Atmos. Chem. Phys. Discuss., 13, C929–C950, 2013
www.atmos-chem-phys-discuss.net/13/C929/2013/

Atmospheric Chemistry and Physics Discussions

Interactive comment on "Combustion efficiency and emission factors for US wildfires" *by* S. P. Urbanski

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Received and published: 4 April 2013

Response to Referee #1

We would like to thank all three referees for their constructive comments and suggestions. The referees' comments and suggestions have greatly improved our manuscript. We truly appreciate the effort that all three referees invested in reviewing our manuscript. The original comments of referee #N are labeled RN.X and our response is labeled AN.X. We have proposed significant revisions to some sections of the manuscript. These significant revisions may respond to the comments of multiple referees and are provided as a supplement to this comment. The proposed significant revisions are labeled SR.Y and are ordered according to page and line number of the original manuscript. When one of the referee's comments has been addressed with significant revisions to the manuscript the relevant SR.Y are referenced.

Referee #1

Quite often variable phenomena are assigned average values in models. The average value may not occur for single events, but assigning a large group of events the average value should minimize error in scaled up applications. Wildfires are an important influence on the atmosphere for which average values are poorly characterized. In this work the author measures MCE (which can be used a predictor of emissions) for three wildfires. The number of samples per fire was very high, the data appear to be of excellent quality, and fires were often sampled on multiple days so the fire-average values are likely to be highly accurate within the limitations of the sampling strategy – chiefly that the fires burned for several months and also at night or produced some unlofted emissions. The paper is well-written and should be published after addressing a few general comments and few specific issues.

R1.1. Most importantly, the author should determine the scope of the paper, clarify that scope specifically at the outset, and then maintain that scope consistently throughout the paper. Normally it is safest to limit the scope to what was actually studied; in this case the emissions of three gases from three wildfires at high elevation in the mountains of Montana. If additional conclusions about some, specified subset of CONUS wildfires can be supported (which is highly likely), then that will also be very useful. In the western US alone, wildfires burn a variety of fuels including sagebrush, grass, pinion-pine/juniper, ponderosa pine, etc. and overall western wildfires fires likely burn over a wide range of MCE. Here based on three fires there is a narrow range of MCE, likely resulting from the small sample size. Most statements in the paper are well- qualified, but a few may be a bit too general. Some of the other general issues noted next are interactive with deciding on the scope.

A1.1. The scope of the paper has been narrowed and the revised scope is clearly presented in the abstract and the final paragraph of the Introduction. The revised scope of the paper is measurements of combustion efficiency and emission factors for CO2, CO, and CH4 for wildfire season fires in mixed conifer forests of the northern Rocky Mountains, US. We present our airborne emission measurements from 4 wildfire season forest fires in the Rocky Mountains, US. Our revision includes an expanded discussion of our measurement results (in response to Referee #3). We compare our emissions measurements (MCE and EFCO2, EFCO, EFCH4) with emission measurements of previous field studies of temperate forest fires. The MCE measured in our field study are used to estimate wildfire season forest fire EF for 5 additional species using previously published EF – MCE relationships. The EF estimates for wildfire season Rocky Mountain forest fires are compared with a recent review article and a national emissions inventory.

We propose changing the title of the paper to: Combustion efficiency and emission factors for wildfire season fires in mixed conifer forests of the northern Rocky Mountains, US

R1.2. Northern California wildfires were sampled during the ARCTAS campaign in 2008 and that should be recognized in some way. In particular, Hornbrook et al., (2011) provide MCE for 7 wildfires (0.91, 0.90, 0.915, 0.90, 0.88, 0.92, and 0.95 in order of date). Additional emissions info is likely recoverable from that paper, other companion papers, or the ARCTAS archive. For instance, plumes classified as "CARB-BB" in Hecobian et al., (2011) are said to be from California wildfires. Papers with emissions info are referenced within these papers, e.g. Singh et al., (2010). These data could potentially be integrated into an expanded analysis that addresses a broader range of wildfire types. Or if a more specific scope that excludes these fires is decided on, the main features of these fires just over the boundary of what the author addresses should be noted.

A1.2. We appreciate the referee mentioning the ARCTAS CARB-BB measurements, and even though we have narrowed the scope of our paper (from western US wildfires to wildfire season forest fires in the Rocky Mountains), the MCE reported in Hornbrook et al. (2011) are relevant to our study and have been included in our discussion. Using the DC-8 1-minute merge data and back trajectories from the ARCTAS data archive (http://www-air.larc.nasa.gov/cgi-bin/arcstat-c) and fire data (fire perimeters from the Monitoring Trends in Burn Severity Project (MTBS) (www.mtbs.gov), MODIS active fire detections, and daily burned area maps from the wildland fire emission inventory of Urbanski et. al (2011)) we attempted to identify the source fires or source regions of the 7 California wildfire plumes reported in Hornbrook et al (2011). We could only confidently associate 2 of the 7 California biomass burning plumes (plumes #12 and #18) with coherent source areas. Plume 18 (MCE=0.88, sampled on June 26) emissions clearly originated from the wide spread wildfires occurring in the mountains (northern Sierra Nevada, Klamath, southern Cascade, and Coastal mountains) on the northern end of the Central Valley. The fire data were combined with vegetation maps (Ruenfenacht et al., 2008) to estimate the ecosystems involved (by area) as 83% forest (52% California Mixed Conifer, 22% Western Oak, 9% other forest types) and 17% non-forest. Since fuel consumption (and hence emissions) are typically much higher for wildfires in forest compared to non-forests, the emissions in plume 18 were likely overwhelmingly from forests. The elevation of the source area averaged 1230 m a.m.s.l. (170 to 2280 m a.m.s.l.).

Back trajectories indicate the Basin Complex Fire was the main contributor to the biomass burning sampled in plume 12 (MCE = 0.91, sampled on June 18). Fire data and vegetation maps indicate the fuels involved were (by area) 40% forest (Western Oak) and 60% non-forest (mostly chaparral). We do not consider the fire we measured in our study to be a proxy for this fire / plume.

The segment of plume 39 (MCE = 0.95, July 15) that was intercepted in the northeastern end of the Central Valley (20:32 – 21:01 UTC) could have originated from several fires in the northeastern valley and foothills. However, MODIS active fire detections suggest the only fire active fire of these was the Humbolt Fire. Our analysis estimates the vegetation cover impacted by the Humbolt Fire was (by area) 73% non-forest (mostly pine woodland savanna and chaparral) and 27% Western Oak forest. Since we could not identify a likely source region for the eastern segment of Plume 39 (east of Sierra Nevada Mountains) we have not included this plume in our discussion. We were unable to identify a coherent source for 4 of the BB plumes (plumes 13, 14 (sampled June 20), 17, (sampled June 24), and 26 (sampled July 4)). The area burned in California during ARCTAS (Jun 15 – July 15, 2008) was 30% non-forest and 70% forest. Forest was 40% western oak, 23% California mixed conifer, and 10% ponderosa pine. Non-forest vegetation was primarily chaparral and oak woodland.

We have revised the manuscript by mentioning the California WF average MCE (0.91) reported by Hornbrook et al. (2011). We note that area burned in California during the ARCTAS experiment was 70% forest and 30% non-forest, but that it is difficult to attribute the emissions sampled in most of the plumes to a specific source area. We specifically discuss plumes 12 and 18 since the source area of the sampled emissions could be confidently identified as wildfires burning in western US forests. We use these observations to assess the applicability of our measurements and EF – MCE analysis to wildfire season forest fires outside of the Rocky Mountains. Specific revisions to the manuscript are: SR.7, SR.10

R1.3. Once a scope of the paper is determined, the significance of the subset of wildfires that the author elects to discuss should be estimated. For example, high elevation mountain wildfires similar to the ones sampled by the author can sometimes be a major part of area burned in the western US with the 1988 Yellowstone fires coming to mind as an example. On the other hand, a list of the largest wildfires in the US at (http://www.nifc.gov/fireInfo/fireInfo_stats_lgFires.html) implies that grass fires account for most or many of the largest wildfires in CONUS. It should also be made clear what resources are available and on what time scale (operational or how long after the fact) to identify whether a fire is wild or prescribed. The author is well-qualified to summarize this sort of thing and it would be a good addition to the paper for the interested reader.

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A1.3. The four fires sampled in our study burned forest dominated by Lodgepole Pine, Douglas-fir, Engelmann Spruce / Subalpine Fir. Non-forest cover was negligible for all of the fires sampled. We assessed the importance of different cover types in western US wildfires through a geospatial overlay of 2001-2010 Monitoring Trends in Burn Severity fire boundaries (MTBS, www.mtbs.gov) and a Remote Sensing Application Center / Forest Inventory Analysis forest map (Ruenfenacht et al., 2008). This analysis indicates that the forest types involved in our study accounted for about 19% of total area burned and about 43% of forest area burned by wildfires in the western US from 2001-2010. If the fires sampled in our study are representative of wildfire season fires in these forest types, and we believe they are, then our measurements may have important implications for western US wildland fire emission inventories. While we have narrowed the scope of our paper to wildfire season forest fires, we would like to address the role of wildfires in non-forest ecosystems. Our MTBS – RSAC/FIA based analysis indicates forests comprised only $\sim$ 44% of wildfire burned area in the western US from 2001- 2010. However, even though grass and shrubland cover types may account for a majority of burned area ($\sim$56%), wildfire emissions in the western US are dominated by forest fires. This is because the average fuel mass consumed per unit area burned for forests is $\sim$ 3 times that of non-forest fuels (Urbanski et al., 2011). We note that the two forest types involved in the Hornbrook et al. (2011) plumes 12 and 18, California mixed conifer and Western Oak, each accounted for 4% of total burned area (western US wildfires 20001 – 2010). See author response A1.2 for details. We have revised the manuscript to stress our measurements are directly applicable to wildfire season fires in mixed conifer forests of the Rocky Mountains, specifically Lodgepole Pine, Douglas-fir, and Fir/Spruce forests. We highlight the fact that these forest types are found not just in the Rocky Mountains, but also in the Cascade Mountains, and portions of the Sierra Nevada Mountains and the North Coast Ranges in California, and that these forest types comprised 19% of total burned area and 43% of forest burned area in the western US from 2001-2010. We state that our measurements may be generally applicable to wildifre season fires in these forest types throughout the west. We

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note that our measurements did not include Ponderosa Pine dominated forests which are an important ecosystem in the mountain west. The Introduction has also been revised to include a description of the wildfire season and prescribed burning practices in the western US. This description will help users of the EF data differentiate between wildfire season fires and prescribed fires outside of the wildfire season. Significant manuscript revision(s) addressing this comment are: SR.1, SR.2, SR.10

References: Ruefenacht, B, Finco, MV, Nelson, MD, Czaplewski, R, Helmer, EH, Blackard, JA, Holden, G R, Lister, AJ, Salajanu, D, Weyermann, D, and Winterberger, K (2008) Conterminous U.S. and Alaska forest type mapping using forest inventory and analysis data, Photogrammetric Engineering & Remote Sensing, 74, 1379-1388.

Urbanski, S. P., Hao, W. M. and Nordgren, B.: The wildland fire emission inventory: western United States emission estimates and an evaluation of uncertainty, Atmos. Chem. Phys., 11(24), 12973–13000, doi:10.5194/acp-11-12973-2011, 2011.

R1.4. It is not clear to me how to classify the ecosystem for the fires the author sampled, which interacts with both the scope and how emissions for additional species could be estimated. The wildfires (WF) sampled in this work consumed forest fuels at elevations of 1000-2650 m. The alpine tree line in Montana is at 2400-2700 m. Many ecologists classify high elevation forests in the Appalachians and Rocky Mountains as boreal ecosystems, although classification schemes vary depending on the goals of the scheme. From a species overlap (presence of picea often an indicator species for boreal forest), cold-climate leading to slow decomposition and accumulation of heavy fuels, and long fire-return intervals a “boreal” classification seems reasonable for the fires in this work. Further, the average MCE the author measured (0.883) is almost identical to the MCE recommended for boreal forest fires (0.882) in the A11 emission factor (EF) review used by the author. This suggests that one simple, reasonable way to estimate the EF of unmeasured species for the author’s fires could be to extract EF directly from the A11 boreal forest fire recommendations. This might produce as good or better recommendations than an EF vs. MCE equation. A related minor issue is that any comparison of "temperate" WF to temperate prescribed fires (PF) should ideally involve comparing WF and PF that occurred at the same latitude, elevation, and ecosystem. So for example the B11 southeastern prescribed fires should ideally be compared to wildfires at 35 degree latitude and sea level. Lastly on this topic, it could be useful to support the idea that ecosystem classification should consider altitude as well as latitude.

A1.4. To be employed in emissions modeling EF must be associated with a land cover type or a fuel classification which provides input to fire effects models used to simulate biomass combustion. Global emission models (e.g. Wiedinmyer et al., 2011; van der Werf et al., 2010) typically use generalized cover types (boreal forest, temperate forest, savanna, etc.) while regional emission models (e. g. Urbanski et al., 2011; Strand et al., 2012) often use more detailed maps of vegetation or fuels. We have revised the paper to classify the forests burned in our study as Northern Rockies mixed conifer forest. We have also revised the manuscript to describe the forest types involved (Lodgepole Pine, Douglas-fir, Engelmann Spruce/ Subalpine Fir) which allows emission modelers to apply our EF to these forests outside the Northern Rockies. Our revised Table 1 includes "Vegetation Involved as Percent of Burned Area". While we agree with Referee #1 that the forests studied in this work are more similar to boreal forests than conifer forests of the southeast US, we disagree that they could be classified as boreal. Boreal ecosystems are characterized by low frequency, stand replacing fires (long fire-return intervals). However the fires we studied did not occur in regions which can be narrowly defined as having long fire-return intervals. The Hammer Creek and Big Salmon Lake fires occurred in the Bob Marshall Wilderness of northwestern Montana. The fire regime of the Bob Marshall Wilderness has regions of both mixed severity fire regime - high to low frequency of return (25 to 150 year fire rotation) and stand replacing fire regime – low frequency of return and regions (120 to 350 year fire rotation) (Teske et al., 2012). The Hammer Creek Fire, which burned into previous burns (burns less than a decade old), was located in the South Fork Flathead drainage an area where Douglas-fir/Lodgepole Pine forests are maintained by mixed-severity fire regime (Arno

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et al., 2000). While dominant species in the Hammer Creek and Big Salmon Lake burn areas were Lodgepole Pine, Douglas-fir, and Engelmann spruce/ subalpine fir, Larch was an important species in both areas (Arno et al., 2000; Keane, 2013). The Hammer Creek fire included areas where Ponderosa Pine was an important species (Arno et al., 2000; Keane, 2013; Larson, 2013). The Saddle Complex was adjacent to Frank-Church River of No Return Wilderness and partially burned into the wilderness area. The Frank-Church River of No Return Wilderness has areas of low severity (high frequency, 4 to 84 year fire rotation), mixed severity (low to high frequency, 35 to 105 year rotation) and stand replacing (low-frequency, 40 to 200 year rotation)fire regime (Arno, 1980; Teske et al., 2012). Overall the fire regime of the Frank-Church River of No Return Wilderness is classified as mixed severity regime (Teske et al., 2012).

References: Arno, S. F., Parsons, D. J., and Keane, R. E.: Mixed-severity fire regimes in the Northern Rocky Mountains: consequences of fire exclusion and options for the future, in Wilderness science in a time of change conference-Volume 5: Wilderness ecosystems, threats, and management; 1999 May 23-27, comps.: Cole, D. N., McCool, S. F., Borrie, W. T., and O'Loughlin, J., 225-232, USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, available at: http://www.fs.fed.us/rm/pubs/rmrs_p015_5.html, 2000.

Keane, R. E.: Personal communication, US Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana, 2013.

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Strand, T. M. et al.: Analyses of BlueSky gateway PM2.5 predictions during the 2007 southern and 2008 northern California fires, J. Geeophys. Res., 117, D17301, doi:10.1029/2012JD017627, 2012.

Teske, C. C., Seielstad, C. A., and Queen, L. P.: Characterizing fire-on-fire interactions in three large wilderness areas, Fire Ecology, 8, 82-89,

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Urbanski, S. P., Hao, W. M. and Nordgren, B.: The wildland fire emission inventory: western United States emission estimates and an evaluation of uncertainty, Atmos. Chem. Phys., 11(24), 12973–13000, doi:10.5194/acp-11-12973-2011, 2011.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10(23), 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J. and Soja, A. J.: The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning, Geoscientific Model Development, 4(3), 625–641, doi:10.5194/gmd-4-625-2011, 2011.

R1.5 Further, the average MCE the author measured (0.883) is almost identical to the MCE recommended for boreal forest fires (0.882) in the A11 emission factor (EF) review used by the author. This suggests that one simple, reasonable way to estimate the EF of unmeasured species for the author's fires could be to extract EF directly from the A11 boreal forest fire recommendations. This might produce as good or better recommendations than an EF vs MCE equation.

A1.5 This comment is closely related to comment 7 and we include our response to R1.5 in A1.7.

R1.6. A related minor issue is that any comparison of "temperate" WF to temperate prescribed fires (PF) should ideally involve comparing WF and PF that occurred at the same latitude, elevation, and ecosystem. So for example the B11 southeastern prescribed fires should ideally be compared to wildfires at 35 degree latitude and sea level. Lastly on this topic, it could be useful to support the idea that ecosystem classification

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should consider altitude as well as latitude.

A1.6. Our discussion/comparison does include prescribed fires from similar latitude/elevation/ecosystem. We believe our comparison vs. other temperate forest prescribed fire data is important to include since widely used EF reviews (Akagi et al., 2011; Andrea and Merlet, 2001) have grouped EF data from a wide range of latitude/elevation/ecosystem.

R1.7. More on estimating EF for unmeasured species. This can only be a rough estimate by any method, but it's a valuable addition that should be included by some method. However, I was not sure the estimation method used was optimal or that the likely error was clear. The author uses EF vs MCE equations from the B11 reference to predict EF not measured in his study. These two studies can be directly compared for CH4. The authors EFCH4 vs MCE slope coefficient is -54 while the B11 study had a slope coefficient of -pl96(10) for CH4. A variety of papers displaying this type of regression data for CH4 are easily found. The Yokelson et al., (1996) lab study shows air, tower, and lab experiments all yielding slopes near -52. McMeeking et al. (2009) give a slope of -37. The B10 lab study is slope is -49. The Akagi et al., (2013) field measurement slope is - 65. The Urbanski et al., (2009) field data gives slopes in the -30 to -70 range. So it's not clear to me that it is easy to choose a-priori which study to base predictions on – or if the predictions of several studies are useful, which would likely imply a higher uncertainty. The ARCTAS study may provide some insight into this. Two other factors affect the uncertainty of the current predictions based on the B11 equations. (1) Other than CH4 and CH3OH the B11 equations were not that highly correlated. (2) Several studies show low correlation for EF vs MCE measured in burning duff or dead, down woody debris (here-in "heavy fuels") (Bertschi et al., 2003; B11, Akagi et al., 2013). Some of these additional sources of error are acknowledged on page 45 and elsewhere, but don't seem to be formally incorporated into an error estimate. This overly lengthy comment isn't meant to argue against the author's estimates, but point out the high uncertainty, which should be clear.

In light of that, perhaps some conclusions should be tempered or qualified. Given the qualitative nature of these estimates a complex prediction step may be un-needed if using A11 boreal EF, but the complex approach may yield additional insight and be worth retaining.

A1.7. We agree that using EF – MCE relationships to estimate EF for unmeasured species provides only a rough estimate. The reviewer suggests alternatives for estimating the EF of unmeasured species. One suggestion is to use the boreal fire EF from the Akagi et al. 2011 (A11) as an estimate for EF not measured in our study (the reviewer notes the similarity in MCE between A11 (MCE = 0.882) and our measurements (MCE=0.883)). The reviewer suggests that if we choose to use an EF – MCE approach for estimating unmeasured EF that we consider including additional studies to provide a better representation of the uncertainty involved in this approach. We have revised the paper to employ a less complex approach for estimating EFPM2.5. We use airborne EF measurements from wildfires and prescribed fires in mixed conifer forests of the northwestern US: Radke et al., 1991 (R19) and Hobbs et al., 1996 (H96) and the Burling et al. (2011) (B11) results for their 2 Sierra Nevada fires. R91 and H96 reported EFPM3.5; however, since coarse mode particles (2.5 – 10 μm diameter) typically account for only ~10% of the mass fraction of fresh smoke particles (Reid et al., 2005), EFPM3.5 will not be significantly different from EFPM2.5. These nine fires have an average MCE of 0.888 which is very close to that measured in our study (MCE=0.883). Their average EFCH4 (8.2) is also in good agreement with the EFCH4 measured in our study (7.3) differing by only 11%. The average EFPM2.5 for these nine fires is 23.2 $\pm$ 10.4 (uncertainty 1 standard deviation) and we adopt this as our best estimate of EFPM2.5 for the fires we measured and more generally for wildfire season fires in mixed conifer forest of the northwestern US. We also considered alternate estimates based on EFPM2.5 vs. MCE regression approaches from the airborne NW fires and other field studies of mixed conifer forests (uncertainties are 95% confidence intervals): Airborne NW fires (n=9): EFPM2.5 = 213.9 -214.7 x MCE, R2=0.62, EFPM2.5 (@ MCE = 0883) = 24.3 $\pm$ 10.8

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Airborne NW fires and tower based NW fires from Urbanski (2009) (n=18): EFPM2.5 = 223.3 – 226.7 x MCE, R2 = 0.61, EFPM2.5 (@ MCE = 0.883) =23.4±6.4

Airborne NW fires and tower based NW and SW fires from Urbanski (2009) (n=25): EFPM2.5 = 226.9 – 230.5 x MCE, R2 = 0.58, EFPM2.5 (@ MCE = 0.883) = 23.3 ± 5.3. The mean MCE of these fires = 0.905.

All airborne of B11 with R91 and H96 (n = 15): EFPM2.5 = 212.2 – 212.6 x MCE, R2 = 0.69, EFPM2.5 (@ MCE = 0.883) = 24.5 ± 8.7. The mean MCE of these fires = 0.912.

All B11, R91 and H96, and all U09 (n = 50): EFPM2.5 = 201.5 – 202.4 x MCE, R2 = 0.62, EFPM2.5 (@ MCE = 0.883) = 23.2 ± 4.3. The mean MCE of these fires = 0.919.

Neither Akagi et al. (2013) or Hornbrook et al., (2011) report EFPM2.5.

The expanded EFPM2.5 vs. MCE analysis is discussed in our revised paper and the fit statistics and plots are provided in a supplement. We believe the revised analysis provides a better representation of the uncertainty involved in our estimate of EFPM2.5 for wildfire season fires in mixed conifer forest of the western US. We note that the EFPM25 estimated in the original manuscript using the EFPM25 vs. MCE regression equation from B11 produced similar results (EFPM25 = 25.8 ± 9.3). The combined northwestern EFPM2.5 measurements of R91, H96, and B11 (Shaver and Turtle fires) provide a sample of fires with average MCE similar to that measured in our study. The average EFPM2.5 of these fires is in good agreement with estimates based EFPM2.5 vs. MCE relationships from multiple datasets airborne and tower based EFPM2.5 for fires in mixed conifer forests of the US. This gives us confidence that our EFPM2.5 estimate is reasonable and probably within ±50% of the true value for a given wildfire season fire in western US mixed conifer forest. Unfortunately, H96 does not have measurements of NMOC and R91 does not include oxygenated NOMC. Therefore we used the combined airborne and tower based field datasets of emissions from fires in mixed conifer forest in the western and southeastern US (B11, Akagi et al. 2013, U09, and R91) and used EF – MCE regressions to derive rough estimates of EF at

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our study average MCE for C2H6, C3H6, CH3OH, and HCHO. We only include EF estimates for these compounds since we consider the EF – MCE correlation of the remaining compounds too low (R2 < 0.6). Fit statistics and plots are provided in a supplement. We did not use the A11 boreal forest EF as estimates our work for the following reasons:

The A11 boreal EF are a combination of airborne measurements of prescribed and wildfires in boreal forests and laboratory measurements of emissions from forest floor fuels (boreal organic soil, boreal Alaskan duff, and boreal peat) and coarse woody debris. A11 use a 50/50 average of the lab and airborne EF measurements (when both are available) as their best estimate EF (Table 1 of A11).

It is uncertain how well lab studies replicate fuel arrangement of the natural environment. How well does 'pure smoldering' combustion in the lab simulate smoldering combustion in the natural environment? The lab fires measured emissions from an isolated smoldering chunk of duff/soil/peat, log or stump while in the natural environment these fuels burn within a fuel bed.

Uncertainties regarding lab measurements of PM2.5 – Extrapolation of lab measured particulate EF to fires in the natural environment is highly uncertain given potential differences in in the condensation rates of SVOC (and possibly inorganics) due to differential cooling dilution/cooling environments experienced by emissions in the lab and in a naturals setting (Yokelson et al., 2013; A11).

Weighting of smoldering combustion – the weighting of fuel components in their estimation of smoldering combustion does not seem appropriate for mixed conifer forest of the western US. The A11 weighting of duff/organic soil/peat to coarse dead wood was 4:1. This likely is too heavily weighted towards forest floor for boreal forests and almost certainly so for the forests considered in our study. Recent field measurements of fuel consumption for 4 wildfires that occurred in mixed conifer forest of the northern Rockies found the ratio of duff consumed to CWD consumed was 1.4 (Karau and Keane, 2010;

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Karau, 2013 – detailed fuel consumption data was obtained directly from E. Karau).

Emissions from smoldering of duff and CWD are likely different (as noted by the reviewer) and evident from A11 Table S2. The duff/CWD weighting used by A11 to produce estimates boreal forest EF in Table 2 are not likely appropriate for the forests in our study and therefore are we do not consider these EF the best proxy for our fires.

Summary of Revisions: Given the similarity in MCE and forest types we have used the mean EFPM2.5 of the airborne EF measurements from wildfires and prescribed fires in mixed conifer forests of the northwestern US: Radke et al., 1991 (R19) and Hobbs et al., 1996 (H96) and the Burling et al. (2011) (B11) results for their 2 Sierra Nevada fires as a rough estimate of EFPM2.5 for the wildfire season fires measured in our study. We derive rough estimates of EF for C2H6, C3H6, CH3OH, and HCHO at our wildfire season MCE of 0.883 using data combined airborne and tower based field datasets of emissions from fires in mixed conifer forest in the western and southeastern US (B11, Akagi et al. 2013, U09, and R91). The EF – MCE regression statistics and plots of EF vs. MCE have been included in a Supplement. We have revised Table 3 to include EF for only CO2, CO, CH4, PM2.5, C2H6, C3H6, HCHO, and CH3OH. Our revised Table 3 includes the boreal forest EF from A11.

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

Karau, E. C.: Personal communication, US Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana, 2013.

Karau, E. C. and Keane, R. E.: Burn severity mapping using simulation modeling and satellite imagery, Int. J. Wildland Fire, 19, 710-724.

R1.8. P35, L1: trivial, but if there is another adjective besides “heavy” to describe an amount of fuel then “heavy” can be reserved to describe a type of fuel.

A1.8. Throughout the manuscript we have decided to use “coarse fuels” when referring to the CWD and duff rather than use “heavy”. We have replaced heavy fuel fraction (HFF) with coarse fuel fraction (CFF). “heavy” has been reserved to refer to the amount (loading) of fuels or a fuel type.

R1.9. P35, L24: I get the author’s point, but “failure” seems a bit strong when discussing wildfires in general since the study so far deals with a subset of wildfires.

A1.9. The abstract has been significantly modified at the urging of Referee #3. The revised abstract has significantly softened our claims regarding the implications of our study. Significant manuscript revision(s) addressing this comment are: SR.1

R1.10. P37, L1: Clarify that these estimates of WF contributions are before adjusting EFPM based on the author’s findings in this work?

A1.10. Yes, these WF contributions are based on EFPM2.5 and EFCO published prior to this study. To clarify we have revised the text as: “Recent emission estimates published prior to this study suggest that wildland fires account for a sizeable fraction of the annual total PM2.5 and CO emissions in the western US (as much as 39% and 20%, respectively)(Urbanski et al., 2011). Because wildfire emissions are episodic and highly concentrated both temporally and spatially (Urbanski et al., 2011), such annualized comparisons may greatly understate the potential impact of the wildfires on the day time scale that is pertinent to air quality forecasting and management.” This revised text is included in SR.2.

R1.11. P40, L8: Should the year be 2011? A1.11. Yes. The year has been corrected to “2011”. The revision is included in SR3.

R1.12. P42, L9: add “of” after “measurement” A1.12. We have added “of” after “measurement”

R1.13. P46, L28: add uncertainties? A1.13. We have added uncertainties. The

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revisions are included in SR.5.

R1.14. Section 3.2: Two things might be clarified here: (1) Does the fuel based analysis suggest that WF without heavy fuels would have EF similar to temperate PF? (2) Possibly cite a database that gives the amount of heavy fuels for the western US?

A1.14. We believe the referee's points are best addressed in Sect 3.4 and we have revised Sect. 3.4 to do so. The fuels based analysis suggests that wildfires or wildfire season prescribed fires burning in forests without significant loadings of coarse woody debris or duff would have EF similar to those of typical TF prescribed fires (e.g. Burling et al., 2011; TF recommendations of A11 and A&M 01). The presence of significant loadings coarse woody debris and/or duff and conditions which promote the consumption of these fuels, in particular low fuel moisture, lead to relatively low MCE. We have revised Sect. 3.4 to better emphasize this point. There are two published fuel classifications that may be used to estimate CWD and duff fuel loading for western US forests, the Fuel Characteristics Classification Systems (Ottmar et al., 2007) and the Fuel Loading Models (Lutes et al., 2009) as well as the reference database in the First Order Fire Effects Model (FOFEM 6, 2012). In our revision we refer readers to these sources. We note here that a paper currently under review (Keane et al., 2013; I am a co-author) used fuel loading data from ∼14,000 USFS Forest Inventory and Analysis (FIA) plots to develop a new fuel classification system and evaluate the accuracy of the FCCS and FLM fuel models. Once published this will be an excellent source for western US forest fuel loading data.

R1.15. P52, L10: In light of the limitations of this study and the ARCTAS data, I recommend inserting "some" before "western wildfires." Caveats do appear below on same page, but the implications are too general here. This is an example of how maintaining a consistent scope for the paper will clarify its message.

A1.15. We have significantly revised this part of Discussion Sect. 3.3 (P52, L10 – P53, L2). The revision specifies our measurements cover only some mixed conifer forests of

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the western US and we have removed the generalizations of the original manuscript. The revision stresses that our measurements are directly applicable to wildfire season fires in mixed conifer forests of the Rocky Mountains, specifically Lodgepole Pine, Douglas-fir, and Fir/Spruce forests. We note that these forest types are found not just in the Rocky Mountains, but also in the Cascade Mountains, and portions of the Sierra Nevada Mountains and the North Coast Ranges in California. We state that our measurements may be applicable to these forest types throughout the west. We note that our measurements did not include Ponderosa Pine dominated forests which are an important ecosystem in the Rocky Mountains. Significant manuscript revision(s) addressing this comment are: SR.10

R1.16. P52, L25: text is "the failure to use wildfire appropriate EFPM2.5 has significant implications for the forecasting and management of regional air quality. The contribution of wildfires to NAAQS PM2.5 and Regional Haze may be underestimated by air regulatory agencies. This is especially true considering . . ." Again "failure" and "especially true" seem a bit strong, because when more WF of other types are measured it could turn out that the current values are not the biggest source of error at least for some fires. Interesting forecasting-related questions that the author could potentially summarize at this point include: how does uncertainty in WF EFPM compare to uncertainty in forecasting WF size, or the possible error from using average values for a specific event, etc?

A1.16. We have revised the manuscript to scale back the original claims regarding the broad applicability of our measurements to "western US wildfires" (see response A1.15). We have added paragraph discussing the other sources of uncertainty in emission modeling and emission inventories: "Emission factors are not the only source of uncertainty in emission inventories. Biomass burning emission models typically estimate emissions as the product of area burned, fuel load, combustion completeness, and EF (Urbanski et al., 2011; Wiedinmyer et al., 2011; van der Werf et. al. 2010; Larkin et al., 2009). The contribution of these components to uncertainty in emission estimates is not equal and varies with spatial and temporal scale (Urbanski et al., 2011). In general, fuel loading is considered to be the greatest uncertainty in emission estimates (Urbanski et al., 2011; French et al., 2011). The impact of biomass burning emissions on air quality depends not only on emissions but also on plume rise, transport, and chemistry, all of which introduce additional uncertainty (Goodrick et al., 2013; Achtemeier et al., 2011)." The revisions are included in SR.10.

R1.17. P53, L19: The lab finding that "MCE tend to increase with decreasing fuel moisture" seems inconsistent with author's analysis and with the findings of others (next comment).

A.1.17. We do not believe the lab results are necessarily inconsistent with our analysis or the findings of others (e.g. Akagi et al., 2011). The lab studies we cite observed an MCE – fuel moisture relationship for homogeneous fuel beds, which we didn't clarify. The studies also focused on fine fuels. Our analysis (and that of Akagi et al., 2011) pertains to the heterogeneous fuels found in the natural environment. Even if the MCE of fine fuels is higher during the wildfire season compared to a spring/fall prescribed burn, the amount of fine fuel consumed will be similar. Increased emissions from the increased consumption of CWD & duff, which burns with a lower MCE than fine fuels, could easily offset the MCE gain due to drier fine fuels. This is the scenario we layout P53, L25 – P 54, L17. To clarify that the lab studies which reported MCE – fuel moisture link focused on homogenous fine fuels we have revised the text at P53, L18-21 as follows: "In addition to fuel geometry and arrangement, recent laboratory studies suggest a linkage between fuel moisture and MCE, with MCE tending to increase with decreasing fuel moisture for a homogeneous fine fuels of constant fuel type and fuel mass (Chen et al., 2010b; McMeeking et al., 2009)."

R1.18. P54, L1: Akagi et al., (2011) discuss literature fuel consumption data from Africa that suggest that more of the large-diameter fuels burn late in the dry season. I think this assumption is also built into the latest version of GFED. Since heavy fuels tend to burn with lower MCE then the drying of the heavy fuels should lower MCE as the author argues.

A1.18 This the scenario we layout P53, L25 – P 54, L17 to explain the lower MCE observed for forest fires during the wildfire season.

R1.19. P56, L12: Heavy fuel loading, moisture (and geometry) is widely accepted as a driver of emissions variability; but it is one of many factors, which the author does seem to clarify on P57, L28.

A1.19. We have revised the text at P56, L12 to clarify that the consumption of heavy fuels is likely one of the factors responsible for the MCE differences between typical prescribe fires and wildfire season fires: "Nonetheless, the analysis identifies relative CWD and duff consumption as a driver of fire average MCE and a likely factor behind the differences in MCE measured for temperate forest fires."

R1.20. Section 3.4 summary comment: This section contains a lot of good information, points out that heavy fuels impact emissions, and Figure 5 relates PF MCE to heavy fuel fraction. It's possible that the purpose or applications of the section could be clarified a bit more in a focused way. There are limitations to predicting emissions based on the heavy fuel fraction since the "non-heavy" understory and canopy fuels could impact WF emissions differently. Also duff and logs are lumped together in the heavy fuel category when they may contribute differently to emissions under some circumstances (Bertschi et al., 2003, Fig 5, B11 Fig 5). In general the emissions from these "heavy fuels seem less tightly correlated with MCE suggesting a high degree of uncertainty in predictions based on this approach as the above papers note. Overall this section is interesting, but speculative and based on limited data at the moment. It's not clear if the author is proposing an application for the results of this section. It's interesting that in this work the author assumes that WF are essentially low MCE PF for purposes of predicting emissions, but also stresses throughout the text how different WF are from PF in terms of more heavy fuel, different weather conditions, etc. Perhaps the overall message is that PF are a good proxy for WF, but only with

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appropriate caution?

A1.20.We did not intend that the data or analysis of this section be used for the prediction of MCE. As the referee notes, there are many other factors that influence the combustion process and emissions. We have changed the text at P56, L10 to emphasize this point: "For these reasons we stress that these fuel consumption data and the analysis are not intended to be applied for predicting MCE." Regarding the referee's comment on WF vs. PF; we have clarified the focus of our paper as "wildfire season forest fires" as opposed to simply "wildfires". We argue that the low MCE measured in our study is partly due to the presence of ample CWD / duff and weather conditions (primarily fuel moisture) that promote the consumption of these fuels. Weather conditions favorable for significant consumption of CWD & duff are typical of the wildfire season. In the western US, most prescribed burning is conducted in the spring or fall, outside the wildfire season when conditions do not favor appreciable consumption of CWD & duff. (We have revised the Introduction (revision SR1) to emphasize this point). One of the 4 fires we sampled, the North Fork Fire, was a wildfire season PF in an area with high loadings of dead wood. The MCE of this fire was similar to the 3 wildfires. Also, the Shaver PF reported by Burling et al (2011) occurred in an area with very high loadings of down dead wood and was conducted in early November when CWD fuel moistures were fairly low (18%) (P55, L 8 - L16). The MCE of the Shaver Fire was roughly the same as our wildfire season average (0.885 vs. 0.883). So, yes some PF are a good proxy for WF. However, much of the published emissions data for temperate forest fires is based on PF that burned under conditions that were not representative of the fires we studied.

R1.21. Table 3: title needs a little work. A1.21. Table 3 has been revised and the title improved to: "MCE and EF for this work, A11 (temperate forest (TF) and boreal forest (BF)), and NEI and the ratio of EF from this work to EF from A11 and NEI."

R1.22. Figure 5: If available some x-y error bars would be interesting. A1.22. Unfortunately we do not have reasonable uncertainty estimates for most of the fuel consump-

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tion measurements.

R1.23. Main suggestions summarized: 1. Maintain one consistent level of specificity on the scope through-out the text. As it is more general statements are common early on, followed by caveats later. 2. Add an estimate to the text of what percent of CONUS wildfires are being discussed in the paper (it's likely significant) and make the title more specific (e.g. at least add "projected" before "emission factors" and "some western" before "US", which may be better as CONUS). 3. Mention briefly any resources or common sense guidelines available to interested modelers that would allow them to distinguish wild and prescribed fires on a routine operational basis. E.g. I suspect there are very few if any PF in western US during summer. 4. Use the A11 boreal wildfire EF as one or the only method to estimate the missing EF for the authors WF in Table 3. 5. If EF vs MCE based predictions are retained use (or discuss the impact of using) a larger selection of the available data: e.g. ARCTAS, Urbanski et al., (2009), Akagi et al., (2013), etc to get a better feel for the uncertainty in the predictions.

A1.23. These suggestions have been fully addressed in response to R1.1. – R.1.22.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/13/C929/2013/acpd-13-C929-2013-supplement.pdf

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