Thanks. Line 47 has been changed to:

“The global average mortality attributable to landscape fire smoke exposure was estimated at 339,000 deaths annually (Johnston et al., 2012).”

Line 63: Start a new sentence to declare the second limitation of Briggs scheme.

Thanks for the comment. It has been changed to:

“Also, some of the input parameters, such as heat flux, are difficult to obtain.”

Line 69: Please provide the reference of Siberia study

Thanks for the comment. The data are from the MISR plume height project. The following two papers have been added as the reference:

Line 72 is changed to:

“The parameters of the new scheme were determined using the plume height observations collected by the Multi-angle Imaging SpectroRadiometer (MISR) Plume Height Project (Kahn et al., 2008; Mazzoni et al., 2007) in North America (Val Martin et al., 2010) and Siberia.”

The following lines are added to the reference part:

Kahn, R. A., Chen, Y., Nelson, D. L., Leung, F.-Y., Li, Q., Diner, D. J., and Logan, J. A. Wildfire smoke injection heights: Two perspectives from space, Geophys. Res. Lett., 35, L04809, doi:10.1029/2007GL032165, 2008

Mazzoni, D., Logan, J.A., Diner, D., Kahn, R. A., Tong, L., and Li, Q.: A data-mining approach to associating MISR smoke plume heights with MODIS fire measurements, Remote Sens. Environ., 107, 138-148, 2007.

Line 69: “height”

Thanks. It's a typo. We have changed it to “height”.

Line 72: Suggest start a new sentence here.

Line 87 has been changed to:

“They found that there was a large spread of the modelled plume heights.”

Line 162: “from... from...” redundancy

Line 190 has been changed to:

“...we derive the heat flux from FRP provided by the GBBEPx dataset ...”

Line 185: lower case

We think it is okay to use “the Equator” here. The Equator is the invisible line that runs around the center of the Earth at 0 degrees latitude. An equator is an imaginary line around the middle of a planet or other celestial body. It's a proper noun. Proper nouns should be capitalized.

Line 263: lower case

We think it is okay to use “the Earth”, as we're referring to the specific planet. The word “earth” refers to the soil or surface of a stratum. Earth is a proper noun. It names a specific place. Proper nouns should be capitalized.

Figure 6: Increase the tick font size of the colorbar

Thanks for the comment. The font size has been enlarged in Figure 6 (Now it is figure 7).

Line 296: The difference ratios in NO₂ is higher than the ones of AOD can only prove the concentration of NO₂ is not linearly proportional to AOD.

Thanks for the comment. The discussion of NO₂ is deleted. The change of NO₂ is very complicated and beyond the scope of this paper.

Line 297: The reaction rate of NO₂ (for this NO₂ -> NO + O reaction) is the product of <NO₂_IUPAC10> and the concentration of NO₂. The comparison of reaction rates between different plume schemes is needed to support your conclusion.

Thanks for the comment. The discussion of NO₂ is deleted.

Figure 7: Increase the tick font size of the colorbar

Thanks for the comment. The font size has been enlarged in Figure 7 (Now it is figure 8).

Other comments

Line 67: This sentence means Sofiev scheme used the MISR observed plume height to determine the modeled plume height. I am a bit confused about it (Line 67 - 69).

The Sofiev et al. (2012) scheme uses the plume height collected within the MISR Plume Height Project to calculate the parameters used in the Sofiev et al. (2012) scheme. More information can be found in the reference:

Sofiev, M., Ermakova, T., and Vankevich, R.: Evaluation of the smoke-injection height from wild-land fires using remote-sensing data, Atmos. Chem. Phys., 12, 1995–2006, <https://doi.org/10.5194/acp-12-1995-2012>, 2012.

Line 76: Please provide the reference of the burned area. (I remembered the burned area in the western US in 2020 is high but below 10 million acres. The entire US is larger than 10 million acres)

Thanks for the comment. The reference has been added.

National Interagency Fire Center. 2020 National Large Incident Year-to-Date Report (PDF). Geographic Area Coordination Center (Report). December 21, 2020.

Reviewer #3

Review comment on “Impacts of estimated plume rise on PM2.5 exceedance prediction during extreme wildfire events: A comparison of three schemes (Briggs, Freitas, and Sofiev)

The authors compared three popular plume rise schemes, namely Briggs 1969, Freitas 2007 and Sofiev 2012, and their impacts on the simulated plume heights, AOD, PM2.5 and NO2 photochemistry using the CMAQ model driven by WRF meteorology data for the 2020 western U.S. wildfire season. With global warming, the increasing trend in western U.S. fire activities, and the need to predict hazardous air quality associated with wildfires, the study would make a timely and significant contribution to wildfire and air quality modeling science. So publication is recommended. However, I believe, the presentation can be significantly improved to increase the scientific impact of this study.

Major comments:

The descriptions of each of the plume rise schemes are short. More details of the schemes could be provided to help readers know better of the differences of the schemes (length of description can be doubled or tripled). Also, the authors focus mainly on plume top height, however plume extension (top and bottom of a plume) in the vertical at emission is as important as plume top. Information about plume vertical extension at emission and how emission mass is distributed in the vertical (e.g. evenly or weighted) from the schemes should be provided.

Thanks for the comments. More details of the three plume rise schemes have been added in section 2.3.

For B69 scheme, we add the equation:

“It uses a set of semi-empirical formulas to estimate plume injection height (H_p) in different atmospheric stability states (i.e., neutral, stable, and unstable). Heat flux (B), horizontal wind speed (U), static stability (S), and friction velocity (x^) are used to estimate the plume injection height:*

$$H_p = \begin{cases} 1.33 \times BU^{-1}x^{*-2}, & \text{neutral} \\ 2.6 \times (BU^{-1}S^{-1})^{\frac{1}{3}}, & \text{stable} \\ 30 \times (BU^{-1})^{\frac{3}{5}}, & \text{unstable} \end{cases} \quad (1)$$

Previous studies found that FRP is about 10-20% of the total fire heat (Wooster et al., 2005; Freeborn et al., 2008). In this study, we derive the heat flux from FRP provided by the GBBEPx dataset multiplied by a factor of 10 following Val Martin et al. (2012).”

For F07 we add more information:

“It takes in fire information, including fire area and heat flux, as well as atmospheric profile information, including temperature, moisture, density, and wind velocity. The plume top height is defined as the altitude at which the plume is neutrally buoyant, and is approximated as a vertical velocity < 1 m/s.”

For S12 we add the equation:

“It utilizes FRP, PBL height (H_{PBL}), and the Brunt-Vaisala frequency in the free troposphere (BV_{FT}) to estimate the plume injection height from wildfires:

$$H_p = \alpha H_{PBL} + \beta \left(\frac{FRP}{FRP_0} \right)^\gamma \exp \left(-\frac{\delta BV_{FT}^2}{BV_0^2} \right) \quad (2)$$

Where FRP_0 is the reference fire radiative power which equals 10^6 W, BV_0 is the reference Brunt-Vaisala frequency which equals $2.5 \times 10^{-4} \text{ s}^{-2}$, and α , β , γ , δ are constants.”

The plume is distributed between 0.5-1.5 times the plume injection height (default setting in CMAQ).

The following lines have been added to the paper in line 236:

“After getting the estimated plume injection height from the three schemes, the fire emissions were distributed between 0.5-1.5 times plume injection height (default setting in CMAQ).”

It's not clear how model and MISR plume heights were compared. The model and MISR observations don't have the same spatial and temporal resolutions, and MISR observations are not continuous in time and space. So some spatiotemporal interpolation is expected. The treatment of the model and MISR data for comparison should be clearly stated.

Thanks for the comment. The simulated plume height is mapped to MISR pixels based on the nearest point. We compared the CMAQ with MISR at the MISR local overpass time of around 19 UTC. local time. The following lines have been added to line 284.

“The simulated plume heights from three simulations: B69, F07, and S12 are compared with MISR observations for the Milepost 21 Fire on August 15th, 2020, and the August Complex Fire on August 31st, 2020 (Figure 3) at the MISR local overpass time of around 19 UTC. The simulated plume heights were interpolated to the MISR observation MISR pixels using the nearest neighbor approach.”

Section 3.3 and conclusion: Why do F07 and S12, which tend to have lower plume height than B69 near source region, have higher AOD than B69 near source region? What is the column total PM2.5 differences in the source region for the three schemes? Is the difference small? (You could consider providing total/average PM2.5 or even better dry mass in Figure 4 for the different regions and schemes) If so, what causes the 20-30% AOD difference in source region? Is it purely because of different vertical distributions of same mass? For example, there could be more aerosols in the lower altitude in F07 and S12 (and RH tends to be higher than higher altitude), so that hygroscopic growth of smoke in the lower layer leads to the higher AOD? Or is it due to different SOA production rate? The authors should be able to provide some discussions through analysis.

Thanks for the comment. Previous studies found that a higher plume height will inject more aerosol into the free troposphere where the wind speed is stronger and accelerate the dispersion

of the fire pollution. Therefore, the higher plume height will lead to lower AOD near the source region but higher AOD in the downwind region. We have added more discussion in section 3.3 to make it clear:

“One possible reason that B69 predicts lower AOD near the source region and higher AOD in the downwind region compared to F07 and S12 is that a higher plume height will inject more aerosol into the free troposphere where the wind speed is stronger, accelerating the dispersion of the fire pollution. Therefore, the higher plume height will lead to lower AOD near the source region but higher AOD in the downwind region. The result is consistent with previous studies (Mallia et al., 2018; Vernon et al., 2018; Li et al., 2020).”

The AOD is a quantitative estimate of the amount of aerosol present in the atmosphere. The difference in the total column PM_{2.5} could be informed by the AOD comparison. Therefore, we think the plots for total column PM_{2.5} is not necessary.

The only difference between the three runs is the estimated plume injection height. We use the same chemistry mechanism, same emission, and same dynamic for the three runs. Any difference between the three runs is caused by the difference in the plume injection height. Of course, the difference in the plume height will lead to the difference in dispersion, and aerosol concentration, and affect the reaction rate of some chemistry or photolysis reactions which we discussed in the later part of section 3.3. However, all of the following differences are the results of the difference in the plume injection height. We have added more discussion in section 3.3 to make it clear:

“The difference in the dispersion of fire pollution caused by the various estimated plume injection heights leads to further differences in the chemistry and photolysis reactions. Previous studies found that the thicker smoke, indicated by higher AOD, may absorb and/or scatter a larger fraction of sunlight, hence affecting photolysis reactions (Dickerson et al., 1997; Castro et al., 2001; Kumar et al., 2014; Baylon et al., 2018).”

Since the difference in the photolysis rate is not the main focus of this study. We think more detailed discussions are beyond the scope of this paper.

Figure 9: This is a case study of PM_{2.5} exceedance. Using a color wheel with overlapping colors to represent simulated PM_{2.5} exceedance regions from the three schemes is brilliant. I do have a few questions though: Why August 20th is chosen as the case? The authors should provide a reason. Since this is a case study, some background of the wild fires and PM transport should be provided. Did you compare the plume heights with MISR (This case was not included in the earlier section or Figure 3)? Why F07-B69 difference in daily surface PM_{2.5} is provided, but not S12-B69? The authors should provide the reasoning of leaving this comparison out or making this comparison.

Thanks for the comments. Based on the previous discussion, the difference between F07 and B69 is larger than S12 and B69, so we just show the plot for F07-B69 to save space. August 20 is the first peak of the 2020 wildfire season. There is no MISR observation in the fire source region on that day. We have added more explanation in the paper:

“...for Aug 20th, 2020 (the first fire peak during the study period).”

Also, we add more discussion and a figure to show the map of the total number of PM_{2.5} exceedance days and the difference in the total number of exceedance days between the three runs. This analysis can show the overall condition of the whole study period. The following lines and figure 11 have added to the end of section 3.4:

“The total number of predicted exceedance days from the B69 simulation and the differences between B69, F07, and S12 are shown in Figure 11. All the states in the western coast and mountain region experienced at least one day of PM_{2.5} exceedance (Figure 11a). Most of the region in northern California experienced more than 20 exceedance days, with a maximum of more than 35 days. F07 and S12 simulate more exceedance days on the west coast near the source region and in the southeast. The difference in the exceedance days could be as large as 20 days in northern California. B69 simulates more exceedance days in downwind regions such as Nevada, Idaho, Montana, and Wyoming. The difference could reach 4 days in the downwind regions.”

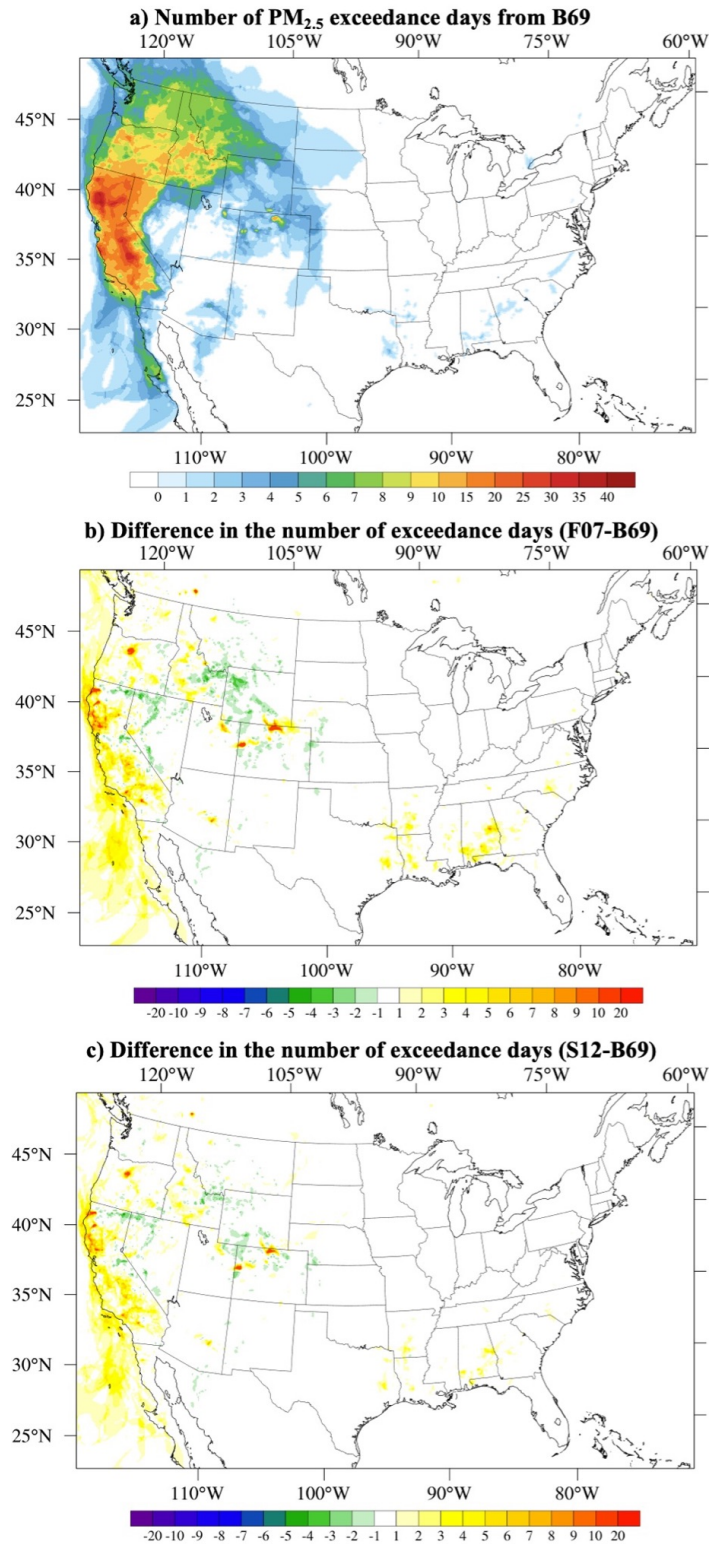


Figure 11: The CMAQ B69 predicted total number of PM_{2.5} exceedance days during Aug-Sep, 2020 (a); the difference in the number of predicted exceedance days between B69 and F07 (b), and between B69 and S12 (c).

Minor comments:

Line 69: “heigh” should be “height”.

Thanks. The “heigh” is changed to “height”.

Line 77-78: Please define “PM2.5 exceedance”. Is it based on daily-mean or hourly PM data? Also for the 3720 observations, how many sites are the observations based on?

Thanks for the comments. The definition of NAAQS PM_{2.5} exceedance has been added:

“...observed PM_{2.5} exceedances (daily PM_{2.5} > 35 µg/m³ based on National Ambient Air Quality Standards...”

The number of AirNow PM_{2.5} is not fixed every day. Usually, it is around 1000. For more details about the previous study, please refer to the following paper:

*Li, Y., Tong, D., Ma, S., Zhang, X., Kondragunta, S., Li, F., & Saylor, R.: Dominance of wildfires impact on air quality exceedances during the 2020 record-breaking wildfire season in the United States. *Geophysical Research Letters*, 48, e2021GL094908.*

<https://doi.org/10.1029/2021GL094908>, 2021.

Line 79-80: There is no direct visual link between “hazy” and AOD shown in Figure 1. I would suggest adding a matching VIIRS true color image and/or define “hazy” in terms of AOD and PM values.

Thanks for the comment. Figure 1 is changed. VIIRS true color image is added to figure 1.

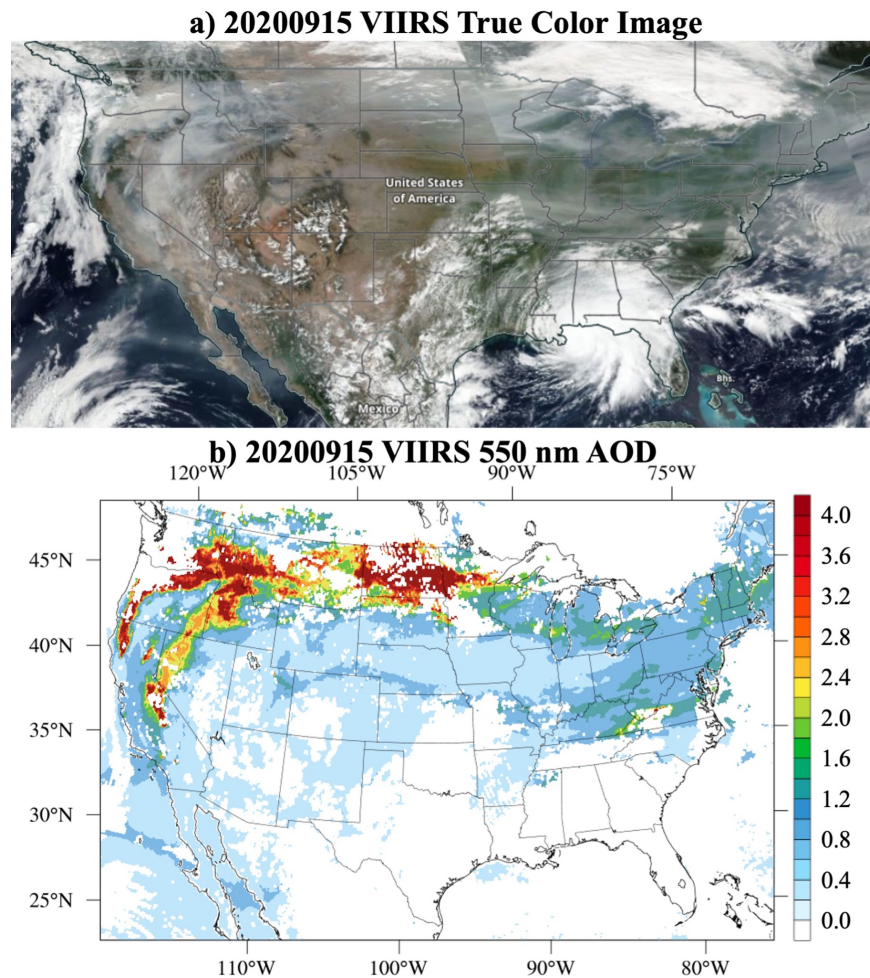


Figure 1. Observations of wildfire smoke on September 15, 2020, over the continental United States by the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi-NPP satellite: a) true color image and b) 550 nm aerosol optical depth (AOD).

*The following sentence has been changed to make it clear in line 96:
 “caused hazy days (indicated by the high AOD region) in 19 states (Figure 1).”*

Figure 2: What is the data source of this figure and pie chart in the figure. The authors should cite some papers on fire emission chemistry (currently there are none) in the introductory paragraph (line 95-105) of experiment design. Below are a few examples:

Koppmann, R., von Czapiewski, K., and Reid, J. S.: A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds, *Atmos. Chem. Phys. Discuss.*, 5, 10455–10516, <https://doi.org/10.5194/acpd-5-10455-2005>, 2005.

Schlosser, J. S., Braun, R. A., Bradley, T., Dadashazar, H., MacDonald, A. B., Aldhaif, A. A., Aghdam, M. A., Mardi, A. H., Xian, P., and Sorooshian, A.: Analysis of aerosol composition data for western United States wildfires between 2005 and 2015: Dust emissions, chloride depletion, and most enhanced aerosol constituents, *J. Geophys. Res.-Atmos.*, 122, 8951–8966, <https://doi.org/10.1002/2017JD026547>, 2017.

Thank you for providing us with these papers. All are added to the main text and the reference list.

Line 145-146: To be more accurate, the vertical profiles of PM_{2.5} would match the “vertical profiles of backscatter” from CALIPSO.

Thanks for the comment. Line 177 has been changed to:

“the simulated PM_{2.5} vertical profiles in the West Coast and Central U.S. matched the vertical profiles of backscatter from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) ...”

Line 156-157: Not a complete sentence.

Thanks for the comment. Line 244 has been changed to:

“The main focus of this study is to evaluate the impact of different plume injection heights on the near source and downwind air quality, and the two-month average state is more important to our results and future health studies.”

Line 183: “70°” instead of “70”.

Thanks for the comment. “70” has been changed to “70°”.

Line 232: “...which include nitrate formation from both wildfires and anthropogenic emission”. This is confusing. I would expect no anthropogenic influence, as “the impact of other PM_{2.5} sources was removed by subtracting the results of NoFire run” from line 224.

Thanks for the comment. The part about “anthropogenic emission” is removed. Line 354 has been changed to:

“A higher portion of NO₃ in the downwind region than in the source region reflects the decreased contribution of primary aerosols, and increases in secondary aerosols.”

It may be worth labeling the longitudes on the upper x axis on the geographical plots (e.g. at least Figure 1), so that readers would know the projection of the maps and where the division lines lie between the regions. This information is currently not straight forward. An alternative is to plot the division lines on the maps.

Thanks for the comment. The longitudes on the upper x-axis are added to all maps.

Line 298-299: “The consumption of NO₂ is slowed down so that the NO₂ concentration is higher in the high AOD area.” I think you meant “so” instead of “so that”.

The discussion related to NO₂ is deleted.

Line 271: You could consider updating the subsection title to include the impact of plume rise on photochemistry besides AOD.

Thank you for the comment. The subsection title has been updated:

“3.3 Impact of estimated plume rise on aerosol optical depth and photochemistry”

Line 321-325: The description of color scales is already included in the figure caption, which is the right place. It is redundant here in the text.

Thanks for the comment. They are deleted in the text.

Figure 8: It would be helpful if a plot of the average surface PM_{2.5} from B69 overlaid with AirNow measurement is provided, as the difference plots here are based on B69 surface PM_{2.5}. Also the addition of AirNow would provide some kind of evaluation for the model.

Thanks for the comment. We added the plot of the average surface PM_{2.5} from B69 overlaid with AirNow measurements to Figure 9 (old Figure 8):

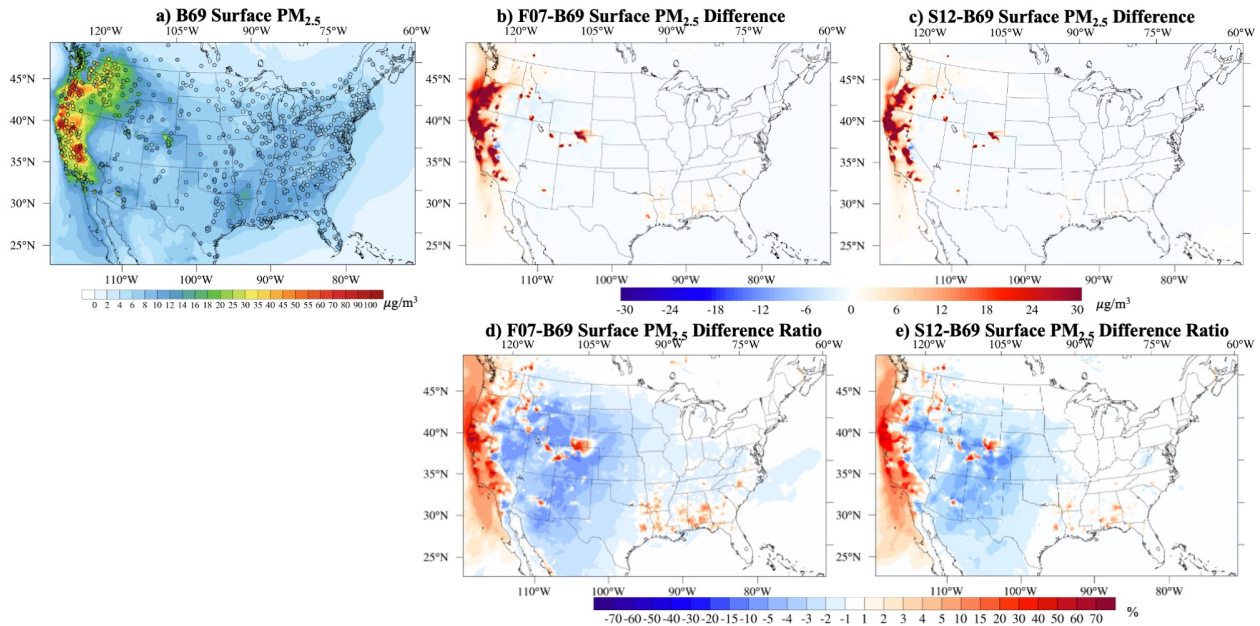


Figure 9: Simulated and observed surface PM_{2.5} from August 1st, 2020, to September 30th, 2020: a) average surface PM_{2.5} simulated with B69 overlaid by AirNow observations; b) difference in averaged surface PM_{2.5} between F07 and B69; c) difference between S12 and B69; d) and e) same as b) and c), but for the differences in percentage (%) between F07 and B69, and between S12 and B69, respectively.