Response to Reviewer #1 Comments (Bob Yokelson)

The authors monitored three stable trace gases (CO2, CO, and CH4) that were emitted by fires located upwind of a tower in Alaska. They derived emission ratios and emission factors for two of the gases (not sure why EFCO2 was not reported?). The study sampled smoke, when present, 24/7 for a whole fire season so it has a big effective sample size compared to individual past studies. It was also sensitive to examples of much, if not most, of the lifecycle of the upwind fires with exceptions including e.g. intense combustion episodes that lead to free-troposphere injection and long-range transport. In theory, the most important use of this tower data is to test model predictions of smoke production and transport for the stable species measured. This is discussed a little and could be very valuable for future model evaluation in other papers. The work is new, very valuable, and should definitely be published with minor revisions as summarized next and also pointed out in the specific comments.

Response: We are grateful to Dr. Yokelson for providing additional detailed and valuable feedback on our manuscript. His suggestions have considerably improved the paper. We now mention in the conclusions the potential value of the tower data to test model predictions of smoke emissions and transport for CO, CO_2, and CH_4.

General Comments

The study has some weaknesses, which need to be recognized in a more balanced discussion. In no particular order:

Response: We completely revised the discussion to address these reviewer comments.

1. Towers can only monitor upwind fires limiting the range of sampling.

   We now include a paragraph in the discussion discussing the limits of ground-based sampling with towers. We make this point in that new paragraph.

2. Any ground-based site may have some bias to smoldering or miss the type of emissions subject to long-range transport in the free troposphere. This is a difficult topic to achieve certainty on.

   We agree and recognize this in the discussion paragraph by describing the limits to ground based sampling. We also acknowledge this in the revised conclusions. In the revised discussion, we also provide arguments that the CRV tower is not highly sensitive to this type of bias, because it is at a higher elevation than most of the fires and far downwind. We also now make the point to the reader that analysis of MISR satellite observation suggest most (but not all) fire plumes reside within the PBL in boreal North America, again suggesting the CRV tower measurements can provide representative estimates.

3. The uncertainty in the background at the tower is pretty large compared to the observed enhancements (in 2015) when far downwind and so the tower-based approach may only work in near-record fire years whose representativeness is unknown.

   We agree and make this point now in the discussion paragraph describing the limits of ground-based sampling.

4. The initial emissions can only be measured for a few stable species but the vast majority of interesting fire products are reactive.

We agree and make this point now in the first paragraph in the discussion (final sentence).

In summary, we added the following paragraph in the discussion to address many of these reviewer concerns:

"In the context of these comparisons among ecoregions and sampling strategies, it is important to recognize that tower-based sampling strategies, including the methodology presented in this study, have important limits. Ground-based sites may potentially miss some of the emissions injected above the planetary boundary layer which are subject to long-range transport in the free troposphere. The fixed nature of this sampling technique also restricts the range of sampling, because towers can only monitor upwind fires. Although the tower-based sampling strategy allows for integration of emissions from fires across a range of environmental conditions and at different stages of fire life cycles, it does not allow for emission ratio measurements of non-conserved species, including particulate matter and many fire-emitted volatile organic compounds that have short lifetimes. The technique is also subject to higher uncertainty in the definition of background mole fractions for fire-affected trace gases, because of the dilution and mixing of fire emissions that occurs during transport, and thus may not be a feasible sampling methodology during years with low fire activity. "

The current discussion is written as if the authors discovered potential sampling biases specific to geographic regions and platforms that have already been major concerns in mainstream thinking for decades. At the same time, they fail to emphasize the exciting finding, which is that past attempts to overcome the limitations of any one sampling platform appear to have worked pretty well according to the perspective provided by this novel, unique study. In other words, past compilations averaged together the results from multiple platforms in an attempt to overcome the limitations of using just airborne, ground-based, or lab data. The results in these compilations are virtually indistinguishable from the authors results for the two species they report, which is pretty remarkable. It inspires more confidence in the previous recommendations for countless other species reported in those compilations, which is good news from a fresh perspective.

Response: We have fully revised the discussion, carefully considering these reviewer points. The first paragraph of the revised discussion highlights the agreement of our measurements with past studies and the validation these measurements provide for non-conserved species that cannot be measured with a tower-based sampling approach.

The authors miss the mark by instead dwelling on air/ground differences, which are worth pointing out, but were already well-known. I think the authors deserve credit for recognizing the unique opportunity they had to evaluate past recommendations, but mistakenly focus their discussion on the limitations of a subset of previous work. The value of validating previous recommendations is huge because past work was actually vastly more complete chemically and probed many other fire seasons and geographic areas. Imagine the millions of dollars it would cost to outfit a tower with instrumentation similar to that on the NASA DC-8 for just one summer and then maybe have a year like 2012 with no smoke or only downwind fires!

Response: We have considerably revised our discussion with this reviewer concern in mind. Again, we note that we emphasize the agreement between our measurements and the mean reported in past syntheses in the first paragraph of our discussion. We specifically note the point that this validation is important because it confirms estimates made for short-lived species that cannot be measured by a remote tower-sampling approach.

However, we have not previously seen a breakdown and synthesis of ground-based versus aircraft-based sampling approaches for northern boreal forests. While we make it clear in the revised text that its been well appreciated in the literature for quite some time that aircraft-based and ground-based sampling approaches are known to yield different outcomes, ***the magnitude of these differences and comparison with our new***

measurements is a new finding that we think is important for readers, and advances the field. We are more careful in our comparisons in the revised discussion, making it clear our measurements have a mean that is 39% higher than the mean solely derived from aircraft sampling in North America. We also show that emission ratios for Eurasian forests are quite a bit higher than those from North America. We also more forcefully make the case for why our remote tower-based sampling approach is likely to yield a more representative estimate of emission ratios than one might expect in other places.

In addition, the study makes speculative, unsupported tangential claims about the particles from boreal fires despite the lack of any PM data. Despite validating previous recommendations, it is guessed that EFPM, and therefore health and climate effects, might be underestimated in models. However, the authors a) did not sample PM, b) may not have sampled the type of combustion that leads to long-range transport and wider impacts, c) did not consider secondary aerosol processes such as evaporation (see detailed comments), and d) fail to recognize that a PM network is in place that constrains the amount of PM in populated areas.

Response: We have removed this paragraph and discussion of implications for PM and organic aerosols, following the reviewer's suggestion.

A brief warning, compared to other journals, ACP has pretty lax quality control and rarely sends papers back to the Referees for a second look. Thus the authors will be well advised to proofread future versions more carefully. There are typos that could be recycled or should have been caught by a spell-checker that I note along with other specific comments below by page and line number.

Response: We have carefully revised the manuscript following the reviewers detailed suggestions below, making changes for most (but not all) of the reviewer's specific comments. We have carefully spell-checked and proof read the revised manuscript.

Specific Comments (format is page, line number: "comment")

1, 18: example typo, see page 6, line 35 EFCH4 is 5.3+/-11.8

Response: We apologize for the typo and have corrected it. The mean and standard deviation for the CH4 emission factor should be 5.3 ± 1.8.

1,22-24: How does smoke age impact sampling times? I.e. can't you measure 24/7 from anywhere?

Response: We modified the sentence to make it clear we are describing the transit times between combustion within a fire perimeter and downwind measurement at the tower. We describe carefully in the main text what we mean by transit times. The new sentence reads: "The model also indicated that typical mean transit times between trace gas emission within a fire perimeter and tower measurement were 1-3 days, indicating that the time series sampled combustion across day and night burning phases (Figure 3)."

1, 24: high compared to what? not recommendations. How does "variable" inform a comparison? delete "high and variable"

Response: We deleted "variable" from the sentence. We retained "high" because this is a major point of our analysis and paper, that emission factors from our tower observations are higher than the mean of past aircraft sampling from boreal North America.

1, 25: more prominent than what? Keep "prominent", delete "more", "continuously" > "continuous"

Response: We agree with the reviewer and have removed "more" and changed "continuously" to "continuous." The new sentence reads: "The high CO emission ratio estimates reported here provide evidence for a prominent role of smoldering combustion, and illustrate the importance of continuously sampling fires across time-varying environmental conditions that are representative of a range of fire season."

1, 26: change "typical" to "a range of" since 2015 not a typical year according to authors.

Response: As noted in the response above, we changed "typical" to "a range of".

1, 29: could add albedo and aerosol for completeness of overview here

Response: We added aerosols to this first sentence, following the reviewer's suggestion. The Johnson book we cite is a classic and we wanted to open the paper with this reference. However, this book does not describe the complex relationship between boreal forest fires and planetary albedo changes (Randerson et al., 2006), so we did not add albedo to the overview.

1, 32 – 2, 2 – 2, 7: Exactly, but these "many" fires are forgotten about in the rest of the paper as it stands now.

Response: We respectfully disagree with the reviewer on this point. We are directly reporting on an extreme wildfire season in Alaska. It is in our title. Trace gases and aerosols from the very large complex of 2015 wildfires did get transported widely across the North American continent, in a way that is similar to the examples we provide of other fire events in the introduction.

2, 9: delete "future"

Response: We deleted "future" from in front of projections. Thank you.

2, 11: delete "feedbacks"

Response: We deleted "feedbacks" following the reviewer suggestion.

2, 13: add "emissions of" before "specific" or it makes no sense.

Response: We added "emissions of" before "specific." The sentence now reads: "Emission factors provide a straightforward way to convert fire consumption of dry biomass into emissions of specific trace gas species, such as CO, CH_4, and CO_2."

2, 19: "have sometimes been" … Recommendations from Andreae weight all studies included equally, but the Akagi recommendations often consider amount of sampling, representativeness, quality of technique, etc. in recommendation as explained for each fire type in Sect 2. Users are encouraged to change the averaging formulas in the supplemental tables if justified for their application.

Response: We added "sometimes" in the place recommended by the reviewer.

2, 22: "near and within" or "through" or "across"

Response: We changed the sentence to "...fly aircraft through plumes."

2, 23: not just IR and WAS, other instruments include diode lasers, mass spec, and many others too, especially in ARCTAS.

Response: We removed "infrared" following the reviewer's suggestion.

2, 24: I'm not checking this number of fires, but note past work coves a variety of places and years, which is good.

Response: We believe this number represents all fires measured in previous studies, and agree with the reviewer that the synthesis should cover a representative sampling of location and years.

2, 22-30: This is a nice overview of limitations of aircraft sampling, but equal attention is needed on limitations of fixed surface sites as noted in general comment.

Response: We added a sentence to the end of this paragraph to briefly describe limits to surface sampling. The final sentence of this paragraph reads: "Surface sampling near or within fire perimeters may have an advantage with respect to providing measurements during intervals when aircraft are unable to fly, but are also more likely to under sample emissions injected above the boundary layer by fire plumes and within pyro-cumulus clouds."

2, 31: I would change "surface tower" to "fixed surface site" to make it more general and include the work by Collier, Gilman, Selimovic et al cited just below. Selimovic et al., 2019a is now just
"2019" and "2019b" is now "2020."

Response: We changed "surface tower" to "fixed surface site" and modified the references as suggested.

Selimovic, V., Yokelson, R. J., McMeeking, G. R., and Coefield, S.: Aerosol mass and optical properties, smoke influence on O_3, and high NO_3 production rates in a western US city impacted by wildfires, J. Geophys. Res., 125, e2020JD032791, 2020.

2, 34: delete "]."

Response: We removed the typo.

2, 37: add "of" before "smoldering"

Response: We added "of" before "smoldering"

2, 40: "fromfrom"

Response: We removed the typo following the reviewer suggestion.

3, 3: fyi, smoldering converts solid biomass to gases, flaming oxidizes some of those gases. Yokelson et al., 1996, 1997

Response: We changed the sentence to "Smoldering combustion converts solid biomass to gases and aerosols, while flaming oxidizes some emissions [*Yokelson et al.*, 1996, 1997]."

3, 6-7: Actually no way to have an open fire with low oxygen so delete "in a high oxygen environment."

Response: We deleted "in a high oxygen environment."

3, 3 – 3, 13 and 3, 14 – 3, - 21: good overviews.

Response: We appreciate the reviewer's comment that our text here in the introduction is clear summary of past work on this topic.

3, 24: 5,858,000 30 s samples would be almost 3 million minutes, >48,000 hours, or >2000 days all within a ~90 day period! 58,000 samples is only 20 days….?

Response: This is a typo. We updated the text to "59,800." The datastream from June 9 – August 13th (65 days based on figure 3) had 59824 individual 30s long samples. This excludes 13 mins out of every hour as the Picarro cycles through the lower levels (10 mins of sampling lower levels + 3 mins to flush the lines) and ~ 8 mins out of every 8 hours when the Picarro samples reference gases (5 mins) + 3 mins to flush. We had 4362 total individual 30s long samples used to calculate the emission ratios.

3, 26-28: "Analysis of these data indicate that smoldering processes may have a higher contribution to total wildfire emissions from North American boreal forests than previous estimates derived from aircraft measurements." Out of place as a result in the intro and also comes across as a random change of subject.

Response: We appreciate the reviewer's perspective, but wish to note there are many different possible stylistic approaches for writing the last paragraph in the introduction. It is not uncommon to provide the reader with an overview statement of a main finding at the end of the introduction, and in this context, we would respectfully request to keep this sentence in its present form, changing "measurements" to "sampling".

4,4 move sentence till after next one or rephrase as "… data stream we used …"

Response: We rephrased this sentence as "… data stream we used …"

4,1-17: Take a few sentences to explain the data collection and analysis better and refer to tables. Clarify the following:

1) If you shifted to make continuous data, the time base would get further and further off or have jumps making it harder to compare to model?
2) The instrument sampled for 30 s then did something else for "<15s" then repeated until 50 minutes was up?
3) If 30 or more of the 30 s samples within one 50 min interval each had CO > 0.5 ppm the series was denoted as an emission factor event as shown in tables?
4) elevated CO for less than 30 of the 30s samples was ignored?
5) no emission factor events were allowed to span two different 50 min intervals?
6) How does the sample size criteria impact continuity?

More important than justifying any choice as the best choice is to explain once clearly what was done in section 2.1, how the instrument sampled and how data was reduced and tie that explanation to the Tables – making sure tables are called out in right order.

Response: We considerably revised and clarified the sampling protocol of the spectrometer at CRV tower:

In section 2.1:

"Atmospheric CO, CH_4, and CO_2 mole fractions were measured using a cavity ring-down spectrometer (CRDS, Picarro models 2401 and 2401m) [*Karion et al.*, 2016] at the CRV tower in Fox, Alaska (64.986°N, 147.598°W, ground elevation 611m above sea level). The tower is located about 20 km northeast of Fairbanks Alaska on top of a hill in hilly terrain (Figure 1), and within the interior lowland and upland forested ecoregion in interior Alaska [*Cooper et al.*, 2006]. There are three separate inlets on CRV tower at different heights above ground level from which the spectrometer draws air for sampling. The spectrometer samples air from the highest level for 50 minutes out of every hour, and then draws air from the other two levels for 5 minutes at each level [Karion et al., 2016]. Standard reference gases are sampled every 8 hours for 5 minutes, and measurements are removed for a time equivalent to three flushing volumes of the line, approximately 3 minutes, after a level change or switch to or from a calibration tank. All raw 30 s average measurements were calibrated according to Karion et al. [2016].

We used observations from air drawn from the top intake height at a height of 32 m above ground level in our analysis because this level had the highest measurement density and the smallest sensitivity to local ecosystem CO_2 fluxes near the tower [Karion et al., 2016]. We used gaps in this time series, created when the spectrometer cycled to the lower inlets and following calibration, to separate the time series into discrete time intervals for the calculation of emission ratios. Each 30 s average measurement within a 47-minute sampling interval served as an individual point in our calculation of an emission ratio described below (Table 2)."

We also modified the text to better explain our data screening methodology. It now reads:

"We isolated intervals when fire had a dominant influence on trace gas variability observed at CRV to calculate emission ratios. An interval with dominant fire influence was defined as a continuous 47-minute measurement period that had: 1) a minimum of at least 30 trace gas measurements (with each measurement representing a mean over 30 seconds), 2) a mean CO over the entire interval exceeding 0.5 ppm, and 3) significant correlations between CO and CO_2, and between CH_4 and CO_2, with r^2 values for both relationships exceeding 0.80.

For each interval, we required a sample size of at least 30 individual 30 s measurements. For each interval meeting this criterion, we calculated the mean CO mole fraction and discarded intervals that had a mean CO less than 0.5 ppm. For each of the intervals with mean CO that exceeded the 0.5 ppm threshold, we then extracted the 30 s measurement time series of CO, CH_4, and CO_2 mole fractions and calculated correlation coefficients between the trace gas time series. Only intervals with high and significant correlations between CO and CO_2 and between CH_4 and CO_2 ($r^2 > 0.80$; $p < 0.01$, $n > 30$) were retained, because covariance among these co-emitted species is a typical signature of combustion [*Urbanski*, 2014]. Data from each of the intervals that met the three criteria described above were used to compute emission ratios, emission factors, and MCE. These intervals are reported in chronological order in Table 2."

4, 21: Correlation among these species occurs for all combustion, including traffic in Fairbanks, but hopefully low anthropogenic influence at tower.

Response: We agree that there can be a significant CO:CO_2 correlation generated from traffic, but the CH_4 levels emitted from this activity are quite small compared to fire emissions based on measurements we have made in Los Angeles and other cities [Hopkins et al., 2016], and so our requirement for a significant CH_4:CO_2 correlation reduces our sensitivity to an influence from this source. Especially since during summer, CO_2 fluxes from the terrestrial biosphere are large relative to anthropogenic emissions [Commane et al., 2017]. This site was selected to be 20 km outside of Fairbanks to provide a background station for interior Alaska [Karion et al., 2016]. Finally, in other work, we surveyed Fairbanks for methane leaks using a portable Picarro cavity ringdown spectrometer. The city does not have substantial natural gas infrastructure (and leaks), which was somewhat surprising to us. Thus, we believe our criteria of simultaneous high correlations between CO and CO_2 and between CH_4 and CO_2 are likely to screen out any periods with anthropogenic influence. We also note that our modeling analysis confirms fires were a dominant driver of CO variability at the Fox during the summer of 2015.

4, 23-24: So assumed a flat background for CO and CH4 for the whole summer regardless of wind direction, etc. rather than fitting a baseline from before to after each peak? Aren't ecosystem CH4 fluxes potentially variable?

Response: As shown in Figure 4, fires were burning continuously from DOY 165 through DOY 220. This made it impossible to fit a baseline before or after each 47-minute interval we used to compute an emission ratio. CH_4 levels in interior Alaska at this tower were more variable during the summer 2015 than in other years because of large fire source. As described below in response to the reviewer comment on page 4, 34-36, because we use a linear regression to compute a slope using up to 95 30-second points during each 47-minute interval, our approach is insensitive to background variability on longer timescales.

4, 24-26: So the model reproduced 2012 when few fires occurred and then was run with 2015 input to get a 2015 calculated background?

Response: That is correct. We changed the ordering of the text in this paragraph and added the following sentence to clarify: "After training on data from the summer of 2012, the model was then run using 2015 input variables to calculate time evolving CO_2 background mole fractions during our analysis period."

4, 34-36: Even if the calculated background level changes slowly it could be the wrong level. Fractional uncertainty in the fire excess CO2 is roughly the uncertainty in the background (~3 ppm from Fig. 2a) divided by the size of the enhancement (~15 ppm from Fig 2b) for about 20% uncertainty on average? Or, if you just want one ER for the whole season you could just integrate the excess over the whole summer or do regression on the whole summer and get uncertainty from the uncertainty in the slope. Computing integrals for the whole summer might be a step closer toward a flux-based EF? Could be interesting to see how the result of that approach differs?

Response: We have changed the text in the paragraph to clarify how we computed the emission ratio for each 50-minute measurement interval. Specifically, we first compute the excess mole fractions for CO (or CH_4) and for CO_2. We do this by removing the background value for CO (or CH_4) (this step removes the same value from each 30s mean observation within a measurement interval). We then remove the background level for CO_2, which evolves slowly over time during the 47-minute interval. Once we have the 30s time series of excess mole fractions, we then perform a linear regression with CO (or CH_4) molar excess serving as the y variable and CO_2 molar excess serving as the x variable. The slope of this linear regression is the emission ratio. In this context, a bias in the background subtracted from CO or CH_4 that remains the same over the sampling interval will have no effect on the slope of the regression line. An offset in the baseline will influence the intercept but not the slope.

So this approach is different from what might occur when the CO_2 excess mole fraction is computed using a background from an out-of-plume air sample from an aircraft. In this latter approach, a bias in the CO_2 background translates directly to a bias in the reported emission ratio. This is not the case for our approach because the regression line slope is derived from the covariation of CO and CO_2 within the measurement interval (the variability shown in Figure 7).

The new text reads:

"We estimated an emission ratio (ER_X; equation 1) by calculating the slope from a type II linear regression of CO or CH_4 excess mole fractions (ΔX) relative to the CO_2 excess mole fraction (ΔCO_2) using all of the 30 s observations available within a single 47-minute sampling interval when fire had a dominant influence on tower trace gas variability (up to 95 pairs of measurements). To estimate excess mole fractions (denoted with a Δ), we first removed background mole fractions (described above) before performing the regression analysis and obtaining the slope. The assumed background levels for CO and CH_4 did not influence this emission ratio estimate because they were assumed to remain constant throughout the duration of each 47-minute interval (i.e., they influenced the intercept but not the slope of the regression). In a sensitivity analysis we found that the removal of the CO_2 background, which did evolve within each 47-minute interval, had only a negligible effect, because the CO_2 background did not change rapidly over time."

4, 37: did you get a slope for each 30 data-point+ "interval" and are "intervals" individual peaks or could they be partial or multiple peaks? Are intervals typically associated mainly with one fire?

Response: To answer the first part of this reviewer comment, the answer is yes, we got a single emission ratio for each 47-minute interval (with at least 30 30-s samples) from the linear regression slope. We believe the trace gas variability within a single 47-minute measurement interval used to compute an emission ratio often contained a composition of emissions from multiple fires.

We added the following text to clarify that multiple fires can contribute to excess mole fractions during a single measurement interval.

"Since multiple fires were often burning simultaneously during the 2015 fire season, the emission ratios we report in Table 2 for each interval likely represent a composite of emissions from several fires."

5, 1-9: I did not check formulas, but got same EF results for CO and CH4 from reported ER so probably no typos? Also, why not report EFCO2?

Response: Thank you for checking the ER to EF step. We also doubled checked this using equation 2 and equation 3 and confirmed the numbers in Table 2. The emission factor for CO_2 is fundamentally different, having a high degree of sensitivity to the carbon content of fuels. Since we did not make any direct measurement of fuel consumption of different tree, litter, and surface duff pools (and their carbon content) we prefer not to report CO_2 emission factors. These, of course, can be computed directly from Table 2 for anyone who really needs this information.

5, 17: "the sampled combustion processes"

Response: We added "sampled" to this sentence following the reviewer suggestion.

5, 24-26: Varying plume injection height within the boundary layer may not impact result at tower a lot if PBL well-mixed, but it excludes injection into the free troposphere during intense combustions and arguably would reduce the importance of long range transport, which is highlighted in the intro and conclusions.

Response: We included more text in the introduction and in the discussion sections describing the limitation of using a stationary surface sampling location.

5, 28: "isis" hacked your paper:)

Response: We apologize for the typo and removed it.

5, 33: It's not dark yet at 6 pm in summer in AK? But with this definition, 10% at night seems low, is there GOES FRP to back that up?

Response: Correct, it's not dark at 6 pm or even 1 am at 64°N in late June, but the human eye is very sensitive to low light levels. Eddy covariance tower observations of the diurnal cycles of net radiation and sensible heat fluxes from interior Alaska collected by our group [Liu et al., 2005] show a very clear diurnal cycle and a very much reduced nighttime flux during summer (JJA). This is clearly shown in Figure 8 of that paper.

The collapse of the boundary layer at night, even in Alaska, lowers surface air temperatures and increases relative humidity levels, thus reducing fire activity.

We used FRP to support our partitioning, and we reported on this directly in the previous round of review (and integrated these results from MODIS fire radiative power into the current draft). GOES is not appropriate to use for several reasons: 1) at high northern latitudes with the very large pixel sizes (more than 15 km on a side), threshold fire sizes (and temperatures) for detection are considerable, and may change over the course of a diurnal cycle; 2) there is not a robust FRP product for the GOES-R time series yet.

5, 35: “83% of detected fire activity”

Response: We added “detected” to this sentence following the reviewer’s suggestion.

6, 2: “roughly consistent” i.e. almost a factor of two different

Response: We added “broadly” to the sentence, following the reviewer’s suggestion. The model parameterization is a 90:10 split of emissions between day and night intervals, whereas the integral of FRP from MODIS satellite observations suggests an 83:17% split. These are similar given uncertainties and incomplete diurnal coverage of the satellite data.

6, 3-13: Nice modeling application here. Were the individual fire contributions too mixed-fire events at the tower computed on a whole season daily, hourly, or interval basis? Some large fires may not have grown much on the day they impacted the tower?

Response: The individual fire contributions were calculated over the 2015 fire season. We modified the following sentence in the methods section to clarify: “The difference between the original model and the updated coupling was equal to an individual fire’s contribution to CO at the CRV tower, when integrated over the 2015 fire season.”

6, 14: units are not immediately understandable, maybe explain in a bit more detail?

Response: We explain the “footprints” in more detail in a later sentence that reads: “These functions provide an estimate of the impact of upwind surface fluxes at different times in the past on CRV tower trace gas mole fraction measurements at a given time.”

We also included more information in our model description: “For this application, STILT [*Lin et al.*, 2007] was used to estimate the adjoint of PWRF [*Skamarock et al.*, 2005; *Chang et al.*, 2014; *Henderson et al.*, 2015] during the summer of 2015 at the location of the CRV tower, to generate surface influence functions that relate surface fluxes from Alaska to trace mole fractions at the CRV tower. These gridded influence functions are known as footprints and have units of mole fraction per unit of surface flux (ppm/(μmol m^{-2} s^{-1}).”

6, 18 & 20: Useful to define emission factor “event” or “period” earlier when describing how data stream analyzed?

Response: We have attempted to standardize our language in response to an earlier reviewer comment. Please see our response to comment 4,1-17. We now use the term “interval” to refer to the period of time over which we compute an emission factor. We modified the text here so it now reads: “We analyzed the footprints for each interval used to calculate emission factors to confirm…”

6, 20-25: This is a cool analysis and useful that likely represents a lot of work! Not a criticism, but the finding that 27% of smoke impacting the tower was emitted at night, but the model assumes 10% of total AK smoke was emitted at night kind of shows the difficulty in proving representative sampling. Or what else does it mean? One general philosophy for dealing with this quandary has traditionally been to sample in multiple ways and synthesize the results; and simultaneously take the differences between approaches as a rough estimate of overall uncertainty. This is sort of what happens when using a literature average/stdev, while I acknowledge weighted averages can be better than straight averages in some cases.

Response: We agree with the reviewer that it is important to report these numbers. We also agree it makes sense to combine information from different measurement approaches and models to further reduce uncertainties in emission factors. In this context, it is also important to consider differences in fire behavior and ecosystem type when creating a literature mean and std deviation, especially for use in global models. We return to this issue in the discussion and our response to reviewer comments in the discussion.

6, 29: Are these 55 events the same as the EF events or periods? Are they all < ~50 minutes long? If the CO rose for two 50 minute periods and then fell for two 50 minute periods, is that one peak an emission factor event or is it 4 events? The data reduction can easily be spelled out clearly at the outset for folks that did not do the calculations and might wonder. Has the table of events been called out yet?

Response: Yes, these are the same. We clarified by modifying the following sentence: "We identified 55 individual fire-affected events intervals in the observational data from CRV tower (that each span about 50 minutes each) to calculate emission factors from the elevated trace gas observations (Figure 5; Table 2)." We also refer to table 2 in section 2.2 of the Methods.

6, 29-30: The definition of an event earlier was lasting ~900 or more s? Here all the events lasted 50 minutes? So each hourly measurement interval with high enough CO was an event? I think it might be easy to take a few sentences above to just spell out how data was analyzed. Then I look at Table 2, are these the events and is N the number of 30 s increments? Maybe explain that earlier and include if each of these events is separated by a clean period?

Response: We addressed this comment by modifying the methods to make our approach clearer. Please see response to comment 4,1-17.

6, 31: it would be interesting to see range in CH_4/CO also in this sentence.

Response: We are using CO_2 as our reference species, and prefer to only include the ratios with respect to CO_2. This can be computed from Table 2.

7, 8: "within" should be "with"? Table 3 called out by mistake? Also on line 16?

Response: We changed "within" to "with" and removed the reference to Table 2.

7, 20: diddid

Response: We removed the typo.

7, 21, 22, 23: Variability < 5% probably not significant. Were events actually different fires? What is meant by flux-weighted estimates? Accounting for fuel consumption rate in a weighted average EF or windspeed at tower? The highest flux periods at the fire may produce high injection altitudes.

Response: We believe that different fires contributed significantly to emission ratios computed for different time intervals. The temporal evolution of different fires shown in Figure 10 provides evidence for this. To address the reviewer comments we changed the final sentence of this paragraph to read: "Although the variation introduced from different weighting approaches was relatively small, the analysis highlights the challenge of combining information from different individual fires, and the importance of moving toward flux-weighted estimates in future work."

7, 25-27: Figure 7 shows some big peaks at tower, but not in model (doy ~188) or modeled peaks not seen at tower. The text says the model confirms elevated CO was primarily from fires. So I guess "primarily" signals > 50% and signals rough agreement? The authors stand by the unmodeled peaks being due to fires? How was it possible to get the fires contributing to the signal at the tower when the model did not capture a peak?

Response: We stand by our assertion that unmodeled peaks are caused by fires. We acknowledge that the model is imperfect. We explain possible causes for the model missing elevated CO peaks in the following sentence: "Differences between the model simulations and observations were likely caused by errors in the magnitude and timing of fire emissions within AKFED as well as the limited spatial resolution and incomplete representation of atmospheric transport within PWRF-STILT. Nevertheless, the broad agreement between the model and the observations, including the timing of the large burning event between DOY 173 and 179, provides some confidence that our model can be used to explore the influence and contribution of individual fires."

7, 28: "likelycaused"

Response: We removed the typo, added an extra space.

7, 34: average distance weighted by fractional contribution?

Response: We added "average distance weighted by fractional contribution."

7, 36: What is meant by "integrate emissions from multiple fires through the full planetary boundary layer"?

Response: We removed this sentence and rewrote the discussion in our revised paper.

7, 39: > 8% in Table 3

Response: We removed the typo. We now say more than 10%.

8, 1: delete "significantly"

Response: We deleted "significantly."

8, 3: 4646%

Response: We removed the typo.

8, 8: Andreae-associated recommendations averaged the values from studies using different platforms partly in recognition of bias being possible for any one platform. Akagi et al pioneered splitting extratropical forests into boreal and temperate. They (Sect 2.3.2) actually used a pretty complex scheme averaging smoldering fuels from lab studies by fuel type rather than by study to get a ground-based average, which was then averaged with airborne results for an overall average roughly consistent with about 70% of overall fuel consumption by smoldering. They mentioned evidence that smoldering might be even more important. They devised formulas to estimate compounds measured only in lab or air and invited users to modify any of the formulas in their Table S2 if they preferred. Remarkably, their default recommendations are almost indistinguishable from this work. Regarding "important" differences on P8, L15, keep in mind that modelers determine the level of detail that works for them and it often involves model domain, scope of study, availability, reliability, and complexity of operational input, but also completeness, i.e. they need ERs/EFs for more than 2 species!

Response: We acknowledge that the Akagi et al. approach for combining smoldering fuels and combining it with aircraft observations is an important advance, especially for shorter lived compounds. However, without long-term environmental sampling over the full lifecycle of fires and time-varying environmental conditions that wildfires are experiencing over a period of weeks to months, it is impossible to know how to combine information from smoldering combustion measurements in the laboratory and aircraft samples that may be sampling more flaming combustion phases. This is where the duration and extent of our observations are valuable, as we develop this idea further in the revised discussion.

We agree with the reviewer that the first step in the discussion is to acknowledge the consistency with past work, and we have modified the first paragraph of the discussion to highlight our agreement with previous compilation studies and their strengths with regard to modeling. It now reads:

"The most widely used emission factors for boreal forest fires are derived from syntheses that average together data from individual field campaigns [*Andreae and Merlet*, 2001; *Akagi et al*., 2011; *Andreae*, 2019]. Our mean emission factor for CO (127 ± 59 g CO per kg of dry biomass consumed) is similar to the mean reported in past syntheses for boreal forests, including estimates by *Andreae* [2019] (121 ± 47 g CO per kg of dry biomass consumed) and *Akagi et al.* [2011] (127 ± 45 g CO per kg of dry biomass consumed). Considering boreal forests as a whole, our measurements provide a partial validation of the approach taken in previous compilations, which have attempted to combine information from different sampling strategies and boreal forest ecoregions. The broad level of agreement provides confidence in the estimates of emission factors for non-conserved species that cannot be measured using our remote tower-based approach."

8, 13 re Table 1: Good idea to parse out data by location and platform and nice overview of data collected. Note Yokelson et al 1997 is missing (used in Akagi Table S2). Boreal peat was burned in Stockwell et al., 2015. Double check if Siberian fires were wild or prescribed, I think at least some were prescribed. Split Siberian fires out by air or ground? Siberian average row has possibly wrong total? Remove line numbers from number of fires column, "McMeeking has two capital "M"s, etc…

Stockwell, C. E., Veres, P. R., Williams, J., and Yokelson, R. J.: Characterization of biomass burning emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-reaction time-of-flight mass spectrometry, Atmos. Chem. Phys., 15, 845-865, doi:10.5194/acp-15-845-2015, 2015.

Yokelson, R.J., D.E. Ward, R.A. Susott, J. Reardon, and D.W.T. Griffith, Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy, J. Geophys. Res., 102, 18865-18877, 1997.

Response: Table 1 includes both airborne and surface measurements from Siberian fires (as noted with the "a" or "s" and explained in the figure caption).We now include Yokelson et al., 1997 and Stockwell et al., 2014 in Table 1, and we identify the type of fuel burned in the North American laboratory studies.

8, 15: "measurement technique" should be "sampling strategy" to be consistent and precise?

Response: We changed "measurement technique" to "sampling strategy" throughout the paper.

8, 17-36: The overview of air versus ground sampling of sources is pretty good, a little disorganized but all the most important points emerge clearly! A few points to add could be: Aircraft can replicate tower-based sampling with downwind vertical profiles, but not on a continuous basis like a tower. Also, any aircraft bias toward flaming combustion may actually be partly okay if it weights the EF towards times of higher fuel consumption, relevant to author's desire for flux-based EFs? Flaming always entrains some smoldering, and the entrainment footprint is larger with more intense flaming. Best not to oversimplify a complicated situation.

Response: To simplify the discussion, we revised this paragraph.:

"In contrast with remote tower sampling, aircraft-based studies often sample fires that have a strong contribution from flaming combustion, which releases enough energy to generate well-defined plumes at an altitude accessible by the aircraft. This methodology provides an opportunity to comprehensively measure the vertical and horizontal distribution of emissions from an individual fire and their atmospheric evolution in a smoke plume. However, airborne sampling techniques are often limited to daytime periods with good visibility, making it difficult to comprehensively measure emissions over a diurnal cycle or over the full lifetime of a fire which may span several periods with inclement weather. Due to these sampling constraints, aircraft studies are less likely to measure emissions from less energetic smoldering combustion, since these emissions are more likely to remain near the surface [*Ward and Radke*, 1993; *Selimovic et al.,* 2019]. Emissions from smoldering boreal forest fires can sometimes be entrained in the convective columns of certain flaming fires and can be sampled by aircraft, but nighttime emissions or residual smoldering emissions from fires that have weak convective columns usually cannot be measured in this way [*Bertschi et al.,* 2003; *Burling et al.,* 2012]. While past studies have attempted to combine information from aircraft (more likely sampling flaming combustion phases) with laboratory observations of emissions from smoldering combustion [*Akagi et al.*, 2011], the balance of emissions is well known to be highly sensitive to environmental conditions that can rapidly change over the lifetime of a wildfire; this highlights the importance developing sustained sampling approaches that provide regionally-integrated estimates over the full duration of a wildfire event or regional fire complex."

8, 29: "weak or non-existent" convection columns (aka "updraft cores"). Mostly true for fresh RSC emissions, so "usually" is a good qualifier since some RSC may get to aircraft altitude by non-fire uplift or be sampled in rare missed approaches.

Response: We agree and will keep "usually."

8, 35: "yet rarely" is okay – a fresh RSC sample would require "a really good drill on the front of the plane" to quote a DC-8 pilot.

Response: We agree and will keep "yet rarely."

9, 4: "combustion of"

Response: We changed the text to "combustion of."

9, 4-5: Organic soils were focus of lab study of Yokelson et al., 1997 and included in Stockwell et al., 2015 during FLAME-4.

Response: These studies are now included in Table 1 and the type of fuel burned is denoted.

9, 7: "should" > "could" or "might" (see above on models)

Response: We changed the text to "should."

9, 8: At least five lab studies burned boreal fuels, the CO/CO2 ratios for FLAME-4 for black spruce and boreal peat are in supplement of Stockwell et al., 2015. Listing what fuels were included in averages in Table 1 would be helpful.

Response: The fuels per study are now denoted in Table 1.

9,12 "McMeeking"

Response: We changed all references to the correct name: "McMeeking."

9, 18-29: The claim of different ERs is not strongly supported. The quoted (Table 1), purely surface-based sampling of Siberian fires had *lower* CO/CO2 than the authors NA work, and, even more remarkably, only about half the CO/CO2 ratio as the studies that included some airborne sampling of Siberian fires. So maybe better to say, the ecosystems differ and the emissions might as well, but not enough data to know yet.

Also work on the Siberia/NA differences goes back to at least 1993 when the Bor Island Experiment was started. Differences in Siberian and North American boreal fires were noted in publications 20-24 years ago with hundreds of references cited and a more recent review on that:

Goldammer, J.G., and V.V. Furyaev. 1996. Fire in ecosystems of boreal Eurasia. Ecological impacts and links to the global system. In: Fire in ecosystems of boreal Eurasia (J.G. Goldammer and V.V. Furyaev, eds.), 1-20. Kluwer Academic Publ., Dordrecht, 528 pp. https://link.springer.com/chapter/10.1007%2F978-94-015-8737-2_1

E.S.Kasischke and B.J.Stocks, eds. 2000. Fire, climate change, and carbon cycling in the boreal forest. Ecological Studies 138, Springer-Verlag, Berlin-Heidelberg-New York, 461 p.

Goldammer, J.G. (ed.) 2013. Prescribed Burning in Russia and Neighbouring Temperate-Boreal Eurasia. A publication of the Global Fire Monitoring Center (GFMC). Kessel Publishing House, 326 p. (ISBN 978-3-941300-71-2). http://www.forestrybooks.com/

Response: We respectfully disagree with the reviewer about this point. A Student's t test shows that the set of the Siberian forest fire emission ratios shown in Table 1 are significantly different (and higher) than the remote tower estimates from boreal North America. While it's true there are two fires that are lower than the NA remote tower observations, 7 other fires are quite a bit higher. We acknowledge that more observations are needed with the sentence: "Although more measurements are needed, higher CO emission ratios for Siberian fires appears consistent with past work showing that boreal fire behavior is considerably different between North American and Eurasian continents as a consequence of differences in tree species and their impacts on fire dynamics [*Goldammer and Furyaev*, 1996; *Cofer et al.,* 1996].

We think its important that readers understand that many of Eurasian boreal forest fire emission ratio values are higher than those reported for North America. This is a contributing factor to why there is apparent agreement between our mean emission factor and the ones reported in Akagi et al. [2011] and Andreae [2019]. Lower North American aircraft studies are being offset in a global average in these syntheses by high values measured in Eurasian boreal forests.

We also note that we include both aircraft and surface sampling of Siberian fires (as noted with the "a" or "s" and explained in the figure caption). We explain that the CO emission factor from Siberian boreal fires is higher than North American boreal fires, but "more measurements are needed."

9, 23: “hotter” okay, but there is no single temperature that defines any landscape fire, more aggressive flaming is probably what is meant.

Response: We changed the text to fire radiative power, which was the actual quantity reported in Rogers et al. [2015].

9, 30: “Stronger” than what? Not a complete thought. Here the work goes off on a random tangent rehashing a long-recognized issue. Concerns about air/ground bias are discussed in Andreae and Merlet, 2001, which supports this with the following citation:

Andreae, M. O., E. Atlas, H. Cachier, W. R. Cofer, III, G. W. Harris, G. Helas, R. Koppmann, J.P. Lacaux, and D. E. Ward, Trace gas and aerosol emissions from savanna fires, in Biomass Burning and Global Change, edited by J. S. Levine, pp. 278 – 295, MIT Press, Cambridge, Mass., 1996.

Previous recommendations by Akagi and Andreae appear to have compensated adequately for this issue according to this studies results to the extent that we are ever likely to know. The authors could claim that they have investigated the extent of platform-based bias in additional detail and present a useful contribution in that way, but the issue of the existence of differences is not a new finding.

Perhaps an appropriate header is: “A detailed examination of tower versus airborne sampling”. Either include or don’t include the enigmatic data from Siberia and make a new, useful point if you can, perhaps: a) mean difference is “X”, or b) surprisingly no conclusion.

Response: We considerably revised the discussion in response to this reviewer and the other reviewers. We no longer have this section title or use the word “stronger”.

9, 38 – 10, 1: The authors have good evidence that tower-based platforms see more smoldering that the aircraft studies to date (in NA) and that is useful, but you don’t know for sure if the tower might under-estimate flaming or why the Siberian data is enigmatic. And “previous reports” should be changed to “the average of previous airborne studies” since “previous reports” could imply all studies.

Response: We changed the text to “from aircraft studies”. We now report the difference in the means in the following sentence in the second paragraph of the discussion.

We make the case now in the revised discussion that the tower-based approach likely does a good job of providing a representative sample over the 2015 fire season (second paragraph of discussion):

“Although differences in reported emission ratios are expected between aircraft and ground based sampling approaches [*Christian et al.*, 2007; *Burling et al.*, 2011; *Akagi et al.*, 2014; *Collier et al.*, 2016; *Benedict et al.*, 2017; *Selimovic et al.*, 2019], several features of the CRV tower sampling are conducive to providing a regionally-representative mean estimate of emission ratios during the 2015 Alaska fire season. First, we note that the CRV tower was located at a higher elevation (611 m above sea level) than the core fire complex located in western Alaska and several hundreds of kilometers downwind. Multi-angle Imaging SpectroRadiometer (MISR) satellite observations from Alaskan wildfires indicate most fire plumes reside within the planetary boundary layer, which is typically between 1 and 3 km during midday in summer [*val Martin et al.*, 2010; *Wiggins et al.*, 2016]. Combining this vertical length scale with the mean horizontal distance of the 34 fires that most influenced CO at CRV (259 km), we obtain a factor of about 100 for a back-of-the-envelope ratio of horizontal to vertical mixing processes. This ratio, together with the simulated time delay of 1-2 days between emission and detection of CO anomalies at CRV (Figure 3), imply that mesoscale atmospheric circulation played an important role in averaging together trace gas emissions from multiple fires before the air masses were sampled (Figure 10). As a result, observations from the CRV tower represent a temporal integration of fire emissions over day-night burning cycles as well as a spatial integration across flaming combustion at active fire fronts along with residual smoldering combustion in soils that often persists for days after a fire front moves through an area. Collectively, the fires sampled at CRV appeared to experience time-varying environmental conditions that were less ideal for flaming combustion than the fire plumes sampled in past work by aircraft. This finding is consistent with remote tower observations of the black carbon to CO ratio measured for wildfires from temperate North America [*Selimovic et al.*, 2019]."

We also acknowledge that ground-based sampling may under sample some emission injected above the pbl: "Ground-based sites may potentially miss some of the emissions injected above the planetary boundary layer and subject to long-range transport in the free troposphere."

10,1-2: at a minimum change to "some previous" , "some flaming", "some residual"

Response: This text has been deleted in the revised discussion.

10, 1 – 8: Showing that the tower and aircraft got different overall average CO/CO2 ratios is straightforward and useful. But both platforms could have some error so proving that 100% of the error in representativeness is with the aircraft is not really doable. Every fire that impacted the tower also, undoubtedly produced some emissions that did not impact the tower due to wind shifts, altitude, or whatever, it's just basic common sense. The most exciting thing about this work is not even stressed. That is, by measuring downwind of many fires burning at all stages of their life cycle around-the clock, the authors have created a high-quality data set for evaluating fire emissions models performance at a regional level (as in Selimovic et al., 2019; 2020). I.e. AKFED did pretty well integrating the effects of many fires around the clock and predicting the tower "point CO" specifically. What would need to be changed in AKFED/STILT to improve performance could be a great follow-on study along with how do larger-scale models such as GFED, GFAS, FINN, etc., perform against the tower observations! Regardless of the "real, unknown total fire emissions," the signal at the tower is well-measured now and very useful to test models!

Response: We modified our conclusions section to highlight the potential use of the CRV tower dataset to evaluate regional fire emissions model performance. Please see response to the reviewer's general comments for more information.

10, 9: This next paragraph repeats some of the material in the previous paragraph. If the text survives editing, change "crown" to "surface fuels" since the NW Territory crown fire experiment found that often the fires propagate in surface fuels followed by torching

Response: This text was deleted in the revised discussion.

10, 10: not a sentence, delete "that" to fix?

Response: This text was deleted in the revised discussion.

10, 11: substantial contributions of RSC were stressed by Bertschi et al 2003 in their Table 3.

Response: This text was deleted in the revised discussion.

10, 12: not only FRP-based, but any thermal signal. Smoldering involves temperature high enough to saturate the 3.9 micron channel if widespread enough, but obstruction is more of an issue for deep smoldering.

Response: This text was deleted in the revised draft.

10,16: "previously thought" by who? If you mean the studies mentioned directly above, no comparison is possible unless you also have the relative consumption of above- and belowground fuels. If you mean a previous compilation, Akagi et al estimated 70% of all boreal fuel was consumed by smoldering based on an MCE similar to this work.

Response: This section has been removed from the discussion.

10, 18: “most” is not “all” and MISR only looks at 1030 AM long before both the most intense combustion and diurnal cycle fuel consumption peak. I would change “most” to “many” or “some”

Response: We changed “most” to “many.”

10, 19: “length scale”?

Response: We changed this to “vertical length scale” and denote the distance is in reference to the “horizontal.”

10, 20 – 21: good point there is time for vertical mixing, if the atmosphere is not too stratified.

Response: We agree and appreciate the reviewer’s confirmation.

10, 22-25: This sentence is not accurate as Collier et al sampled smoke up to 48 hours old and Selimovic et al 2019; 2020 sampled smoke from fires in the range 20-800 km upwind.

Response: We agree, and have cited the Selimovic et al. and Collier et al. studies in other places for other specific contributions of this work.

10, 24: if text survives “band” > “and”

Response: This section was removed.

10, 26-35: This discussion is oversimplified since dry weather can make larger fuels that tend to smolder more likely to burn. See section 2.4 in Akagi et al and the papers referenced therein by Hoffa et al., 1999, Shea et al., 1996, Kauffman et al., 1998; 2003, etc. Hot, dry weather can increase smoldering. Note also that most airborne studies occurred in years that were arguably more “typical”.

Response: We believe it’s important to remind the reader that 2015 was an extreme fire season with very high surface air temperatures during June. This is important context for interpreting our emission ratios. It’s also important, we believe, to let the reader know that we attempted to examine day to day variations in regional weather and link these variations to emission ratios.

Coming at the problem from a different perspective, its very clear that periods of hot and dry weather (higher VPD) allow for faster fire spread rates in interior Alaska [*Sedano and Randerson*, 2014], likely as a consequence of fires moving through the crowns of black spruce rather than along the surface where fires move slowly. VPD also may have a small but significant effect on fire severity and fuel consumption [*Veraverbeke et al.*, 2015]. While we agree that hotter and drier weather may allow coarser fuel classes to burn, it’s not clear to us that in boreal forests this is enough to offset a stronger crown burning and flaming combustion phase. This why we frame our inquiry here as a question. We revised the text in the paragraph, but would respectfully prefer to keep this paragraph in our revised paper:

“During the latter half of June and early July of 2015, weather in Alaska was very hot and dry, allowing for a record number of fires to rapidly expand in size, and yielding the second highest level of annual burned area in the observed record. The extreme fire weather conditions would be expected to reduce fuel moisture content, thus promoting crown fires and flaming combustion processes [e.g., *Sedano and Randerson*, 2014]. This raises the question of whether longer term monitoring of many normal and low fire years (which tend to co-occur in cooler and wetter conditions) would provide evidence for an even larger role of smoldering combustion compared to the estimates we report here for 2015. Another related question is whether even within a fire season, do day-to-day or week-to-week variations in fire weather influence variability in emission ratios? We explored this latter question with the datasets described here but were unable to uncover structural relationships between daily meteorological variables such as vapor pressure deficit and CO emission ratios. Together, these questions represent important directions for future research and emphasize the critical need of sustained long-term support for trace gas monitoring networks and field campaigns."

10, 40: I don't think any new ideas "emerged", but the authors work can help continue to evaluate some long-recognized issues and maybe help reduce uncertainty.

Response: We considerably revised this paragraph, recognizing the reviewer's suggestion regarding tone. We no longer use the word "emerged". The topic sentence for this paragraph is now: "The observations summarized in Table 1 also show there are several important differences in boreal forest emission ratios that exist as a function sampling strategy and ecoregion."

11, 1: it always makes sense to "report" what you measured and studies of Siberian fires report their location. "Using" regionally-specific EFs might make sense, but is a separate decision for the modelers that is hard because few measurements have occurred in Russia where research access is super-problematic. A colleague had their canisters confiscated by the Russian military
and "filled for them at undisclosed locations."

Response: We agree more measurements are needed, and we qualify our statement in the following sentence: "More data, particularly for Siberian fires, is needed to assess whether the differences in emission factors noted here are robust."

11, 5 – 11: This is not that big a deal, the complex averaging scheme of Akagi gave almost the same answer as this study or the simple averaging scheme of Andreae. Adding this studies extensive results in a weighted or simple average to the "evolving literature average" is BAU and will have little impact on the average; though it is important to be clear about how things are synthesized.

Response: We modified our discussion section to highlight the agreement between our measurements and the compilation studies: "Considering boreal forests as a whole, our measurements provide a partial validation of the approach taken in previous compilations, which have attempted to combine information from different sampling strategies and boreal forest ecoregions. The broad level of agreement provides confidence in the estimates of emission factors for non-conserved species that cannot be measured using a remote tower sampling approach." However, we also believe it is important to quantify the magnitude of the differences in measured emission ratios between sampling strategies. Please see response to the reviewer's general comments for more information.

11, 12 - 18: It is not clear what is meant by flux-weighted EF? Aircraft measurements may in fact be weighted towards times with high fuel consumption rates. Fires can produce multiple plumes. A flux of emissions in models results from the fuel consumption rate assumptions.

Response: We modified this section to better explain flux-weighted emission factors: "Long-term monitoring from remote towers has the potential to provide new information about fire complexes in other biomes, integrating across day-night variations in fire behavior, periods with different environmental conditions, and across multiple fires in different stages of growth and extinction. In this context, more work is needed to find ways to combine tower and aircraft sampling to attain accurate estimates of the total budget of fire-emitted trace gases and aerosols (i.e., estimating flux-weighted emission factors), given the large differences in data density and the different strengths and weaknesses of the two approaches."

11, 18-23: This is just stating obvious that if we could measure everything, we'd know more. I would very strongly recommend deleting sections 4.3 (and 4.4) and instead have a section to highlight the exciting model evaluation now possible with what you *already* measured.

Response: We deleted sections 4.3 and 4.4, following the reviewer suggestion. In the conclusions, we now comment on the value of our observations for testing models. We specifically added the following sentence: "Together, the two-month near continuous time series of CO_2, CO, and CH_4, along with the derived emission ratios reported here, may provide a means to test and evaluate models that couple together fire processes, emissions, and regional atmospheric transport."

11, 24: "larger" than what?
4.4 is all speculation about PM, which was not even measured and the section doesn't consider SOA or PM evaporation where the latter was significant in Selimovic et al., 2019, 2020, and references there-in. Also, health impacts are based on measured PM and this study does not suggest the regional PM networks are inaccurate.

Response: This section was removed.

11, 27: higher than some studies doesn't equal higher than "previously thought".

Response: We deleted this section.

11, 28 – 29: Long range transported smoke was not sampled in this study and that type of smoke may actually be better sampled from aircraft.

Response: We deleted this section.

11, 25 – 36: delete, all speculation, not a topic or result of this paper.

Response: We deleted this section.

12, 3: after "Our results" I would delete the rest and fill in the valuable insights that you actually learned about the AKFED model. I.e. it underestimated nighttime combustion impacts at the tower, it captured X of the Y peaks, seasonal average CO was within Z%, etc… Highlight potential for additional, future model evaluation and improvement.

Response: We changed this sentence to: "Our results suggest the CRV tower-based dataset can be used to evaluate model predictions of fire emissions and their transport at a regional scale."

References

Commane, R., Lindaas, J., Benmergui, J., Luus, K.A., Chang, R.Y.W., Daube, B.C., Euskirchen, E.S., Henderson, J.M., Karion, A., Miller, J.B. and Miller, S.M.: Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra. Proc. Natl. Acad. Sci., 114, 21, 5361-5366, 2017.

Hopkins, F.M., Kort, E.A., Bush, S.E., Ehleringer, J.R., Lai, C.T., Blake, D.R. and Randerson, J.T.: Spatial patterns and source attribution of urban methane in the Los Angeles Basin. J. Geophys. Research: Atmospheres, 121, 5, 2490-2507, 2016.

Randerson, J.T., Liu, H., Flanner, M.G., Chambers, S.D., Jin, Y., Hess, P.G., Pfister, G., Mack, M.C., Treseder, K.K., Welp, L.R. and Chapin, F.S.: The impact of boreal forest fire on climate warming, Science, *314*, 5802, 1130-1132, 2006.

Yokelson, R.J., Griffith, D.W. and Ward, D.E.: Open-path Fourier transform infrared studies of large-scale laboratory biomass fires. J. Geophys. Res. Atmos., 101, D15, http://doi.org/10.1029/96JD01800, 21067-21080, 1996.

Yokelson, R. J., Susott, R., Ward, D. E., Reardon, J., and Griffith, D. W. T.: Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy, J. Geophys. Res., 10, D15, 18865–18877, doi:10.1029/97JD00852, 1997.

Response to Reviewer #3 comments

Boreal forest fire CO and CH4 emission factors derived from tower observations in Alaska during the extreme fire season of 2015

This paper presents trace gas observations of CO, CH4, and CO2 at the CRV tower to estimate emission factors from boreal forest fires during the Alaska extreme fire season of 2015. The high-quality boreal forest fire smoke measurements are combined with Lagrangian modelling to characterize wildfire emissions.

The work is of high quality and excepting some few points, that need to be addressed, both description and discussion of measurements/modelling are well founded. The manuscript contributes to scientific progress within the scope of the journal, therefore it is suitable to be published in ACP.

General comments:

The resubmitted manuscript has been largely improved. There is only one general point, which needs some detailed discussions. The authors state that PWRF-STILT forward simulations were done (Page7Line25) to determine footprint fields necessary for the convolution with fire emissions from AKFED. To interpret observation at the CRV tower is a classic case of source-receptor studies that usually employ LPDM backward runs starting at the observation site, as shown by Henderson et al. (ACP2015). The authors should comment on that.

Response: We added the following sentence in the first paragraph of our model description to address this reviewer comment.

For this application, STILT [*Lin et al.*, 2007] was used to estimate the adjoint of PWRF [*Skamarock et al.*, 2005; *Chang et al.*, 2014; *Henderson et al.*, 2015] during the summer of 2015 at the location of the CRV tower, to generate surface influence functions that relate surface fluxes from Alaska to trace mole fractions at the CRV tower. These gridded influence functions are known as footprints and have units of mole fraction per unit of surface flux (ppm/(μmol m^{-2} s^{-1}).

Specific Comments

Equation 2 still needs small revisions: replace 12.01 by MM_{C} as carbon molar mass; remove g/kg and explain the conversion factor 1000 in text.

Response: Following the reviewer's suggestion, we modified equation 2, replacing 12.01 with the molar mass of carbon and taking the units away from the factor of 1000, but explaining the units of this factor in text.

- Page2Line34 remove [.

Response: We removed the extra "[", correcting this typo.

- Page7Line28 a blank is missing between 'likely' and 'caused'

Response: We inserted a space between these two words.

- Page9Line insert 'CO' prior to 'emissions': 'Yet, Table 1 shows CO emission ratios from wildfires in boreal Siberia tend to be higher than emission ratios from North American wildfires'

Response: We considerably revised the discussion in response to reviewer #2. This discussion header no longer exists. We modified the following sentence in the second paragraph of the discussion to make this point, replacing “fire” with “CO” in the revised sentence: “Within North American boreal forests, the CRV observations we analyzed here provide evidence that smoldering combustion contributes more to CO emissions than what has been estimated from previous aircraft studies. Specifically, our mean CO emission ratio from the CRV tower is 39% higher (and significantly different at a $p < 0.01$ level using a Student’s t test) than the mean derived from 19 aircraft studies of North American boreal wildfires (Table 1).”

References

Chang, R.Y.W., Miller, C.E., Dinardo, S.J., Karion, A., Sweeney, C., Daube, B.C., Henderson, J.M., Mountain, M.E., Eluszkiewicz, J., Miller, J.B. and Bruhwiler, L.M.: Methane emissions from Alaska in 2012 from CARVE airborne observations, Proc. Natl. Acad. Sci., 111, 47, 16694–16699, https://doi.org/10.1073/pnas.1412953111, 2014.

Henderson, J. M., Eluszkiewicz, J., Mountain, M. E., Nehrkorn, T., Chang, R. Y. W., Karion, A., Miller, J. B., Sweeney, C., Steiner, N., Wofsy, S. C. and Miller, C. E.: Atmospheric transport simulations in support of the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), Atmos. Chem. Phys., 15, 4093-4116, doi:10.5194/acp-15-4093-2015, 2015.

Lin, J., Gerbig, C., Wofsy, S., Chow, V., Gottlieb, E., Daube, B., and Matross, D.: Designing Lagrangian experiments to measure regional scale trace gas fluxes, J. Geophys. Res., 112, D13312, doi:10.1029/2006JD008077, 2007.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W. and Powers, J.G.: A description of the Advanced WRF Version 2, Tech. Note NCAR/TN-468+ STR, Natl. Cent. for Atmos. Res., Boulder, Colo., 2005.

Boreal forest fire CO and CH_4 emission factors derived from tower observations in Alaska during the extreme fire season of 2015

Elizabeth B. Wiggins[1], Arlyn Andrews[2], Colm Sweeney[2], John B. Miller[2], Charles E. Miller[3], Sander Veraverbeke[4], Roisin Commane[5], Steven Wofsy[6], John M. Henderson[7], and James T. Randerson[1]

[1]Department of Earth System Science, University of California, Irvine, California, USA, [2]National Oceanic and Atmospheric Administration, Boulder, Colorado, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [4]Vrije University Amsterdam, Netherlands, [5]Department of Earth and Environmental Sciences, Columbia University, Palisades, New York, USA, [6]School of Engineering and Applied Sciences, Harvard, Cambridge, Massachusetts, USA, [7]Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA,

Correspondence to: Elizabeth B. Wiggins (Elizabeth.b.wiggins@nasa.gov)

Abstract. Recent increases in boreal forest burned area, which have been linked with climate warming, highlight the need to better understand the composition of wildfire emissions and their atmospheric impacts. Here we quantified emission factors for CO and CH_4 from a massive regional fire complex in interior Alaska during the summer of 2015 using continuous high-resolution trace gas observations from the Carbon in Arctic Reservoirs Vulnerability Experiment (CRV) tower in Fox, Alaska. Averaged over the 2015 fire season, the mean CO/CO_2 emission ratio was 0.142 ± 0.051 and the mean CO emission factor was 127 ± 40 g kg^{-1} dry biomass burned. The CO/CO_2 emission ratio was about 39% higher than the mean of previous estimates derived from aircraft sampling of wildfires from boreal North America. The mean CH_4/CO_2 emission ratio was 0.010 ± 0.004 and the CH_4 emission factor was 5.3 ± 1.8 g kg^{-1} dry biomass burned, which are consistent with the mean of previous reports. CO and CH_4 emission ratios varied in synchrony, with higher CH_4 emission factors observed during periods with lower modified combustion efficiency (MCE). By coupling a fire emissions inventory with an atmospheric model, we identified at least 34 individual fires that contributed to trace gas variations measured at the CRV tower, representing a sample size that is nearly the same as the total number of boreal fires measured in all previous field campaigns. The model also indicated that typical mean transit times between trace gas emission within a fire perimeter and tower measurement were 1-3 days, indicating that the time series sampled combustion across day and night burning phases. The high CO emission ratio estimates reported here provide evidence for a prominent role of smoldering combustion, and illustrate the importance of continuously sampling fires across time-varying environmental conditions that are representative of a fire season.

1 Introduction

Boreal forest fires influence the global carbon cycle and climate system through a variety of pathways. These fires initiate succession, influence landscape patterns of carbon accumulation, and directly release carbon dioxide and other trace gases and aerosols into the atmosphere [*Johnson*, 1996]. One of the largest reservoirs of global terrestrial carbon resides in organic soils underlying boreal forests [*Apps et al.*, 1993; *Rapalee et al.*, 1998; *Tarnocai et al.*, 2009], and fires in the boreal forest can consume significant amounts of aboveground and belowground biomass [*Harden et al.*, 2000; *French et al.*, 2004; *Boby et al.*, 2010; *Walker et al.*, 2018]. Many boreal forest fires are stand replacing and high energy [*Johnstone et al.*, 2011; *Rogers et al.*, 2015], with enough convective power to inject aerosols into the upper troposphere and lower stratosphere where they can be widely dispersed across the Northern Hemisphere [*Fromm et al.*, 2000; *Forster et al.*, 2001; *Turquety et al.*, 2007; *Peterson et al.*, 2018].

Formatted: Add space between paragraphs of the same style, Don't suppress line numbers

Deleted: With recent

Deleted: within boreal forests that

Deleted: to

Deleted: there is a

Deleted: impact on

Deleted: composition. Most previous studies have estimated boreal fire emission factors from daytime samples collected by aircraft near fire plumes or at the surface near actively burning fires

Deleted: 056

Deleted: 59

Deleted: CO per

Deleted: of

Deleted: consumed

Deleted: aircraft

Deleted: for fresh emissions

Deleted: wildfires

Deleted: 33 ± 2.51

Deleted: CH_4 per

Deleted: of

Deleted: consumed,

Deleted: a

Deleted: similar to

Deleted: factors

Deleted: that

Deleted: 35

Deleted: and variable

Deleted: factor

Deleted: more

Deleted: highlighting

Deleted: of

Deleted: typical burning conditions.

Formatted: English (US)

Deleted: Boreal forest

Deleted: *Apps et al.*, 1993; *McGuire et al.*, 2010

Deleted: smoke

Deleted: it

Deleted: transported

Emissions from boreal fires are known to considerably influence atmospheric composition in downwind areas. Fire plumes from regional fire complexes in Alaska and western Canada, for example, have been shown to influence air quality over Nova Scotia [*Duck et al.*, 2007], the south-central United States [*Wotawa et al.*, 2001; *Kasischke et al.*, 2005] and Europe [*Forster et al.*, 2001]. Similarly, emissions from boreal forest fires in Russia have caused unhealthy air quality in Moscow [*Konovalov et al.*, 2011] and have affected ozone and other trace gases concentrations across the western United States [*Jaffe et al.*, 2004]. Over the past few decades, annual burned area in several regions in boreal North America has increased [*Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006; *Veraverbeke et al.*, 2017], and projections suggest further increases may occur in response to changes in fire weather and a lengthening of the fire season [*Flannigan et al.*, 2001; *de Groot et al.*, 2013; *Young et al.*, 2017]. As a consequence, fires are likely to play an increasingly important role in regulating air quality and climate during the remainder of the 21st century.

Emission factors provide a straightforward way to convert fire consumption of dry biomass into emissions of specific trace gas species, such as CO, CH_4, and CO_2. This technique is commonly used to model emissions of select species in fire inventories, allowing for comparison of atmospheric model simulations with in-situ or remotely sensed mole fraction or concentration observations. The most frequently used boreal forest fire emission factors are derived from meta-analyses that average together information from individual field campaigns [*Andreae and Merlet*, 2001; *Akagi et al.*, 2011; *Andreae*, 2019]. These syntheses often include in situ airborne and ground based measurements along with laboratory measurements of combusted fuels. There is no consensus on how to combine information from different studies, and in past work individual studies have sometimes been given equal weight when estimating biome-level means, even when the number of fires and duration of sampling has varied considerably from one field campaign to another.

In past work, the most common approach for measuring emission factors from boreal fires is to fly aircraft through smoke plumes, measuring trace gases using gas analyzers mounted in the aircraft or by collecting flasks of air that are measured later in the laboratory. Over a period of more than 25 years, a total of at least 42 boreal fires have been sampled by aircraft, including 19 wildfires and 14 prescribed land management fires from boreal North America and 9 prescribed fires in Siberia (Table 1). Aircraft sampling is a highly effective approach for sampling large and remote wildfires, especially for characterizing non-conserved trace gas and particulate emissions that have lifetimes of hours to days. It also important to recognize potential limits associated with sampling fires in this way. Aircraft observations are mostly confined to periods with good visibility, often sampling well-developed fire plumes during mid-day and during periods with relatively low cloud cover. These conditions represent a subset of the environmental variability that a large wildland fire may experience in boreal forest ecosystems as it burns over a period of weeks to months. An alternative approach for measuring in situ emission factors involves using a fixed surface site that continuously samples trace gas concentrations in an area downwind of a fire. This approach has been used to estimate CO emission ratios during a moderate fire season in Alaska [*Wiggins et al.*, 2016] and to estimate emission factors in other biomes [*Collier et al.*, 2016; *Benedict et al.*, 2017; *Selimovic et al.*, 2019; *Selimovic et al.*, 2020]. Surface sampling near or within fire perimeters may have an advantage with respect to providing measurements during intervals when aircraft are unable to fly, but are also more likely to under sample emissions injected above the boundary layer by fire plumes and pyro-cumulus clouds [*Selimovic et al.*, 2019].

Environmental conditions, including weather, vegetation, and edaphic conditions are known to influence the composition of emissions, in part by regulating the prevalence of flaming and smoldering combustion processes [*Ward and Radke*, 1993; *Yokelson et al.*, 1997; *Akagi et al.*, 2011; *Urbanski*, 2014]. The relative amounts of smoldering and flaming combustion are difficult to measure, but can be estimated using the modified combustion efficiency (MCE), defined as $\Delta CO_2/(\Delta CO_2 + \Delta CO)$, where the Δ notation denotes the fire-associated dry air mole fraction of a sample gas after background levels have been removed. Fire emissions dominated by flaming combustion have an MCE from 0.92 – 1.0, whilewhile emissions dominated by smoldering combustion have an MCE that often ranges between 0.65 and 0.85 [*Akagi et al.*, 2011; *Urbanski*, 2014]. MCE can be used to

Deleted: can significantly
Deleted: throughout the Northern Hemisphere
Deleted:] and across
Deleted: US
Deleted: ..,
Deleted: US
Deleted: future
Deleted: feedbacks
Deleted: emissions
Deleted: and or to compare
Deleted: results
Deleted: -
Deleted: A summary of previous studies that measured CO emission ratios for boreal forest fires is shown in Table 1.
Deleted: near or within
Deleted: infrared
Deleted: reactive
Deleted: -
Deleted: tower
Deleted:], from fires in Siberian forests [ref],
Deleted: for fires in other
Deleted: ecosystem types
Deleted: [refs].
Deleted: importance
Deleted:)
Deleted: $\Delta CO_2/(\Delta CO_2 + \Delta CO$
Deleted: Δ
Deleted: greater than
Deleted: while
Formatted: Font: Not Italic

understand the relative contribution of flaming and smoldering combustion processes to the composition of trace gases and aerosols in air measured downwind of a fire. Smoldering combustion converts solid biomass to gases and aerosols, while flaming oxidizes some emissions [*Yokelson et al.*, 1996, 1997]. As a consequence, smoldering combustion produces more CO, CH_4, and organic carbon aerosol relative to CO_2 [*Ward and Radke*, 1993; *Urbanski et al.*, 2008]. Flaming combustion requires the presence of organic material that burns efficiently [*Ryan et al.,* 2002], and often occurs in boreal forests when fires consume dry aboveground fuels, including vegetation components with low moisture content, litter, and fine woody debris [*French et al.*, 2002]. Smoldering, in contrast, is a dominant combustion process for burning of belowground biomass and larger coarse woody debris. Residual smoldering combustion in boreal forests can continue to occur for weeks after a flaming fire front has passed through, especially in peatland areas with carbon-rich organic soils [*Harden et al.*, 2000; *Bertschi et al.*, 2003]. Over the lifetime of a large fire, smoldering combustion is more likely to occur during periods with lower temperatures and higher atmospheric humidity that increase the moisture content of fine fuels [*Stocks et al.*, 2001; *Ryan*, 2002].

Here we used trace gas observations of CO, CH_4, and CO_2 from the CRV tower to estimate emission factors from boreal forest fires that burned during the near-record high Alaska fire season of 2015. The summer of 2015 was the second largest fire season in terms of burned area since records began in 1940 with about 2.1 million hectares burned [*Hayasaka et al.*, 2016; *Partain et al.*, 2016]. An unseasonably warm spring and early snowmelt allowed fuels to dry early in the season [*Partain et al.*, 2016]. In mid-June, thunderstorms caused an unprecedented number of lightning strikes (over 65,000) that ignited over 270 individual fires on anomalously dry fuel beds over the course of a week [*Hayasaka et al.*, 2016; *Veraverbeke et al.*, 2017]. Fires expanded rapidly during several hot and dry periods through mid-July, and then slowed down as multiple precipitation events and cool, damp weather minimized fire growth for the rest of the summer fire season.

The CRV tower captured an integrated signal of trace gas emissions from multiple fires across interior Alaska during the 2015 fire season [*Karion et al.*, 2016]. The data stream was comprised of continuous sampling for about 47 minutes out of every hour from June 9 – August 13, yielding more than 59,800 individual measurements, each with a 30 s duration. We identified intervals when fire emissions had a dominant influence on trace gas variability at CRV tower, and used these intervals to derive emission ratios. Analysis of these data indicate that smoldering processes may have a higher contribution to total wildfire emissions from North American boreal forests than previous estimates derived from aircraft sampling. To quantify the spatial and temporal variability of individual fires and their influence on CO, CH_4, and CO_2 at the CRV tower, we coupled a fire emissions inventory, the Alaska Fire Emissions Database (AKFED) [*Veraverbeke et al.*, 2015] with an atmospheric transport model, the Polar Weather Research and Forecasting Stochastic Time Integrated Lagrangian Transport (PWRF-STILT) model [*Henderson et al.*, 2015]. This modeling analysis indicated that the number of 2015 wildfires sampled in our study is comparable to the total number of North American boreal forest fires sampled in past work.

2 Methods

2.1 CARVE (CRV) Tower Observations

Atmospheric CO, CH_4, and CO_2 mole fractions were measured using a cavity ring-down spectrometer (CRDS, Picarro models 2401 and 2401m) [*Karion et al.*, 2016] at the CRV tower in Fox, Alaska (64.986°N, 147.598°W, ground elevation 611m above sea level). The tower is located about 20 km northeast of Fairbanks Alaska on top of a hill in hilly terrain (Figure 1), and within the interior lowland and upland forested ecoregion in interior Alaska [*Cooper et al.*, 2006]. There are three separate inlets on the CRV tower at different heights above ground level from which the spectrometer draws air for sampling. The spectrometer samples air from the highest level for about 50 minutes out of every hour, and then draws air from the other two levels for 5 minutes

Deleted: Flaming

Deleted: is more efficient at oxidizing organic matter directly…

Deleted: CO_2 gas than smoldering combustion,

Formatted: Font: Not Bold

Deleted: as

Deleted: Smoldering combustion can be defined as combustion with a modified combustion efficiency less than 0.85 [*Urbanski*, 2014].

Deleted: in a high oxygen environment

Deleted: 2004

Deleted:

Deleted: ; *Turquety et al.*, 2007].

Deleted: increases

Deleted: 15

Deleted: 15 with

Deleted: 65,000 samples

Deleted: The CRV tower experienced enhanced and highly correlated CO, CH_4, and CO_2 trace gas signals from fires for about 7% of the duration of the fire season.

Deleted: events

Deleted: events

Deleted: factors

Deleted: measurements

Deleted: further revealed

Deleted: with

Deleted: approach

Deleted: sample

at each level [*Karion et al.,* 2016]. Standard reference gases are sampled every 8 hours for 5 minutes, and measurements are removed for a time equivalent to three flushing volumes of the line, approximately 3 minutes, after a level change or switch to or from a calibration tank. All raw 30 s average measurements were calibrated according to *Karion et al.* [2016].

We used observations from air drawn from the top intake height at a height of 32 m above ground level in our analysis because this level had the highest measurement density and the smallest sensitivity to local ecosystem CO_2 fluxes near the tower [*Karion et al.*, 2016]. We used gaps in this time series, created when the spectrometer cycled to the lower inlets and following calibration, to separate the time series into discrete time intervals for the calculation of emission ratios. Each 30 s average measurement within a 47-minute sampling interval served as an individual point in our calculation of an emission ratio described below (Table 2).

2.2 Emission Ratios, Emission Factors, and Modified Combustion Efficiency

We isolated intervals when fire had a dominant influence on trace gas variability observed at CRV to calculate emission ratios. An interval with dominant fire influence was defined as a continuous 47-minute measurement period that had: 1) a minimum of at least 30 trace gas measurements (with each measurement representing a mean over 30 seconds), 2) a mean CO over the entire interval exceeding 0.5 ppm, and 3) significant correlations between CO and CO_2, and between CH_4 and CO_2, with r^2 values for both relationships exceeding 0.80.

For each interval, we required a sample size of at least 30 individual 30 s measurements. For each interval meeting this criterion, we calculated the mean CO mole fraction and discarded intervals that had a mean CO less than 0.5 ppm. For each of the intervals with mean CO that exceeded the 0.5 ppm threshold, we then extracted the 30 s measurement time series of CO, CH_4, and CO_2 mole fractions and calculated correlation coefficients between the trace gas time series. Only intervals with high and significant correlations between CO and CO_2 and between CH_4 and CO_2 ($r^2 > 0.80$; $p < 0.01$, $n > 30$) were retained, because covariance among these co-emitted species is a typical signature of combustion [*Urbanski*, 2014]. Data from each of the intervals that met the three criteria described above were used to compute emission ratios, emission factors, and MCE. These intervals are reported in chronological order in Table 2.

We calculated background mole fractions of CO and CH_4 by taking an average of observations prior to any major fire activity in interior Alaska during day of year (DOY) 160 – 162.5. This yielded a CO background of 0.110 ppm and a CH_4 background of 1.900 ppm. We modeled hourly CO_2 background mole fractions to account for the influence of net ecosystem exchange (NEE) using a multi-variable linear regression model trained on CRV tower observations during 2012, a year with little to no fire influence on trace gas variability. The variables used in the CO_2 model include DOY and hourly observations of temperature, vapor pressure deficit, precipitation, latent heat flux, and hourly CO_2 observations from Barrow, AK (Figure 2). Meteorological variables were acquired from the National Climatic Data Center Automated Weather Observing System for Fairbanks International Airport (http://www7.ncdc.noaa.gov/CDO/cdopoemain.cmd). This location was chosen due to its proximity to the CRV tower. We obtained 3-hourly latent heat flux estimates from the NOAH2.7.1 GLDAS/NOAH experiment 001 for version 2 of the Global Land Data Assimilation System (GLDAS-2) [*Rodell et al.*, 2015]. Hourly in situ CO_2 observations from a clean air site at Barrow, AK were obtained from the Earth System Research Laboratory Global Monitoring Division [*Thoning et al.*, 2007]. Our model assumed negligible influence from fossil fuel combustion on background mole fraction variability. After training on data from the summer of 2012, the model was then run using 2015 input variables to calculate time evolving CO_2 background mole fractions during our analysis period. In a final step, the hourly CO_2 model was linearly interpolated to have the same temporal resolution as the 30 s individual trace gas measurements.

Deleted: The data stream from this spectrometer has gaps

Deleted: 50

Deleted: as the spectrometer cycles

Deleted: lower inlets.

Deleted: All raw 30 s average measurements were calibrated according

Deleted: *Karion et al.* [2016].

Deleted: factors

Deleted: .

Deleted: tower

Deleted: factors

Deleted: thirty

Deleted: We used the gaps in the data stream when the spectrometer sampled air from the lower levels to separate the dataset into a set of continuous 50-minute intervals of trace gas observations with less than 15 s between

Deleted: new 30 s averaged measurement and by applying a minimum sampling

Deleted: criterion

Deleted: We

Deleted: for each interval

Deleted: removed all

Deleted: with

Deleted: interval

Deleted: high levels of

Deleted: all three gases.

Deleted: periods

Deleted: :

Deleted: :

Deleted: <

Deleted: fire emissions [*Urbanski*, 2014].

Deleted: 170 – 172

Deleted: 90

Deleted: concentrations

Deleted: Bayesian approach

Deleted: We assumed negligible influence from fossil fuel combustion on background mole fraction variability. The hourly CO_2 model was linearly interpolated to have the same temporal resolution as the CRV tower data.

Deleted: , day of year

Deleted:

Deleted: -

Deleted: attained

Deleted: In a sensitivity analysis we found that the ... [1]

Deleted: had only a small effect, because the

Deleted: did not change appreciably

Deleted: duration of each 50-minute time interval used to ... [2]

We estimated an emission ratio (*ER_X*; equation 1) by calculating the slope from a type II linear regression of CO or CH_4 excess mole fractions (*ΔX*) relative to the CO_2 excess mole fraction (*ΔCO_2*) using all of the 30 s observations available within a single 47-minute sampling interval when fire had a dominant influence on tower trace gas variability (up to 95 pairs of measurements). Uncertainty estimates for each interval were estimated as the standard deviation of the slope of the regression. To estimate excess mole fractions (denoted with a Δ), we first removed background mole fractions (described above) before performing the regression analysis and obtaining the slope. The assumed background levels for CO and CH_4 did not influence this emission ratio estimate, because they were assumed to remain constant throughout the duration of each 47-minute interval (i.e., they influenced the intercept but not the slope of the regression line). In a sensitivity analysis we found that the removal of the CO_2 background, which did evolve within each 47-minute interval, had only a negligible effect, because the CO_2 background did not change rapidly over time. Since multiple fires were often burning simultaneously during the 2015 fire season, the emission ratios we report in Table 2 for each interval likely represent a composite of emissions from several fires.

$$ER_X = \frac{\Delta X}{\Delta CO_2} = \frac{X_{Fire} - X_{Background}}{CO_{2\,Fire} - CO_{2\,Background}} \qquad (1)$$

Emission factors (*EF_X*) were calculated using equation 2, where *MM_x* is the molar mass of CO or CH_4, *MM_C* is the molar mass of carbon, *F_C* is the mass fraction of carbon in dry biomass, 1000 is a factor to convert kg to g, *ER_X* is the emission ratio, and *C_T* is given by equation 3. The units for an emission factor are grams of compound emitted per kg dry biomass burned. In equation 3, *n* is the number of carbon containing species measured, *N_i* is the number of carbon atoms in species *i*, and *ΔX_i* is the excess mole fraction of species *i* [*Yokelson et al.*, 1999; *Akagi et al.*, 2011]. Here we computed *C_T* by allowing *i* in equation 3 to cycle over CO_2, CO, and CH_4 (*n* = 3). We assumed the fraction of carbon in combusted fuels, *F_C*, was 0.45 [*Santin et al.*, 2015], but note that *F_C* can range from 0.45 – 0.55 [*Akagi et al.*, 2011].

$$ER_X = \frac{\Delta X}{\Delta CO_2} = \frac{X_{Fire} - X_{Background}}{CO_{2\,Fire} - CO_{2\,Background}} EF_X = \frac{MM_X}{MM_C} * F_C * 1000 * \frac{ER_X}{C_T}$$

(2)

$$C_T = \sum_{i=1}^{n} N_i * \frac{\Delta X_i}{\Delta CO_{2i}} \qquad (3)$$

We also calculated the MCE for each fire-affected interval. Modified combustion efficiency is defined as the excess mole fraction of CO_2 divided by the sum of the excess mole fractions of CO and CO_2 [*Ward and Radke*, 1993]. MCE was used to separate intervals into three categories: smoldering, mixed, or flaming. These categories reflect the dominant combustion process contributing to trace gas anomalies at the CRV tower during the summer of 2015. Periods with an MCE less than 0.85 were considered to consist of mostly smoldering combustion, periods with a MCE of greater than or equal to 0.85 and less than 0.92 were classified as consisting of a mixture of smoldering and flaming combustion, and periods with an MCE greater than 0.92 were classified as flaming [*Urbanski*, 2014]. We performed this classification to allow for a visualization of how the sampled combustion processes varied from interval to interval (and day to day) during the 2015 fire season.

2.3 Transport Modeling

We coupled a fire emission model, the Alaskan Fire Emissions Database (AKFED) [*Veraverbeke et al.*, 2015] with an atmospheric transport model, the Polar Weather Research and Forecasting Stochastic Time Integrated Lagrangian Transport model (PWRF-STILT) [*Henderson et al.*, 2015] to estimate fire contributions to trace gas variability at the CRV tower, following *Wiggins*

Deleted: ratios

Deleted: and

Formatted: Font: Italic

Deleted: (Equation 1). Excess mole fractions denoted with a Δ symbol refer to

Formatted: Font: Italic

Deleted: of trace gas mole fractions during intervals

Deleted: with

Moved (insertion) [4]

Deleted: values subtracted.

Deleted: *F_C* is the mass fraction of carbon in dry biomass,

Deleted: 12.0

Deleted: *ER_x*

Deleted: , where

Deleted: *ΔC_i*

Deleted:] (Equation 2).

Formatted: Font: Italic, Not Superscript/ Subscript

Moved up [4]: $ER_X = \frac{\Delta X}{\Delta CO_2} = \frac{X_{Fire} - X_{Background}}{CO_{2\,Fire} - CO_{2\,Background}}$

Deleted: → →→→→→ → (1)¶

Deleted: $*$

Deleted: $*$

Deleted:

Deleted: modified combustion efficiency (

Deleted:)

Deleted: emission factor

Deleted: events

Deleted: period

Formatted: Tab stops: 3.6", Centered

Deleted: contribution

Deleted: from

Deleted: observations

et al. [2016]. For this application, STILT [*Lin et al.*, 2007] was used to estimate the adjoint of PWRF [*Skamarock et al.*, 2005; *Chang et al.*, 2014; *Henderson et al.*, 2015] during the summer of 2015 at the location of the CRV tower, to generate surface influence functions that relate surface ecosystem fluxes from Alaska to trace mole fractions at CRV. These gridded influence functions are known as footprints and have units of mole fraction per unit of surface flux (ppm/(μmol m^{-2} s^{-1})). Here we emitted fire emissions into the surface influenced volume of PWRF-STILT, which extends from the surface to the top of the planetary boundary layer, with the assumption that fire emissions were equally distributed within the planetary boundary layer [*Turquety et al.*, 2007; *Kahn et al.*, 2008]. In a previous study using the same tower, a sensitivity study revealed that plume injection height contributed only minimally to variability in remotesimulated fire-emitted CO predictions at CRV with PWRF-STILT [*Wiggins et al.*, 2016].

Daily burned area in AKFED was mapped using thermal imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) within fire perimeters from the Alaska Large Fire Database. Both above and belowground carbon consumption were modeled as a function of elevation, day of burning, pre-fire tree cover, and difference normalized burn ratio (dNBR) measurements derived from 500 m MODIS surface reflectance bands [*Veraverbeke et al.*, 2015]. AKFED predicted carbon emissions from fires with a temporal resolution of 1 day and a spatial resolution of 450 m. We regridded AKFED to the same spatial resolution as the atmospheric transport model (0.5°) for the model coupling. To account for diurnal variability in emissions, here we imposed a diurnal cycle on daily emissions following *Kaiser et al.* [2009], where the diurnal cycle was the sum of a constant and a Gaussian function that peaks in early afternoon with 90% of emissions occurring during the day (hours 0600 to 1800 local time) and 10% at night (hours 1800 to 0600 local time). Analysis of the sum of fire radiative power from all of the fire detections in the MODIS MCD14ML C6 product showed that 83% of detected fire activity occurred during the daytime overpasses (10:30am and 1:30pm) relative to the sum across both daytime and nighttime overpasses during the 2015 Alaskan wildfire season (data not shown). The satellite observations, although temporally sparse (with only 4 over passes per day), were broadly consistent with the diurnal cycle we prescribed for fire emissions in the model.

We convolved AKFED with the PWRF-STILT footprints to determine individual fire contributions to CO anomalies at the CRV tower. This was achieved by calculating the total CO contribution from each individual 0.5° grid cell from the AKFED × PWRF-STILT combined model and utilizing the fire perimeters from the Alaska Large Fire Database (data provided by Bureau of Land Management (BLM) Alaska Fire Service, on behalf of the Alaska Wildland Fire Coordinating Group (AWFCG) and Alaska Interagency Coordination Center (AICC)) to identify the location of individual fires. AKFED uses the same fire perimeter database for burned area and carbon emissions estimates [*Veraverbeke et al.,* 2015]. We determined an individual fire's contribution to CO at the CRV tower by setting all emissions in AKFED for a particular grid cell to zero and rerunning the model coupling with PWRF-STILT. The difference between the original model and the updated coupling that excluded emissions from an individual fire was equal to the individual fire's contribution to CO at CRV tower, when integrated over the 2015 fire season. Due to the 0.5° grid cell size used for model coupling, more than one fire perimeter existed in some of the individual grid cells. In these cases, the contribution for each fire was determined by weighting the total signal contribution by fire size.

We also used the footprints from PWRF-STILT to quantify the contribution of day and night emissions and mean transit times (Figure 3). The footprints are on a 0.5° latitude-longitude grid with a temporal resolution of 1 h during hours 0600 to 1800 (day) local time and 3 h during hours 1800 to 0600 local time (night). These functions provide an estimate of the impact of upwind surface fluxes at different times in the past on CRV tower trace gas mole fraction measurements at a given time. We analyzed the footprints for each interval in Table 2 to confirm CRV tower observations integrated emissions from multiple fires and captured variability in emissions across the diurnal fire cycle. Overall, we found that 73% of the summer fire CO anomaly at CRV originated from fire emissions that occurred during the day (0600 to 1800 local time) and 27% from emissions that occurred at night (1800 –

Deleted:

Deleted: from

Deleted: is

Deleted: are

Deleted: based on

Deleted: 500m

Deleted: predicts

Deleted: is

Deleted: product

Deleted: and the number

Deleted: from

Deleted: are

Deleted: CRV tower.

Deleted: In a previous study using the same tower, a sensitivity study revealed that plume injection height contributed only minimally to variability in simulated fire-emitted CO with PWRF-STILT [*Wiggins et al.,* 2016].

Moved (insertion) [1]

Deleted: is equal to

Deleted: the

Moved up [1]: In a previous study using the same tower, a sensitivity study revealed that plume injection height contributed only minimally to variability in simulated fire-emitted CO with PWRF-STILT [*Wiggins et al.,* 2016].

Deleted: influence functions or "

Deleted: " (ppm per μmol/m^2/s)

Deleted: the atmospheric model

Deleted: transport

Deleted: between the point of emission and measurement at the CRV tower.

Deleted:)

Deleted: , and

Deleted: time period associated with an emission factor period…

Deleted: represented an integration of

0600 local time). The footprints associated with each emission factor interval also were used to determine how much of the signal was coming from burning on previous days. We found that more than 99% of the fire emissions that influenced CO at CRV occurred within 3 days of an sampling interval used to derive an emission ratio, with 76% occurring within the first 24 hours, 21% during the next 24 hours, and 3% occurring three days prior to the sampling interval.

2.4 Comparison with Previous CO Emission Ratio Studies

To investigate the possible influence of sampling strategy and differences associated with sampling in different ecosystem types, we compiled available studies that report CO emission ratios for boreal forest fires and organized the studies into several categories with common characteristics, including aircraft sampling of North American boreal forest wildfires, aircraft sampling of North American boreal forest management or prescribed fires, combustion of North American boreal forest fuels measured in the laboratory, and sampling of Siberian boreal fires from both aircraft and surface platforms (Table 1). In our analysis we included original studies reported in Andreae (2019) and Akagi et al. (2011) and several others we found in a literature survey.

3 Results

3.1 Emission Factors and Modified Combustion Efficiency

During the 2015 Alaska fire season, we observed synchronized enhancements of CO, CH$_4$, and CO$_2$ well above background concentrations at CRV from DOY 173 – 196 (Figure 4). We identified 55 individual fire-affected intervals in the measurement time series (that each span about 47 minutes) and used these intervals to calculate emission ratios, emission factors, and MCE (Figure 5; Table 2). CO/CO$_2$ emission ratios ranged from 0.025 to 0.272 and CH$_4$/CO$_2$ emission ratios ranged from 0.002 to 0.020. MCE varied between 0.786 and 0.976 (Table 2). CO emission factors ranged from 25 to 223 g kg^{-1} dry biomass burned and CH$_4$ emission factors ranged from 1.2 to 10.7 g kg^{-1} dry biomass burned.

The mean CO/CO$_2$ emission ratio was 0.141 ± 0.051, the mean CO emission factor was 127 ± 40 g kg^{-1} dry biomass burned, and the mean MCE was 0.878 ± 0.039. Concurrently, the mean CH$_4$/CO$_2$ emission ratio was 0.010 ± 0.004 and the mean CH$_4$ emission factor was 5.32 ± 1.82 g kg^{-1} dry biomass burned.

A strong linear relationship existed between the CH$_4$ emission factor and MCE across the different sampling intervals (Figure 6). Linear relationships between CH$_4$ emission factors and MCE have also been observed in previous studies [*Yokelson et al.*, 2007; *Burling et al.*, 2011; *Van Leeuwen and van der Werf*, 2011; *Yokelson et al.*, 2013; *Urbanski*, 2014; *Smith et al.*, 2014; *Strand et al.*, 2016, *Guerette et al.*, 2018]. The relationship shown in Figure 6 implies MCE can be used to estimate CH$_4$ emissions (and emissions of other closely related trace gases) from North American boreal forest wildfires when measurements of CH$_4$ are not available.

We classified each fire-affected sampling interval as being associated with smoldering, mixed, or flaming combustion processes using thresholds on MCE. This analysis revealed that intervals with different combustion phases were interspersed throughout the fire season, with no clear progression over time, or clustering of flaming or smoldering processes during periods with high or low levels of burning. We identified 12 smoldering intervals, 37 mixed intervals, and 6 flaming intervals throughout the fire season (Figure 5, with examples shown in Figure 7). Smoldering intervals had a mean CO/CO$_2$ ratio of 0.214 ± 0.030, a mean CO emission factor of 183 ± 21 g kg^{-1} dry biomass burned, a mean CH$_4$/CO$_2$ ratio of 0.014 ± 0.003, a mean CH$_4$ emission factor of 6.89 ± 1.18 g kg^{-1} dry biomass burned, and a mean MCE of 0.824 ± 0.020. Mixed intervals consisting of both smoldering and flaming combustion had a mean CO/CO$_2$ emission ratio of 0.131 ± 0.024, a mean CO emission factor of g kg^{-1} dry biomass

Deleted: in
Deleted: tower observations
Deleted: 3
Deleted: events
Deleted: 50
Deleted: each
Deleted: from the elevated trace gas observations
Deleted: 4
Deleted: ranged from
Deleted: to
Deleted: 975
Deleted: CO per
Deleted: combusted
Deleted: 18
Deleted: CH$_4$ per
Deleted: combusted.
Deleted: CO per
Deleted: combusted
Deleted: CH$_4$ per
Deleted: combusted
Deleted: 5
Deleted: 5
Deleted: as a metric for
Deleted: emission factors
Deleted: dominated by
Deleted: events
Deleted: events
Deleted: events
Deleted: 4, within
Deleted: 6 and summarized Table 3).
Deleted: events
Deleted: CO per
Deleted: combusted
Deleted: CH$_4$ per
Deleted: combusted
Deleted: events
Deleted: 120 ± 20
Deleted: CO per

burned, a mean CH_4/CO_2 emission ratio of 0.010 ± 0.003, a mean CH_4 emission factor of 5.28 ± 1.51 g kg^{-1} dry biomass burned, and a mean MCE of 0.884 ± 0.019. Flaming intervals had a mean CO/CO_2 emission ratio of 0.060 ± 0.020, a mean CO emission factor of 59 ± 19 g kg^{-1} dry biomass burned, a mean CH_4/CO_2 emission ratio of 0.004 ± 0.001, a mean CH_4 emission factor of 2.49 ± 0.78 g kg^{-1} dry biomass burned, and a mean MCE of 0.944 ± 0.018 (Table 3).

In our primary analysis described above, each individual fire-influenced interval used to compute an emission ratio was weighted equally in computing a season-wide mean. As a sensitivity analysis, we computed the mean emission ratios weighting each interval according to its mean ΔCO mole fraction, and, alternately, according to its mean ΔCO_2 mole fraction. Weighting by ΔCO caused the CO emission ratio to increase from 0.141 to 0.146 but did not change the CH_4 emission ratio. Weighting by ΔCO_2 caused the emission ratios to slightly increase, yielding a CO emission ratio of 0.144 and, again, no change in the CH_4 emission ratio. Although the variation introduced from different weighting approaches was relatively small, the analysis highlights the challenge of combining information from different individual fires, and the importance of moving toward flux-weighted estimates in future work.

3.2 The Influence of Individual Fires on Trace Gas Variability at the CRV Tower

The forward model simulations combining AKFED fire emissions with PWRF-STILT confirmed that the elevated CO signals at the CRV tower can be attributed primarily to boreal forest fire emissions (Figure 8) and not to fossil fuels or other CO sources. The AKFED model had a Pearson's correlation coefficient of 0.61 with observed daily mean CO and had a low bias of approximately 7%. Differences between the model simulations and observations were likely caused by errors in the magnitude and timing of fire emissions within AKFED as well as the limited spatial resolution and incomplete representation of atmospheric transport within PWRF-STILT. Nevertheless, the broad agreement between the model and the observations, including the timing of the large burning interval between DOY 173 and 179, provides some confidence that our model can be used to explore the influence and contribution of individual fires.

We identified 34 individual fires that contributed to at least 1% of the CO mole fraction time series at CRV tower over the entire 2015 fire season (Figure 9; Figure 10; Table 3). The average distance of these fires from the CRV tower, weighted by their fractional contribution, was 259 ± 134 km. Most of the fires were located to the west of Fairbanks, in the direction of the prevailing summer surface winds. This analysis revealed that the CRV tower was sufficiently downwind to measure the integrated impact of multiple fires on regional trace gas concentration anomalies, sampling air masses that were mixed through the full planetary boundary layer and across several day-night cycles. The total CO emitted from these fires accounted for 75% of the excess CO mole fraction signal during DOY 160 – 200. The remaining CO signal originated from many smaller fires that were widely distributed across interior Alaska. The Tozitna fire was responsible for the greatest percentage of the total CO anomaly integrated over the 2015 fire season at the CRV tower (accounting for more than 10% of the integrated CO anomaly at CRV). The fires that contributed the most to the CO anomaly at CRV tower were not necessarily the closest fires to the tower or the largest fires of the 2015 fire season in terms of burned area. Combined, however, this set of 34 fires accounted for 0.97 Mha, or approximately 46% of the total burned area reported during the 2015 fire season [*Veraverbeke et al.*, 2017].

3.3 Comparison of emission ratios between sampling strategies

Previous studies sampled a total of 45 individual boreal forest fires for $\Delta CO/\Delta CO_2$ emission ratios or CO emission factors, and additional measurements have been made by combusting fuels in a laboratory setting. Solely considering emission ratio measurements from North American boreal forests (excluding boreal forests in Eurasia), the mean of aircraft sampling of wildfires

Deleted: combusted

Deleted: CH_4 per

Deleted: combusted

Deleted: events

Deleted: CO per

Deleted: combusted

Deleted: CH_4 per

Deleted: combusted

Deleted: event

Deleted: event

Deleted: (or decrease)

Deleted: XXX

Deleted: and

Deleted: to change in a similar way

Deleted: , from 0.010 to 0.0XX.

Deleted: change in the opposite direction,

Deleted:

Deleted: XXX

Deleted: a

Deleted: of 0.XXX. The

Deleted: revealed by this

Deleted: 7

Deleted:

Deleted: event

Deleted: 35

Deleted: 8

Deleted: 9

Deleted: On

Deleted: ,

Deleted: were 295 ± 131 km away

Deleted: mostly

Deleted: integrate emissions from multiple fires

Deleted:

Deleted: 8

Deleted: significantly

Deleted: 35

Deleted: 65

(0.102 ± 0.033, n=19) or management and prescribed fires (0.077 ± 0.022, n=14) were significantly lower than the mean derived from tower measurements reported here along with earlier measurements from *Wiggins et al.* [2016] (0.141 ± 0.049, n=37) as evaluated using a Student's t test. The mean emission ratio from Siberian boreal forest fires was 0.219 ± 0.048 (n=9), which was significantly higher than the mean of emission ratios reported for boreal forest wildfires in North America (sampled either by aircraft or tower).

4 Discussion

The most widely used emission factors for boreal forest fires are derived from syntheses that average together data from individual field campaigns [*Andreae and Merlet*, 2001; *Akagi et al*., 2011; *Andreae*, 2019]. Our mean emission factor for CO (127 ± 40 g kg^{-1} dry biomass burned) is similar to the mean reported in past syntheses for boreal forests, including estimates by *Andreae* [2019] (121 ± 47 g kg^{-1} dry biomass burned) and *Akagi et al.* [2011] (127 ± 45 g kg^{-1} dry biomass burned). Emission factors for CH_4 were also similar to the estimates reported in these syntheses. Considering boreal forests as a whole, our measurements provide a partial validation of the approach taken in previous compilations, which have attempted to combine information from different sampling strategies and boreal forest ecoregions. The broad level of agreement provides confidence in the estimates of emission factors for non-conserved species that cannot be measured using a remote tower sampling approach.

The observations summarized in Table 1 also show there are several important differences in boreal forest emission ratios that exist as a function sampling strategy and ecoregion. Within North American boreal forests, the CRV observations we analyzed here provide evidence that smoldering combustion contributes more to CO emissions than what has been estimated from previous aircraft studies. Specifically, our mean CO emission ratio from the CRV tower is 39% higher (and significantly different at a $p < 0.01$ level using a Student's t test) than the mean derived from aircraft based measurements of 19 North American boreal wildfires (Table 1). Although differences in reported emission ratios are expected between aircraft and ground based sampling approaches [*Christian et al.*, 2007; *Burling et al.*, 2011; *Akagi et al.*, 2014; *Collier et al.*, 2016; *Benedict et al.*, 2017; *Selimovic et al.*, 2019], several features of the CRV tower sampling are conducive to providing a regionally-representative mean estimate of emission ratios during the 2015 Alaska fire season. First, we note that the CRV tower was located at a higher elevation (611 m above sea level) than the core fire complex located in western Alaska and several hundreds of kilometers downwind. Multi-angle Imaging SpectroRadiometer (MISR) satellite observations from Alaskan wildfires indicate most fire plumes reside within the planetary boundary layer, which is typically between 1 and 3 km during midday in summer [*val Martin et al.*, 2010; *Wiggins et al.*, 2016]. Combining this vertical length scale with the mean horizontal distance of the 34 fires that most influenced CO at CRV (259 km), we obtain a factor of about 100 for a back-of-the-envelope ratio of horizontal to vertical mixing processes. This ratio, together with the simulated time delay of 1-2 days between emission and detection of CO anomalies at CRV (Figure 3), imply that mesoscale atmospheric circulation played an important role in averaging together trace gas emissions from multiple fires before the air masses were sampled (Figure 10). As a result, observations from the CRV tower represent a temporal integration of fire emissions over day-night burning cycles as well as a spatial integration across flaming combustion at active fire fronts along with residual smoldering combustion in soils that often persists for days after a fire front moves through an area. Collectively, the fires sampled at CRV appeared to experience time-varying environmental conditions that were less ideal for flaming combustion than the fire plumes sampled in past work by aircraft. This finding is consistent with remote tower observations of the black carbon to CO ratio measured for wildfires from temperate North America [*Selimovic et al.*, 2019].

In contrast with remote tower sampling, aircraft-based studies often sample fires that have a strong contribution from flaming combustion, which releases enough energy to generate well-defined plumes at an altitude accessible by the aircraft. This

Deleted: → The footprints associated with each emission factor event also were used to determine how much of the signal was coming from burning on previous days and the fraction of emissions emitted during day and night periods. We found that 99% of the fire emissions that influenced CRV tower trace gas concentrations occurred within 3 days of the sampling interval used to derive the emission factor for an individual event at the CRV tower, with 76% occurring within the first 24 hours, 21% during the next 24 hours, and 2% occurring three days prior to the event (Figure 10). Overall, 64% of the fire emissions that impacted the tower occurred during the day (0900 to 1800 local time) and 36% occurred at night (1900 – 0600 local time). ¶
4 Discussion¶
4.1 Measurement technique and ecosystem type as drivers of variability in boreal forest fire emission ratios¶
→

Formatted: Indent: First line: 0.5"

Deleted: 2011; *Andreae*, 2019]. In order to investigate the possible influence of sampling strategy employed by previous studies, and variations caused by ecosystem type, we compiled available studies that report CO emission ratios for boreal forest fires and organized the studies into several categories with common characteristics, including aircraft sampling of North American boreal forest wildfires, aircraft sampling of North American boreal forest management or prescribed fires, combustion of North American boreal forest fuels measured in the laboratory, and sampling of Siberian boreal fires from both aircraft and surface platforms (Table 1). All previous studies combined have sampled a total of 45

Deleted: individual boreal forest fires for CO emission ratios, and additional measurements have been made by combusting fuels in a laboratory setting. We found several important differences in emission ratios that may be linked with the measurement technique and ecosystem type.

Moved (insertion) [6]

Deleted: → First, solely considering emission ratio measurements from boreal North America, our surface tower measurements of about 35 fires, along with earlier tower measurements from Wiggins et al. (2016) have a considerably higher mean (0.141) than the mean of aircraft measurements sampling wildfires (0.102) or management and prescribed fires (0.077). We believe these differences are linked, in part, with sampling strategy. Aircraft [*Christian et al.*, 2007; *Burling et al.*, 2011; *Akagi et al.*, 2014 *et al.*, 2016; *Benedict et al.*, 2017; *Selimovic et al.*, 2010; *Wiggins et al.*,

Formatted: Indent: First line: 0.5"

Moved (insertion) [5]

methodology provides an opportunity to comprehensively measure the vertical and horizontal distribution of emissions from an individual fire and their atmospheric evolution in a smoke plume. However, airborne sampling techniques are often limited to daytime periods with good visibility, making it difficult to comprehensively measure emissions over a diurnal cycle or over the full lifetime of a fire which may span several periods with inclement weather. Due to these sampling constraints, aircraft studies are less likely to measure emissions from less energetic smoldering combustion, since these emissions are more likely to remain near the surface [*Ward and Radke*, 1993; *Selimovic et al.,* 2019]. Emissions from smoldering boreal forest fires can sometimes be entrained in the convective columns of certain flaming fires and can be sampled by aircraft, but nighttime emissions or residual smoldering emissions from fires that have weak convective columns usually cannot be measured in this way [*Bertschi et al.,* 2003; *Burling et al.,* 2011]. While past studies have attempted to combine information from aircraft (more likely sampling flaming combustion phases) with laboratory observations of emissions from smoldering combustion [*Akagi et al.*, 2011], the balance of these processes is well known to be sensitive to environmental conditions that can rapidly change over the lifetime of a wildfire; this highlights the importance of designing sampling approaches that provide regionally-integrated estimates over the full duration of a wildfire event or a regional fire complex.

During the latter half of June and early July of 2015, weather in Alaska was very hot and dry, allowing for a record number of fires to rapidly expand in size, and yielding the second highest level of annual burned area in the observed record. The extreme fire weather conditions would be expected to reduce fuel moisture content, thus promoting crown fires and flaming combustion processes [e.g., *Sedano and Randerson*, 2014]. This raises the question of whether longer term monitoring of many normal and low fire years (which tend to co-occur in cooler and wetter conditions) would provide evidence for an even larger role of smoldering combustion compared to the estimates we report here for 2015. Another related question is whether even within a fire season, do day-to-day or week-to-week variations in fire weather influence variability in emission ratios? We explored this latter question with the datasets described here but were unable to uncover structural relationships between daily meteorological variables such as vapor pressure deficit and CO emission ratios. Together, these questions represent important directions for future research and emphasize the critical need of sustained long-term support for trace gas monitoring networks and field campaigns.

As a function of ecoregion, emission ratios from fires in boreal Eurasia tend to be higher than emission ratios from fires in boreal North America, and are significantly different than tower or aircraft observations from North America when compared using a Student's t test. Although more measurements are needed, higher CO emission ratios for Siberian fires appear consistent with past work showing that boreal fire behavior is considerably different between North American and Eurasian continents as a consequence of differences in tree species and their impacts on fire dynamics [*Goldammer and Furyaev*, 1996; *Cofer et al.,* 1998]. Notably, as consequence of the presence of black spruce in many boreal forests of North America, fires tend to burn with a higher fire radiative power and faster spread rate, traveling through the crowns of trees and inducing higher levels of tree mortality [*Rogers et al.*, 2015]. This occurs because black spruce is a well-known fire embracer, retaining dead branches that serve as ladder fuels and carry fire into the overstory. Black spruce trees are absent from Siberia, where many pine and larch tree species lack ladder fuels and are known to be fire resistors. In Siberian ecosystems ground fires are more common [*Korovin*, 1996; *Rogers et al.*, 2015], a finding that appears consistent with the higher CO emission ratios (and larger contribution of smoldering combustion) shown in Table 1. Although emission factors from the Siberian boreal forest are often grouped together with emission factors from North American boreal forest in biome-level syntheses [e.g., *Andreae*, 2019], both emission ratio and remote sensing observations of fire severity suggest there may be enough evidence to separate these two ecoregions in future syntheses.

In Table 1 we also separated aircraft-based studies that measured emissions from wildfires from those that measured emissions from prescribed slash and land management fires, where trees are bulldozed, dried and intentionally arranged to promote maximum fuel consumption [*Cofer et al.*, 1990; *Cofer et al.*, 1998]. Land management fires consume dried aboveground fuels with

Deleted: 2012]. Near the end of the lifetime of a long-lived fire, aircraft measurements have sometimes observed a larger smoldering to flaming ratio [*Yates et al.*, 2016].

Moved up [5]: [*Christian et al.*, 2007; *Burling et al.*, 2011; *Akagi et al.*, 2014

Deleted: A few previous studies have investigated the differences in emissions measurements from ground and aircraft sampling of the same fire, reporting significant differences between the relative abundance of the emissions observed depending on the sampling method

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Deleted:]. Emission ratios derived from aircraft measurements are more likely to sample fires during times when flaming combustion processes are dominant [*Babbitt et al.,* 1996, *Akagi et al.*, 2014], yet rarely sample residual smoldering combustion that can substantially contribute to emissions over the full lifetime of an individual fire [*Bertschi et al.*, 2003].

Deleted: → Second,

Moved (insertion) [7]

a different fuel structure and moisture content than fuels consumed in a wildfire, where combustion from soil organic material layers is a dominant component of bulk emissions [Boby et al., 2010; *Dieleman et al.*, 2020]. Although the number of land management fires is relatively small, the mean from these studies suggest flaming processes are a more important contributor to this fire type than for wildfires, and some consideration of this difference should be factored into regional and global syntheses.

Several additional studies report emission ratios from laboratory combustion of fuels collected from North American boreal forests including biomass samples from black spruce, white spruce, and jack pine, as well as moss and surface organic material (duff). The laboratory studies have considerable variability that can be attributed to the type of fuel combusted and fuel moisture content. This work indicates duff consumption yields higher emission ratios for CO and CH_4 than combustion of black spruce or jack pine needles and other fine fuels [*Bertschi et al.*, 2003; *McMeeking et al.*, 2009; *Burling et al.*, 2011]. The fuels used in laboratory studies are usually dried and burned individually, although some studies have attempted to mimic natural fires by placing dried fine fuels on top of damp fuels that undergo residual smoldering combustion [*Bertschi et al.*, 2003]. The structure, composition, and moisture content of fuels are well known as key drivers of the composition and magnitude of emissions. Although these laboratory studies provide valuable information on emissions from individual fuel components, they are not able to capture the full complexity of a wildfire.

In the context of these comparisons among ecoregions and sampling strategies, it is important to recognize that tower-based sampling strategies, including the methodology presented in this study, have important limits. Ground-based sites may potentially miss some of the emissions injected above the planetary boundary layer. The fixed nature of this sampling technique also restricts the range of sampling, because towers can only monitor upwind fires. Although the tower-based sampling strategy allows for integration of emissions from fires across a range of environmental conditions and at different stages of fire life cycles, it may not allow for emission ratio measurements of non-conserved species, including particulate matter and many fire-emitted volatile organic compounds that have short lifetimes. The technique is also subject to higher uncertainty in the definition of background mole fractions for fire-affected trace gases, because of the dilution and mixing of fire emissions that occurs during transport. Thus, tower may not be a feasible or effective sampling methodology during years with low fire activity.

5 Conclusions

Using a remote tower downwind of a large regional fire complex in interior Alaska, we measured CO and CH_4 emission factors from about 34 individual fires during the summer of 2015. This is comparable to the number of individual wildfires sampled in North America in previous studies. Our results indicate smoldering combustion processes in North American boreal forest fires contribute to more trace gas emissions than previous estimates derived from aircraft sampling. Together, the two-month near continuous time series of CO_2, CO, and CH_4, along with the derived emission ratios reported here, may provide a means to test models that couple together fire processes, emissions, and regional atmospheric transport.

Comparison of emission ratios reported here with observations derived other sampling strategies and ecoregions in northern boreal forests provides directions for reducing future uncertainties. For boreal North America, our analysis of CRV tower observations indicate CO emission ratios are likely higher what would be inferred from previous studies, although questions remain regarding the representativeness of remote tower-based sampling. Given recent increases in data density for North America and improvements in our understanding of differences in tree species composition and fire dynamics between North America and Eurasia, it may be possible to reduce uncertainties in future syntheses by separately reporting emission factors for the two continents. More data, particularly for Siberian fires, however, Siberian is needed to assess whether the continental differences in emission ratios noted here are robust. Long-term monitoring from remote towers has the potential to provide new information

Deleted: *Rogers*

Deleted: field study, *Boby et al.*YEAR].

Deleted: Third, three

Deleted: much

Deleted: *Mcmeeking*

Deleted: Fourth, emission factors from the Eurasian boreal forest are often grouped together with emission factors from North American boreal forest in biome-level syntheses [*Andreae*, 2019]. Yet, Table 1 shows emission ratios from wildfires in boreal Asia tend to be higher than emission ratios from North American wildfires. Although more measurements are needed, higher CO emission ratios for Siberian fires appears consistent with past work showing that boreal fire behavior is fundamentally different between North American and Eurasian continents as a consequence of differences in tree species and their impacts on fire dynamics. Notably, as consequence of the presence of black spruce in many boreal forests of North America, fires tend to burn hotter and faster, traveling through the crowns of trees and inducing higher levels of tree mortality [*Rogers et al.*, 2015]. This occurs because black spruce is a well-known fire embracer, retaining dead branches that serve as ladder fuels–carrying fire into the overstory where seeds in serotinous cones are activated by fire. Black spruce trees are absent from Siberia, where many pine and larch tree species lack ladder fuels and are known as fire resistors. In Siberian ecosystems ground fires are more common [*Rogers et al.*, 2015], a finding that appears consistent with the higher CO emission ratios (and stronger contribution of smoldering combustion) shown in Table 1.¶
4.2 Evidence for a stronger role of smoldering combustion in emissions from North American boreal wildfires→¶
Our mean emission factor for CO (127 ± 59 g CO per kg of dry biomass consumed) is similar to the mean reported in past syntheses for boreal forests, including estimates by *Andreae* [2019] (121 ± 47 g CO per kg of dry biomass consumed) and *Akagi et al.* [2011] (127 ± 45 g CO per kg of dry biomass consumed). However, if studies that are not representative of North American boreal forest wildfires are excluded (including measurements from prescribed fires, laboratory studies, and studies of fires from the Eurasian boreal forests) and we focus on emission ratios, to avoid ... [3]

Moved up [6]: *Wiggins et al.*,

Moved up [7]: were unable to uncover structural relationships between daily meteorological variables such as vapor pressure deficit and CO emission ratios. Together, these questions represent important directions for future

Moved (insertion) [8]

Deleted: In the context of interpreting the CRV measurements, it's important to note that MISR satellite observations from Alaskan wildfires indicate most fire plumes reside within the planetary boundary layer, which is ... [4]

Deleted: Eurasian

Deleted: and North American boreal forest fires, given what we know about differences in species composition, fire dynamics, and measurements of emission factors between the two continents. More data, particularly for Eurasian

Deleted: fires,

Deleted: factors

about fire complexes in other biomes, integrating across day-night variations in fire behavior, periods with different environmental conditions, and across multiple fires in different stages of growth and extinction. In this context, more work is needed to find ways to combine tower and aircraft sampling to attain accurate estimates of the total budget of fire-emitted trace gases and aerosols (i.e., estimating flux-weighted emission factors), given the large differences in data density and the different strengths and weaknesses of the two approaches. To make progress on this issue, a closer integration is needed in future field campaigns between measurements of pre-fire ecosystem state, fire behavior (temperature, fire radiative power, and spread rate), measurements of emissions composition, and post-fire sampling of fuel consumption and combustion completeness during times when fire dynamics are fundamentally different. This coordination across disciplines in both study design, data analysis, and modeling is rare and may provide a path toward creating the observations needed to dynamically model the temporal evolution of the chemical composition of wildland fire emissions over the lifetime of an individual fire and, within a region, during different phases of a fire season.

Acknowledgements

E.B.W. thanks the U.S. National Science Foundation for a Graduate Research Fellowship (NSF 2013172241). The CRV tower observations and footprints used in our analysis are archived at the U.S. Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (http://dx.doi.org/10.3334/ORNLDAAC/1316). The trace gas observations, fire emissions time series, and WRF-STILT model were created through funding support to NASA's CARVE field program led by C. Miller. JTR acknowledges additional NASA support from CMS (80NSSC18K0179) and IDS (80NSSC17K0416) programs. We thank the staff of the NOAA Fairbanks Command and Data Acquisition Station that hosts CRV, and especially Frank Holan and Marc Meindl, for their technical support. We also thank NOAA/ESRL/GMD staff, especially Phil Handley, Jon Kofler, and Tim Newberger for ongoing remote maintenance of CRV.

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, 4039-4072, doi:10.5194/acp-11-4039-2011, 2011.

Akagi, S. K., Burling, I. R., Mendoza, A., Johnson, T. J., Cameron, M., Griffith, D. W. T., Paton-Walsh, C., Weise, D. R., Reardon, J. and Yokelson, R. J.: Field measurements of trace gases emitted by prescribed fires in southeastern US pine forests using an open-path FTIR system. Atmos. Chem. and Phys., 14, 199-215, http://dx.doi.org/10.5195/acp-14-199-2014, 2014.

Andreae, M. O. and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochem. Cycles, 15, 955-966, doi:10.1029/2000GB001382, 2001.

Andreae, M.O.: Emission of trace gases and aerosols from biomass burning–an updated assessment. Atmos. Chem. Phys., 19, 8523-8546, https://doi.org/10.5194/acp-19-8523-2019, 2019.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., Simpson, L. G. and Vinson, T. S.: Boreal forests and tundra, Water, Air, Soil Pollut., 70, 39-43, doi:10.1007/BF01104987, 1993.

Deleted: ¶
→ Second, it's important to further explore ways to weight the information content from different studies, considering the number of fires sampled, the duration and intensity of sampling, the representativeness of the sampling approach, and the representativeness of the

Deleted: that were sampled relative to the typical pattern of burning within a biome. Here using a remote surface tower, we were able to get an integrated estimate

Deleted: CO and CH_4 emission ratios from about 35 wildfires from an ecologically significant regional fire complex. While these observations represent a step change in CO and CH_4 data availability for North American boreal forest fires

Deleted: a way

Deleted: systematically

Deleted: this information with other observations generated using different sampling techniques.¶ ... [5]

Deleted: would be an important path toward reducing ... [6]

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: robustness of our mean estimates to weighting ... [7]

Formatted: Font color: Text 1

Deleted: instantaneous

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: structure and

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: were

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: ¶ ... [8]

Moved up [8]: ¶

Deleted: 35 individual fires during the summer of 2015. ... [9]

Deleted: http://dx.doi.org/10.3334/ORNLDAAC/1316).

Deleted:),

Deleted:), and SMAP (NNX16AQ23G

Formatted ... [10]

Formatted ... [11]

Formatted ... [12]

Deleted: &

Moved (insertion) [9]

Deleted: Atmospheric Chemistry

Deleted: Physics,

Field Code Changed

Formatted ... [13]

Formatted: Font: 10 pt

Benedict, K. B., Prenni, A. J., Carrico, C. M., Sullivan, A. P., Schichtel, B. A., and Collett Jr., J. L.: Enhanced concentrations of reactive nitrogen species in wildfire smoke, Atmos. Environ., 148, 8–15, https://doi.org/10.1016/j.atmosenv.2016.10.030, 2017.

Bertschi, I., Yokelson, R. J., Ward, D. E., Babbitt, R. E., Susott, R. A., Goode, J. G. and Hao, W. M.: Trace gas and particle emissions from fires in large diameter and belowground biomass fuels, J. Geophys. Res. Atmos., 108, 8472, doi:10.1029/2002JD002100, 2003.

Boby, L. A., Schuur, E. A. G., Mack, M. C., Verbyla, D. and Johnstone, J. F.: Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest, Ecol. Appl., 20, 1633-1647, doi:10.1890/08-2295.1, 2010.

Burling, I. R., Yokelson, R. J., Akagi, S. K., Urbanski, S. P., Wold, C. E., Griffith, D. W. T., Johnson, T. J., Reardon, J., Weise, D. R.: Airborne and ground-based measurements of the trace gases and particles emitted by prescribed fires in the United States, Atmos. Chem. and Phys., 11, 12197-12216, 2011.

Chang, R.Y.W., Miller, C.E., Dinardo, S.J., Karion, A., Sweeney, C., Daube, B.C., Henderson, J.M., Mountain, M.E., Eluszkiewicz, J., Miller, J.B. and Bruhwiler, L.M.: Methane emissions from Alaska in 2012 from CARVE airborne observations, Proc. Natl. Acad. Sci., 111, 47, 16694–16699, https://doi.org/10.1073/pnas.1412953111, 2014.

Christian, T. J., Yokelson, R. J., Carvalho Jr., J. A., Griffith, D. W. T., Alvarado, E. C., Santos, J. C., Neto, T. G. S., Veras, C. A. G., and Hao, W. M.: The tropical forest and fire emissions experiment: Trace gases emitted by smoldering logs and dung on deforestation and pasture fires in Brazil, J. Geophys. Res., 112, D18308, doi:10.1029/2006JD008147, 2007.

Cofer, W. R., Levine, J. S., Sebacher, D. I., Winstead, E. L., Riggan, P. J., Stocks, B. J., Brass, J. A., Ambrosia, V. G., and Boston, P. J.: Trace gas emissions from chaparral and boreal forest fires, J. Geophys. Res., 94, 2255–2259, doi:10.1029/JD094iD02p02255, 1989.

Cofer, W. R., Levine, J. S., Winstead, E. L. and Stocks, B. J.: Gaseous emissions from Canadian boreal forest fires, Atmos. Environ. Part A, Gen. Top., 24, 1653-1659, doi:10.1016/0960-1686(90)90499-D, 1990.

Cofer, W. R., Winstead, E. L., Stocks, B. J., Goldammer, J. G. and Cahoon, D. R.: Crown fire emissions of CO$_2$, CO, H$_2$, CH$_4$, and TNMHC from a dense jack pine boreal forest fire, Geophys. Res. Lett., 25, 3919-3922, doi:10.1029/1998GL900042, 1998.

Collier, S., Zhou, S., Onasch, T., Jaffe, D., Kleinman, L., Sedlacek, A., Briggs, N., Hee, J., Fortner, E., Shilling, J., Worsnop, D., Yokelson, R., Parworth, C., Ge, X., Xu, J., Butterfield, Z., Chand, D., Dubey, M., Pekour, M., Springston, S., and Zhang, Q.: Regional influence of aerosol emissions from wildfires driven by combustion efficiency: Insights from the BBOP campaign, Environ. Sci. Technol., 50, 8613-8622, doi:10.1021/acs.est6b01617, 2016.

Cooper, D. J., Gallant, A. L., Binnian, E. F., Omernik, J. M. and Shasby, M. B.: Ecoregions of Alaska, Arct. Alp. Res., 29, 494, doi:10.2307/1551999, 2006.

Moved down [10]: E.,

Moved down [11]: E.,

Deleted: Babbitt, R.

Deleted: Ward, D.

Formatted: Font color: Black

Formatted: Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Deleted: Susott, R. A., Artaxo, P., and Kaufmann, J.B.: A comparison of concurrent airborne and ground based emissions generated from biomass burning in the Amazon ... [14]

Formatted: Font: 10 pt

Formatted ... [15]

Formatted: Font: 10 pt

Formatted ... [16]

Formatted ... [17]

Formatted ... [18]

Moved (insertion) [10]

Deleted: Veres, P., Roberts, J.M., Warneke, C., Urbanski ... [20]

Formatted ... [19]

Formatted ... [21]

Deleted: R. and Hao, W.M.: Laboratory measurements ... [22]

Moved up [9]: Atmos. Chem.

Deleted: and Phys., 10, 11115-11130, 2010.¶ ... [23]

Moved down [12]: Griffith, D.

Deleted: W. T.; Johnson, T. J.; Reardon, J.; Weise, D.

Formatted ... [24]

Deleted: .

Formatted ... [25]

Deleted: Chen, L. W. A., Moosmüller, H., Arnott, W. P. ... [26]

Moved down [13]: C.,

Formatted ... [27]

Deleted: Watson, J. G., Susott, R. A., Babbitt, R.

Moved down [14]: E.,

Deleted: Wold, C.

Moved down [15]: E.,

Deleted: Lincoln, E. N. and Wei, M. H.: Emissions from ... [29]

Moved (insertion) [11]

Formatted ... [30]

Moved (insertion) [13]

Formatted ... [28]

Formatted ... [31]

Deleted: Christopher, S.A., Gupta, P., Nair, U., Jones, ... [32]

Formatted: Font: Not Italic

Deleted: 10.1029/JD094iD02p02255

Deleted: ¶ ... [33]

de Groot, W. J., Flannigan, M. D. and Cantin, A. S.: Climate change impacts on future boreal fire regimes, For. Ecol. Manage., 294, 35-44, doi:10.1016/j.foreco.2012.09.027, 2013.

Dieleman, C.M., Rogers, B.M., Potter, S., Veraverbeke, S., Johnstone, J.F., Laflamme, J., Solvik, K., Walker, X.J., Mack, M.C. and Turetsky, M.R.: Wildfire combustion and carbon stocks in the southern Canadian boreal forest: Implications for a warming world. Glob. Change Bio., https://doi.org/10.1111/gcb.15158, 2020.

Duck, T. J., Firanski, B. J., Millet, D. B., Goldstein, A. H., Allan, J., Holzinger, R., Worsnop, D. R., White, A. B., Stohl, A., Dickinson, C. S. and van Donkelaar, A.: Transport of forest fire emissions from Alaska and the Yukon Territory to Nova Scotia during summer 2004, J. Geophys. Res. Atmos., 112, D10S44, doi:10.1029/2006JD007716, 2007.

Flannigan, M., Campbell, I., Wotton, M., Carcaillet, C., Richard, P. and Bergeron, Y.: Future fire in Canada's boreal forest: paleoecology results and general circulation model - regional climate model simulations, Can. J. For. Res., 31, 854-864, doi:10.1139/x01-010, 2001.

Forster, C., Wandinger, U., Wotawa, G., James, P., Mattis, I., Althausen, D., Simmonds, P., O'Doherty, S., Jennings, S. G., Kleefeld, C., Schneider, J., Trickl, T., Kreipl, S., Jäger, H. and Stohl, A.: Transport of boreal forest fire emissions from Canada to Europe, J. Geophys. Res. Atmos., 106, 22887-22906, doi:10.1029/2001JD900115, 2001.

French, N. H. F., Kasischke, E. S. and Williams, D. G.: Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest, J. Geophys. Res. Atmos., 107, 8151, doi:10.1029/2001jd000480, 2002.

French, N. H. F., Goovaerts, P. and Kasischke, E. S.: Uncertainty in estimating carbon emissions from boreal forest fires, J. Geophys. Res. Atmos., 109, D14S08, doi:10.1029/2003JD003635, 2004.

Friedli, H. R., Radke, L. F., Prescott, R., Hobbs, P. V., and Sinha, P.: Mercury emissions from the August 2001 wildfires in Washington State and an agricultural waste fire in Oregon and atmospheric mercury budget estimates, Global Biogeochem. Cycles, 17, 1039, doi:10.1029/2002GB001972, 2003.

Fromm, M., Alfred, J., Hoppel, K., Hornstein, J., Bevilacqua, R., Shettle, E., R. Servranckx, R., Li, Z., and Stocks, B.: Observations of boreal forest fire smoke in the stratosphere by POAM III, SAGE II, and lidar in 1998, Geophys. Res. Lett., 27, 1407–1410, https://doi.org/10.1029/1999GL011200https://doi.org/10.1029/1999GL011200, 2000.

Gillett, N. P., Weaver, A. J., Zwiers, F. W. and Flannigan, M. D.: Detecting the effect of climate change on Canadian forest fires, Geophys. Res. Lett., 31, L18211, doi:10.1029/2004GL020876, 2004.

Goldammer, J.G. and Furyaev, V.V. (Eds.): Fires in Ecosystems of Boreal Eurasia, Springer, Dordrecht 1996.

Formatted: Font: Not Italic, Check spelling and grammar

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue

Formatted: Default Paragraph Font, Font: 10 pt, Font color: Blue

Deleted: 2011

Formatted: Font: Not Italic, Check spelling and grammar

Deleted: 10.1029/2002GB001972

Formatted: Font: 12 pt, Check spelling and grammar

Deleted: ¶

Goode, J. G., Yokelson, R. J., Ward, D. E., Susott, R. A., Babbitt, R. E., Davies, M. A. and Hao, W. M.: Measurements of excess O_3, CO_2, CO, CH_4, C_2H_4, C_2H_2, HCN, NO, NH_3, HCOOH, CH_3COOH, HCHO, and CH_3OH in 1997 Alaskan biomass burning plumes by airborne Fourier transform infrared spectroscopy (AFTIR), J. Geophys. Res. Atmos., 105, 22147-22166, doi:10.1029/2000jd900287, 2000.

Guerette, E., Paton-Walsh, C., Desservettaz, M., Smith, T. E. L., Volkova, L., Weston, C. J. and Meyer, C. P.: Emissions of trace gases from Australian temperate forest fires: Emission factors and dependence on modified combustion efficiency, Atmos. Chem. and Phys., 18, 3717-3735, http://dx.doi.org/10.5194/acp-18-3717-2018, 2018.

Harden, J. W., Trumbore, S. E., Stocks, B. J., Hirsch, A., Gower, S. T., O'Neill, K. P. and Kasischke, E. S.: The role of fire in the boreal carbon budget, Glob. Chang. Biol., 6, 174-184, doi:10.1046/j.1365-2486.2000.06019.x, 2000.

Hayasaka, H., H. L. Tanaka, H. L., and Bieniek, P. A.: Synoptic-scale fire weather conditions in Alaska, Polar Science, 10, 217-226, doi:10.1016/j.polar.2016.05.001, 2016.

Henderson, J. M., Eluszkiewicz, J., Mountain, M. E., Nehrkorn, T., Chang, R. Y. W., Karion, A., Miller, J. B., Sweeney, C., Steiner, N., Wofsy, S. C. and Miller, C. E.: Atmospheric transport simulations in support of the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), Atmos. Chem. Phys., 15, 4093-4116, doi:10.5194/acp-15-4093-2015, 2015.

Jaffe, D., Bertschi, I., Jaeglé, L., Novelli, P., Reid, J. S., Tanimoto, H., Vingarzan, R. and Westphal, D. L.: Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America, Geophys. Res. Lett., 31, L16106, doi:10.1029/2004GL020093, 2004.

Johnson, E. A.: Fire and vegetation dynamics: studies from the North American boreal forest, Cambridge University Press, New York, USA, 1996.

Johnstone, J.F., Rupp, T.S., Olson, M. and Verbyla, D.: Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests, Landscape Ecology, 26, 487-500, 2011.

Kahn, R. A., Chen, Y., Nelson, D. L., Leung, F. Y., Li, Q. B., 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.

Kaiser, J., Suttie, M., Flemming, J., Morcrette, J. J., Boucher, O., and Schultz, M.: Global real-time fire emission estimates based on space-borne fire radiative power observations, in: AIP conference proceedings, 1100, 645, 2009.

Karion, A., Sweeney, C., B Miller, J., E Andrews, A., Commane, R., Dinardo, S., M Henderson, J., Lindaas, J., C Lin, J., A Luus, K., Newberger, T., Tans, P., C Wofsy, S., Wolter, S. and E Miller, C.: Investigating Alaskan methane and carbon dioxide fluxes using measurements from the CARVE tower, Atmos. Chem. Phys., 16, 5383-5398, doi:10.5194/acp-16-5383-2016, 2016.

Kasischke, E. S., Hyer, E. J., Novelli, P. C., Bruhwiler, L. P., French, N. H. F., Sukhinin, A. I., Hewson, J. H. and Stocks, B. J.: Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide, Global Biogeochem. Cycles, 19, GB1012, doi:10.1029/2004GB002300, 2005.

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Deleted: &

Formatted: Font color: Black

Deleted: .

Formatted: Font color: Black

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue

Formatted: Font color: Black

Field Code Changed

Formatted: Font color: Black, Check spelling and grammar

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Field Code Changed

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue, Check spelling and grammar

Formatted: Font color: Black, Check spelling and grammar

Moved down [16]: ., Ryan, K.C.,

Deleted: Putra, E.I., Saharjo, B.H., Nurhayati, A.D., Albar, I. and Yokelson, R.J.: Chemical characterization of fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, Atmos.

Moved down [17]: Chem.

Deleted: Jayarathne, T., Stockwell, C.E., Gilbert, A.A., Daugherty, K., Cochrane, M.A

Deleted: Phys., 18, 2585-2600, https://doi.org/10.5194/acp-18-2585-2018, 2018.¶

Formatted ... [34]

Formatted ... [35]

Deleted: .

Formatted ... [36]

Deleted: ¶

Formatted ... [37]

Formatted ... [38]

Formatted ... [39]

Formatted ... [40]

Formatted ... [41]

Deleted: ¶ ... [42]

Moved down [18]: Geophys. Res

Formatted ... [43]

Deleted: . Atmos., 107, 8146, doi:10.1029/2001jd000461 ... [44]

Moved down [2]: Kasischke, E. S. and Turetsky, M. R.:

Deleted: ¶ ... [45]

Kasischke, E. S. and Turetsky, M. R.: Recent changes in the fire regime across the North American boreal region - Spatial and temporal patterns of burning across Canada and Alaska, Geophys. Res. Lett., 33, L09703, doi:10.1029/2006GL025677, 2006.

Konovalov, I. B., Beekmann, M., Kuznetsova, I. N., Yurova, A. and Zvyagintsev, A. M.: Atmospheric impacts of the 2010 Russian wildfires: Integrating modelling and measurements of an extreme air pollution episode in the Moscow region, Atmos. Chem. Phys., 11, 10031-10056, doi:10.5194/acp-11-10031-2011, 2011.

Korovin, G.N.: Analysis of distribution of forest fires in Russia, in: Fires in Ecosystems of Boreal Eurasia, edited by: Goldammer, J.G. and Furyaev, V.V., Kluwer Academic, Netherlands, 112-128, 1996.

Laursen, K. K., Hobbs, P. V., Radke, L. F., and Rasmussen, R. A.: Some trace gas emissions from North American biomass fires with an assessment of regional and global fluxes from biomass burning, J. Geophys. Res., 97, 20687– 20701, doi:10.1029/92JD02168, 1992.

Lin, J., Gerbig, C., Wofsy, S., Chow, V., Gottlieb, E., Daube, B., and Matross, D.: Designing Lagrangian experiments to measure regional scale trace gas fluxes, J. Geophys. Res., 112, D13312, doi:10.1029/2006JD008077, 2007.

McMeeking, G.R., Kreidenweis, S.M., Baker, S., Carrico, C.M., Chow, J.C., Collett Jr, J.L., Hao, W.M., Holden, A.S., Kirchstetter, T.W., Malm, W.C. and Moosmüller, H.: Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory, J. Geophys. Res., 114, D19210, doi:10.1029/2009JD011836, 2009.

McRae, D.J., Conard, S.G., Ivanova, G.A., Sukhinin, A.I., Baker, S.P., Samsonov, Y.N., Blake, T.W., Ivanov, V.A., Ivanov, A.V., Churkina, T.V. and Hao, W.: Variability of fire behavior, fire effects, and emissions in Scotch pine forests of central Siberia, Mitig. Adapt. Strateg. Global Change, 11, 45-74, 2006.

Nance, J. D., Hobbs, P. V., Radke, L. F. and Ward, D. E.: Airborne measurements of gases and particles from an Alaskan wildfire, J. Geophys. Res. Atmos., 98, 14873-14882, doi:10.1029/93jd01196, 1993.

O'Shea, S. J., Allen, G., Gallagher, M. W., Bauguitte, S. J.-B., Illingworth, S. M., Le Breton, M., Muller, J. B. A., Percival, C. J., Archibald, A. T., Oram, D. E., Parrington, M., Palmer, P. I., and Lewis, A. C.: Airborne observations of trace gases over boreal Canada during BORTAS: campaign climatology, air mass analysis and enhancement ratios, Atmos. Chem. Phys., 13, 12451–12467, https://doi.org/10.5194/acp-13-12451-2013, 2013.

Partain, J. L., Alden, S., Bhatt, U. S., Bieniek, P. A., Brettschneider, B. R., Lader, R. T., Olsson, P. Q., Rupp, T. S., Strader, H., Thoman, R. L., Walsh, J. E., York, A. D. and Ziel, R. H.: An assessment of the role of anthropogenic climate change in the Alaska fire season of 2015, Bull. Am. Meteorol. Soc., 97, S14-S18, doi:10.1175/BAMS-D-16-0149.1, 2016.

Moved (insertion) [2]

Moved down [19]: C.,

Deleted: Lapina, K., Honrath, R. E., Owen, R.

Deleted: Val Martín, M. and Pfister, G.: Evidence of significant large-scale impacts of boreal fires on ozone levels in the midlatitude Northern Hemisphere free troposphere, Geophys. Res. Lett., 33, L10815, doi:10.1029/2006GL025878, 2006.¶

Deleted:

Formatted: Font: Not Italic

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue

Field Code Changed

Deleted: Levine, J. S., and Cofer, W. R.: Boreal forest fire emissions and the chemistry of the atmosphere, in: Fire, climate change, and carbon cycling in the boreal forest, Springer, New York, NY, USA, 138, 31-48, https://doi.org/10.1007/978-0-387-21629-4_3, 2000.¶
McGuire, A. D., Macdonald, R. W., Schuur, E. A. G., Harden, J. W.,

Moved down [20]: Kuhry, P.,

Deleted: Hayes, D.

Moved down [21]: J.,

Deleted: Christensen, T. R. and Heimann, M.: The carbon budget of the northern cryosphere region, Curr. Opin. Environ. Sustain., 2, 231-236, doi:10.1016/j.cosust.2010.05.003, 2010.¶

Moved (insertion) [14]

Formatted: Font color: Custom Color(RGB(28,29,30)), Pattern: Clear (White)

Moved (insertion) [18]

Formatted: Font color: Custom Color(RGB(28,29,30)), Pattern: Clear (White)

Formatted: Font: Not Italic

Deleted: *Res.*, 114, D19210, doi:10.1029/2009JD011836

Deleted: . *Mitigation and Adaptation Strategies for*

Formatted: Font: Not Italic

Formatted: Font: 10 pt

Formatted: Font color: Black, Pattern: Clear, Highlight

Deleted: 4.

Peterson, D. A., Campbell, J. R., Hyer, E. J., Fromm, M. D., Kablick, G. P., Cossuth, J. H. and DeLand, M. T.: Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke, Clim. Atmos. Sci., 1, 30, doi:10.1038/s41612-018-0039-3, 2018.

Radke, L. F., Hegg, D. A., Hobbs, P. V, Nance, J. D., Lyons, J. H., Laursen, K. K., Weiss, R. E., Riggan, P. J. and Ward, D. E.: Particulate and Trace Gas Emissions from Large Biomass Fires in North America, Glob. Biomass Burn. Atmos. Clim. Biosph. Implic., 209-224, 1991.

Rapalee, G., Trumbore, S.E., Davidson, E.A., Harden, J.W. and Veldhuis, H.: Soil carbon stocks and their rates of accumulation and loss in a boreal forest landscape, Global Biogeochem. Cycles, 12, 4, https://doi.org/10.1029/98GB02336, 687-70, 1998.

Rodell, M., Beaudoing, H., and NASA/GSFC/HSL GLDAS Noah Land Surface Model L4 3 hourly 0.25 x 0.25 degree V2. 0, edited, Goddard Earth Sciences Data and Information Services Center (GES DISC) Greenbelt, MD, 2015.

Rogers, B. M., Soja, A. J., Goulden, M. L. and Randerson, J. T.: Influence of tree species on continental differences in boreal fires and climate feedbacks, Nat. Geosci., 8, 228-234, doi:10.1038/ngeo2352, 2015.

Ryan, K. C.: Dynamic interactions between forest structure and fire behavior in boreal ecosystems, in Silva Fennica., 36, 13-39, 2002.

Santín, C., Doerr, S.H., Preston, C.M. and González-Rodríguez, G.: Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle. Glob. Change Bio., 21, 1621-1633, https://doi.org/10.1111/gcb.12800, 2015.

Sedano, F. and Randerson, J. T.: Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems, Biogeosciences, 11, 3739–3755, https://doi.org/10.5194/bg-11-3739-2014, 2014.

Selimovic, V., Yokelson, R. J., McMeeking, G. R., and Coefield, S.: In situ measurements of trace gases, PM, and aerosol optical properties during the 2017 NW US wildfire smoke event, Atmos. Chem. Phys., 19, 3905–3926, https://doi.org/10.5194/acp-19-3905-2019, 2019.

Selimovic, V., Yokelson, R.J., McMeeking, G.R. and Coefield, S.: Aerosol mass and optical properties, smoke influence on O_3, and high NO_3 production rates in a western US city impacted by wildfires, Earth and Space Sci. Open Arc., 52, https://doi.org/10.1002/essoar.10501529.1, 2020

Simpson, I. J., Akagi, S. K., Barletta, B., Blake, N. J., Choi, Y., Diskin, G. S., Fried, A., Fuelberg, H. E., Meinardi, S., Rowland, F. S., Vay, S. A., Weinheimer, A. J., Wennberg, P. O., Wiebring, P., Wisthaler, A., Yang, M., Yokelson, R. J. and Blake, D. R.: Boreal forest fire emissions in fresh Canadian smoke plumes: C1-C10 volatile organic compounds (VOCs), CO_2, CO, NO_2, NO, HCN and CH_3CN, Atmos. Chem. Phys., 11, 6445-6463, doi:10.5194/acp-11-6445-2011, 2011.

Moved (insertion) [22]

Moved (insertion) [15]

Deleted: Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R. and Elliott, C. T.: Critical review of health impacts of wildfire smoke exposure, Environ. Health Perspect., 124, 1334-1343, doi:10.1289/ehp.1409277, 2016.¶

Formatted: Pattern: Clear, Highlight

Deleted: Global

Formatted: Pattern: Clear, Highlight

Deleted: Biology,

Formatted: Pattern: Clear, Highlight

Field Code Changed

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue, Pattern: Clear, Highlight

Formatted: Pattern: Clear, Highlight

Moved (insertion) [23]

Formatted: Font color: Auto, Pattern: Clear

Deleted: 2019

Deleted: ¶

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W. and Powers, J.G.: A description of the Advanced WRF Version 2, Tech. Note NCAR/TN-468+ STR, Natl. Cent. for Atmos. Res., Boulder, Colo., 2005.

Smith, T., Paton-Walsh, C., Meyer, C.P., Cook, G., Maier, S.W., Russell-Smith, J., Wooster, M. and Yates, C.P.: New emission factors for Australian vegetation fires measured using open-path Fourier transform infrared spectroscopy-Part 2: Australian tropical savanna fires., Atmos. Chem. Phys., 14, 11335-11352, 2014.

Stocks, B., Wotton, B., Flannigan, M., Fosberg, M., Cahoon, D., and Goldammer, J.: Boreal forest fire regimes and climate change, in: Remote sensing and climate modeling: Synergies and limitations, edited by: Beniston, M., and Verstraete, M. M., Springer, Dordrecht, 233-246, https://doi.org/10.1007/0-306-48149-9, 2001.

Stockwell, C.E., Yokelson, R.J., Kreidenweis, S.M., Robinson, A.L., DeMott, P.J., Sullivan, R.C., Reardon, J., Ryan, K.C., Griffith, D.W. and Stevens, L.: Trace gas emissions from combustion of peat, crop residue, domestic biofuels, grasses, and other fuels: configuration and Fourier transform infrared (FTIR) component of the fourth Fire Lab at Missoula Experiment (FLAME-4). Atmos. Chem. Phys., 14, 18, 9727-9754, https://doi.org/10.5194/acp-14-9727-2014, 2014.

Strand, T., Gullett, B., Urbanski, S., O'Neill, S., Potter, B., Aurell, J., Holder, A., Larkin, N., Moore, M. and Rorig, M.: Grassland and forest understorey biomass emissions from prescribed fires in the south-eastern United States–RxCADRE 2012. Int. J. Wildl. Fire, *25*, 102-113, https://doi.org/10.1071/WF14166, 2016.

Susott, R. A., Ward, D. E., Babbitt, R. E., Latham, D. J.: The measurement of trace emissions and combustion characteristics for a mass fire, Global Biomass Burning: Atmospheric, Climatic, and Biosphere Implications, MIT Press, Cambridge, MA, 245-257, 1991.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem. Cycles, 23, GB2023, doi:10.1029/2008GB003327, 2009.

Thoning, K., Kitzis, D., and Crotwell, A.: Atmospheric carbon dioxide dry air mole fractions from quasi-continuous measurements at Barrow, Alaska, Mauna Loa, Hawaii, American Samoa, and South Pole, 1973–2006, Version: 2007-10-01, National Oceanic and Atmospheric Administration, Path: ftp://ftp.cmdl.noaa.gov/ccg/co2/in-situ, 2007.

Turquety, S., Logan, J. A., Jacob, D. J., Hudman, R. C., Leung, F. Y., Heald, C. L., Yantosca, R. M., Wu, S., Emmons, L. K., Edwards, D. P. and Sachse, G. W.: Inventory of boreal fire emissions for North America in 2004: Importance of peat burning and pyroconvective injection, J. Geophys. Res. Atmos., 112, D12S03, doi:10.1029/2006JD007281, 2007.

Urbanski, S. P., Hao, W. M. and Baker, S.: Chapter 4 Chemical Composition of Wildland Fire Emissions, Dev. Environ. Sci., 8, 79-107, doi:10.1016/S1474-8177(08)00004-1, 2008.

Urbanski, S.: Wildland fire emissions, carbon, and climate: Emission factors, For. Ecol. Manage., 317, 51-60, doi:10.1016/j.foreco.2013.05.045, 2014.

Moved (insertion) [19]

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue, Check spelling and grammar

Field Code Changed

Deleted: Stockwell, C. E., Jayarathne, T., Cochrane, M.A., Ryan, K. C., Putra, E. I., Saharjo, B. H., Nurhayati, A. D., Albar, I., Blake, D. R., Simpson, I

Moved down [24]: . J.

Deleted: and Stone, E. A.: Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, Atmos.

Moved down [25]: Chem.

Deleted: Phys., 16, 11711-11732, doi: 10.5194/acp-16-11711-2016, 2016.¶

Moved (insertion) [21]

Moved (insertion) [16]

Moved (insertion) [12]

Moved (insertion) [17]

Deleted: *International Journal of Wildland*

Moved (insertion) [24]

Formatted: Font: Not Italic, Check spelling and grammar

Deleted: https://doi.org/10.1071/WF14166

Deleted: biomass buring

Deleted: climatic

Deleted: biosphere implications

Moved (insertion) [20]

Formatted: Font color: Black, Check spelling and grammar

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Deleted: Tosca, M.

Moved up [22]: G.,

Deleted: Randerson, J.T., Zender, C.S., Flanner, M.G. and Rasch, P.J.: Do biomass burning aerosols intensify drought in equatorial Asia during El Niño?, Atmos.

Moved down [26]: Chem.

Formatted: Font color: Black, Check spelling and grammar, Highlight

Deleted:

Moved down [27]: Phys.,

Formatted: Font color: Black, Check spelling and grammar, Highlight

Deleted: 10, 3515-3528, https://doi.org/10.5194/acp-10-3515-2010, 2010. ¶

Moved (insertion) [3]

Deleted: ¶
¶

Val Martin, M., Logan, J. A., Kahn, R. A., Leung, F.-Y., Nelson, D. L., and Diner, D. J.: Smoke injection heights from fires in North America: analysis of 5 years of satellite observations, Atmos. Chem. Phys., 10, 1491–1510, https://doi.org/10.5194/acp-10-1491-2010, 2010.

Van Leeuwen, T. T. and van der Werf, G. R.: Spatial and temporal variability in the ratio of trace gases emitted from biomass burning, Atmos. Chem. Phys., 11, 3611-3629, doi:10.5194/acp-11-3611-2011, 2011.

Vasileva, A., Moiseenko, K., Skorokhod, A., Belikov, I., Kopeikin, V. and Lavrova, O.: Emission ratios of trace gases and particles for Siberian forest fires on the basis of mobile ground observations. Atmos. Chem. Phys., 17, 12303-12325, https://doi.org/10.5194/acp-17-12303-2017, 2017.

Veraverbeke, S., Rogers, B. M. and Randerson, J. T.: Daily burned area and carbon emissions from boreal fires in Alaska, Biogeosciences, 12, 3579-3601, doi:10.5194/bg-12-3579-2015, 2015.

Veraverbeke, S., Rogers, B. M., Goulden, M. L., Jandt, R. R., Miller, C. E., Wiggins, E. B. and Randerson, J. T.: Lightning as a major driver of recent large fire years in North American boreal forests, Nat. Clim. Chang., 7, 529-534, doi:10.1038/nclimate3329, 2017.

Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Johnstone, J. F., Rogers, B. M., Solvik, K., Turetsky, M. R. and Mack, M. C.: Soil organic layer combustion in boreal black spruce and jack pine stands of the Northwest Territories, Canada, Int. J. Wildl. Fire, 27, 125-134, doi:10.1071/wf17095, 2018.

Ward, D. E. and Radke, L. F.: Emissions Measurements from Vegetation Fires: A Comparative Evaluation of Methods and Results, Fire in the Environment: The Ecological Atmospheric and Climatic Importance of Vegetation Fires, Dahlem Workshop Reports: Environmental Sciences Research Report 13, John Wiley & Sons, Chischester, England, 53-76, 1993.

Wiggins, E. B., Veraverbeke, S., Henderson, J. M., Karion, A., Miller, J. B., Lindaas, J., Commane, R., Sweeney, C., Luus, K. A., Tosca, M. G., Dinardo, S. J., Wofsy, S., Miller, C. E. and Randerson, J. T.: The influence of daily meteorology on boreal fire emissions and regional trace gas variability, J. Geophys. Res. Biogeosciences, 121, 2793-2810, doi:10.1002/2016JG003434, 2016.

Wotawa, G., Novelli, P. C., Trainer, M. and Granier, C.: Inter-annual variability of summertime CO concentrations in the Northern Hemisphere explained by boreal forest fires in North America and Russia, Geophys. Res. Lett., 28, 4575-4578, doi:10.1029/2001GL013686, 2001.

Yokelson, R.J., Griffith, D.W. and Ward, D.E.: Open-path Fourier transform infrared studies of large-scale laboratory biomass fires, J. Geophys. Res. Atmos., 101, D15, http://doi.org/10.1029/96JD01800, 21067-21080, 1996.

Yokelson, R. J., Susott, R., Ward, D. E., Reardon, J., and Griffith, D. W. T.: Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy, J. Geophys. Res., 10, D15, 18865–18877, doi:10.1029/97JD00852, 1997.

Moved up [3]: Urbanski, S. P., Hao, W. M. and Baker, S.: Chapter 4 Chemical Composition of Wildland Fire Emissions, Dev. Environ. Sci., 8, 79-107, doi:10.1016/S1474-8177(08)00004-1, 2008.¶
Val Martin, M., Logan, J. A., Kahn, R. A., Leung, F.-Y., Nelson, D. L., and Diner, D. J.: Smoke injection heights from fires in North America: analysis of 5 years of satellite observations, Atmos. Chem. Phys., 10, 1491–1510, https://doi.org/10.5194/acp-10-1491-2010, 2010.¶
¶

Deleted: ¶

Deleted: Van Der

Deleted: *Atmospheric Chemistry & Physics*,

Moved (insertion) [25]

Deleted: 13,

Formatted: Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Deleted: ¶

Moved down [28]: Ward, D.

Formatted: Font color: Auto, Pattern: Clear

Deleted: S., Kloster, S., Mahowald, N. M., Rogers, B. M.,

Moved up [23]: Randerson, J.

Formatted: Font color: Auto, Pattern: Clear

Deleted: T., and Hess, P. G.: The changing radiative forcing of fires: global model estimates for past, present and future, Atmos. Chem. Phys., 12, 10857–10886, 2012. ¶

Moved (insertion) [29]

Deleted: Yates, E.L., Iraci, L.T., Singh, H.B., Tanaka, T., Roby, M.C., Hamill, P., Clements, C.B., Lareau, N., Contezac, J., Blake, D.R. and Simpson, I.J.: Airborne measurements and emission estimates of greenhouse gases and other trace constituents from the 2013 California Yosemite Rim wildfire. Atmospheric Environment, 127, 293-302, https://doi.org/10.1016/j.atmosenv.2015.12.038, 2016.¶

Formatted: Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Moved (insertion) [28]

Formatted: Font color: Auto, Pattern: Clear

Yokelson, R. J., Goode, J. G., Ward, D. E., Susott, R. A., Babbitt, R. E., Wade, D. D., Bertschi, I., Griffith, D. W. T., and Hao, W. M.: Emissions of formaldehyde, acetic acid, methanol, and other trace gases from biomass fires in North Carolina measured by airborne Fourier transform infrared spectroscopy, J. Geophys. Res., 104, D23, 30109– 30125, doi:10.1029/1999JD900817, 1999.

Yokelson, R.J., Karl, T., Artaxo, P., Blake, D.R., Christian, T.J., Griffith, D.W., Guenther, A. and Hao, W.M.: The Tropical Forest and fire emissions experiment: overview and airborne fire emission factor measurements. Atmos. Chem. and Phys., 7, 19, 5175-5196, https://doi.org/10.5194/acp-7-5175-2007, 2007.

Yokelson, R. J., Burling, I. R., Gilman, J. B., Warneke, C., Stockwell, C. E., De Gouw, J., Akagi, S. K., Urbanski, S. P., Veres, P., Roberts, J. M., Kuster, W. C., Reardon, J., Griffith, D. W. T., Johnson, T. J., Hosseini, S., Miller, J. W., Cocker, D. R., Jung, H. and Weise, D. R.: Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires, Atmos. Chem. Phys., 13, 89-116, doi:10.5194/acp-13-89-2013, 2013.

Young, A. M., Higuera, P. E., Duffy, P. A. and Hu, F. S.: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change, Ecography, 40, 606-617, doi:10.1111/ecog.02205, 2017.

Formatted: Default Paragraph Font, Font: 12 pt, Font color: Blue

Field Code Changed

Moved up [29]: Yokelson, R.

Deleted: ¶

Formatted: Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Deleted: J., Susott, R., Ward, D. E., Reardon, J. and Griffith, D. W. T.: Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy, J. Geophys. Res. Atmos., 102, 18865-18877, doi:10.1029/97jd00852, 2004.¶

Moved (insertion) [26]

Deleted: Chem.Phys.,

Formatted: Font color: Black, Check spelling and grammar, Highlight

Moved (insertion) [27]

Formatted: Justified

Formatted: Font: 10 pt

Figures

Deleted: ¶
¶
¶
¶
¶
¶
¶
¶
¶

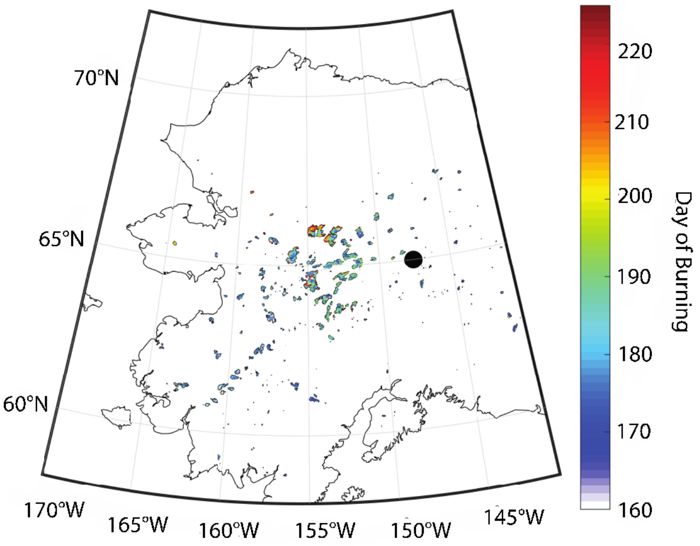
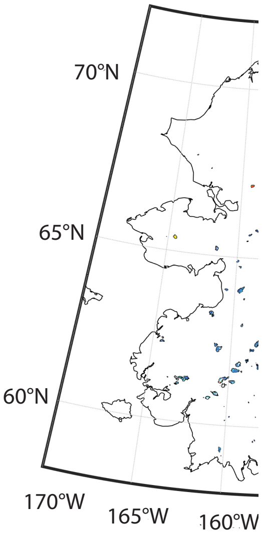


Figure 1. The location of wildfires in Alaska during 2015, with color representing the day of burning estimated from the Alaska Fire Emissions Database (AKFED). The black circle denotes the location of CRV tower.



Deleted:

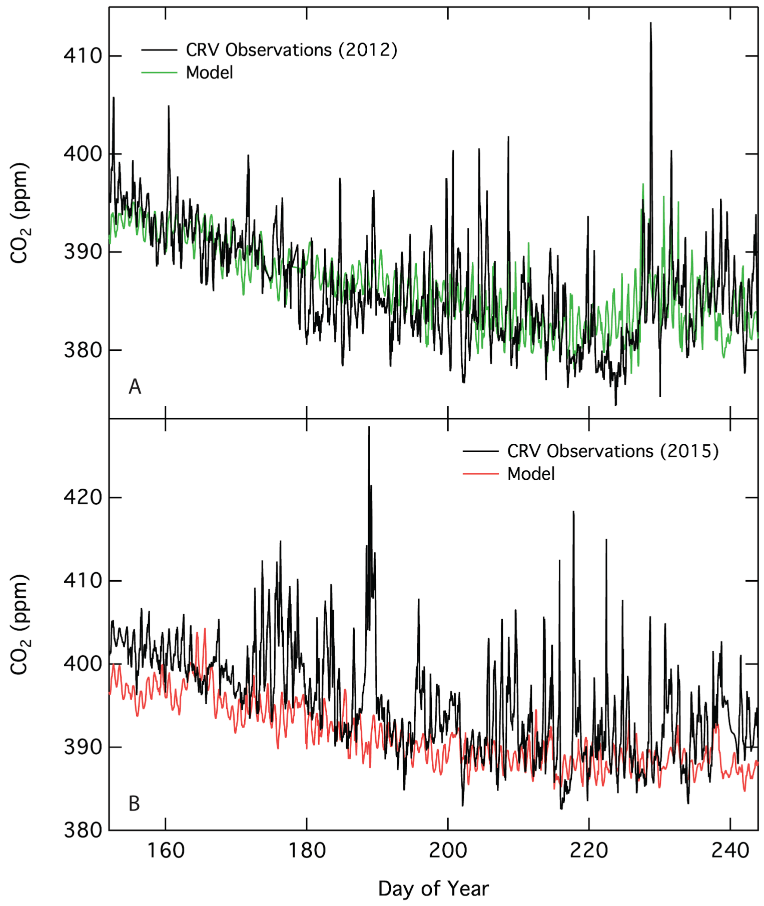
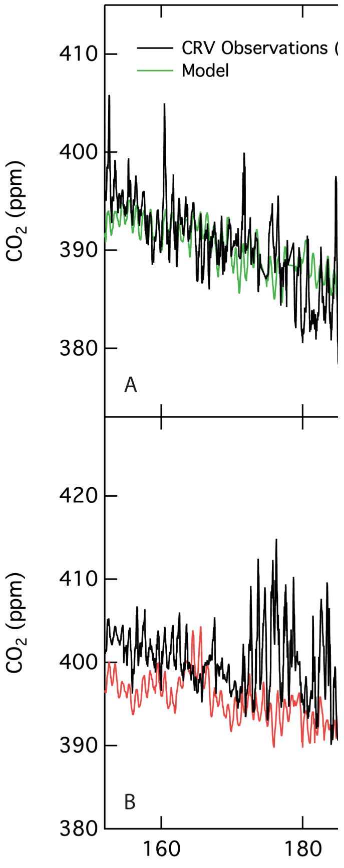


Figure 2. A) Observations of CO$_2$ mole fraction at the CRV tower in 2012 (black line) along with model estimates of the CO$_2$ background (green line) at CRV using the approach described in the main text. Very few fires occurred during 2012, and as a consequence most of the CO$_2$ variability in the observations and in the model are associated with terrestrial net ecosystem exchange. B) In 2015 wildfires in interior Alaska contributed significantly to CO$_2$ variability at the CRV tower, causing positive anomalies in the observations shown in black, particularly between days 170 and 190. The modeled background for 2015 is shown in red. The CO$_2$ mole fraction observations and model estimates have a 1 hr temporal resolution.



Deleted:

Deleted: from

Deleted: is

Deleted: 1X hour or

Deleted: Y s

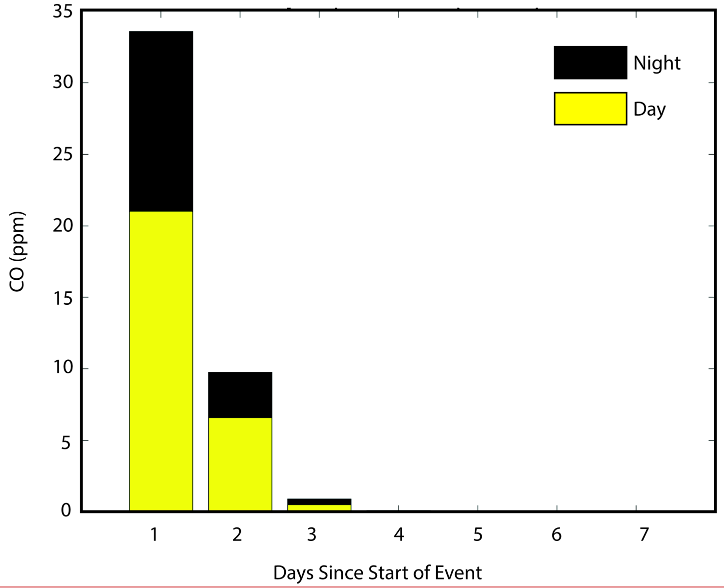


Figure 3. Distribution of transit times representing the difference between the time when CO was emitted by a fire and the time the CO anomaly reached the CRV tower, as estimated by multiplying footprints from PWRF-STILT with fire emissions from AKFED. Only times when fire emission ratios were calculated were used in the analysis.

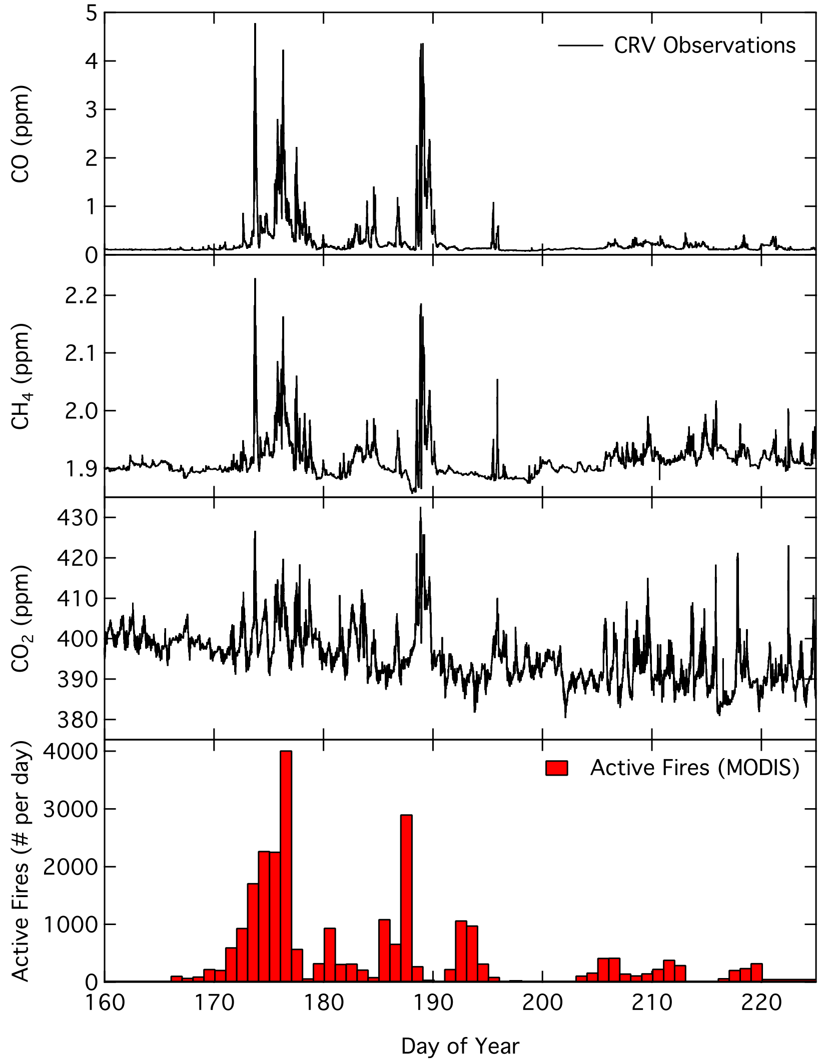
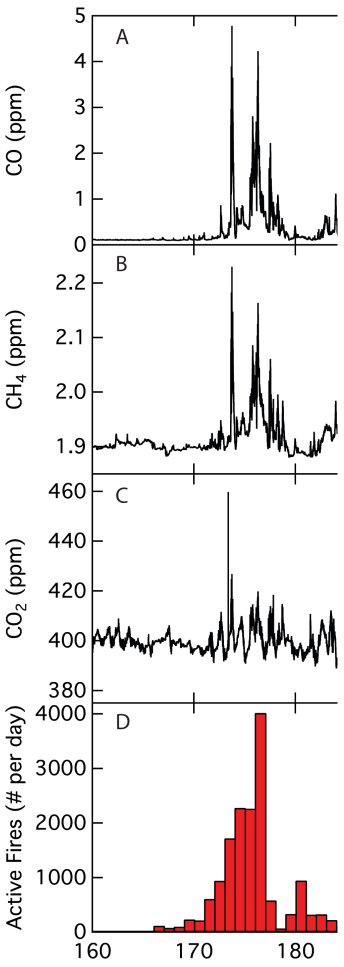


Figure 4. Trace gas observations at the CRV tower during the summer of 2015 for A) CO, B) CH_4, and C) CO_2 mole fractions The trace gas observations are shown at a 30 s temporal resolution. Daily active fire detections derived from the MODIS sensors on Terra and Aqua satellites (MCD14ML C6C6MCD14ML) are shown in panel D.



Deleted:

Deleted: **Figure 3.** when CO was emitted by a fire and the time the CO anomaly reached the CRV tower, as estimated by multiplying footprints from PWRF-STILT with fire emissions from AKFED. Only times when fire emission ratios were calculated were used in the analysis.¶

Moved (insertion) [30]

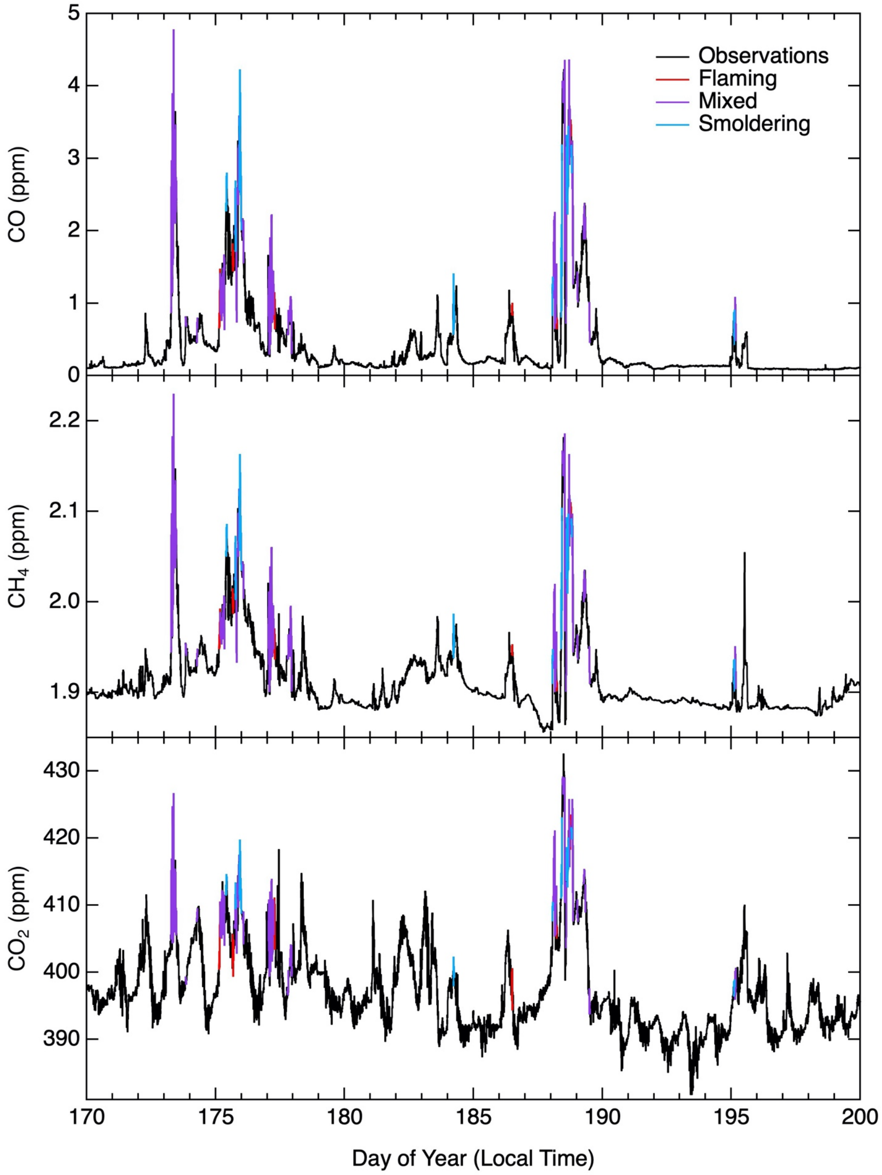
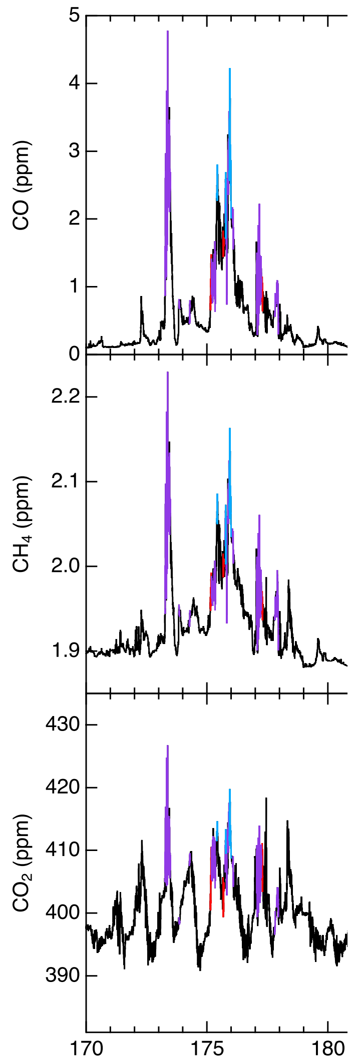


Figure 5. CRV tower observations of A) CO, B) CH_4, and C) CO_2 are shown along with intervals used to calculate emission ratios (shown in color). The primary combustion process is noted with blue for smoldering, purple for mixed, and red for flaming. The trace gas observations are shown at a 30 s temporal resolution.

Moved (insertion) [31]

Deleted: **Figure 4.** Trace gas observations at the CRV tower during the summer of 2015 for A) CO, B) CH_4, and C) CO_2. The trace gas observations are plotted at a 30 s? temporal resolution. Daily active fire detections derived the MODIS instrument on Terra and Aqua satellites (MCDproduct name) are shown in panel D.¶



Deleted:

D

Moved up [31]: **Figure 4.**

Moved (insertion) [32]

Deleted: periods…used to calculate emission ratios (shown in color)..…The primary dominant process of …ombustion process is noted with blue for smoldering, (blue),…purple for mixed, and red for flaming. The trace gas observations are shownplotted…at a XX s? hour?

... [46]

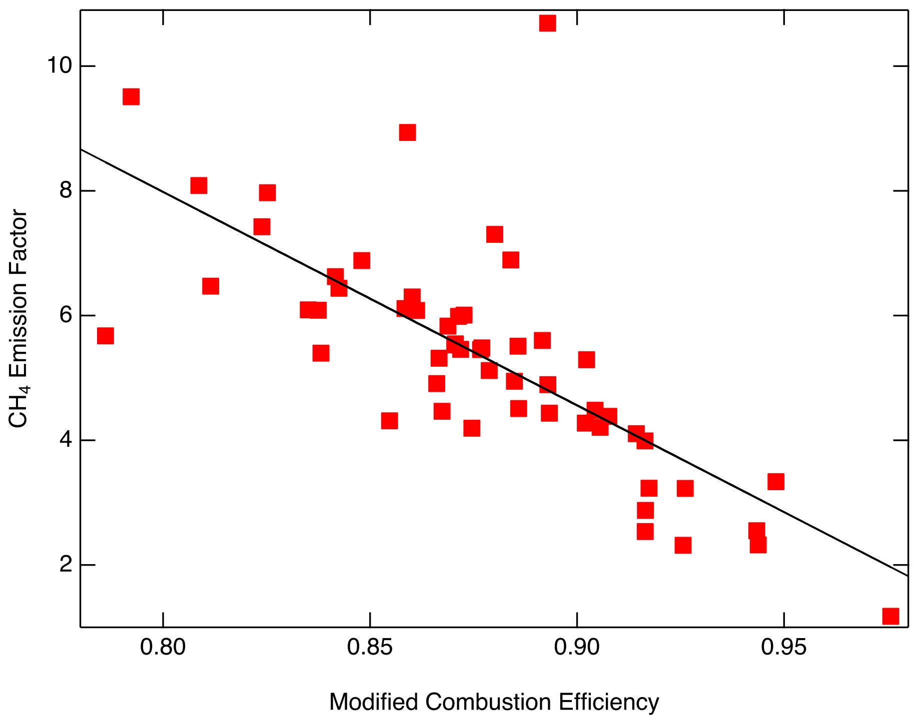
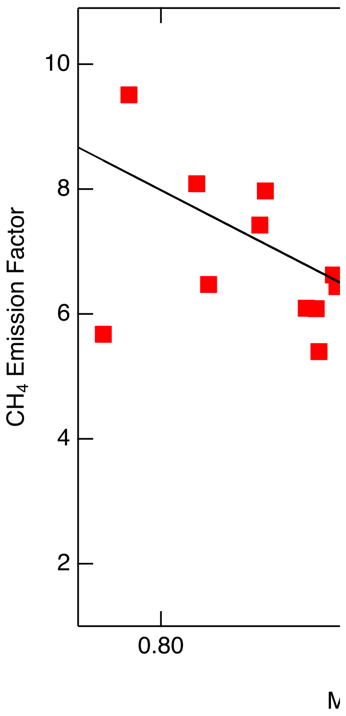


Figure 6. Relationship between CH_4 emission factor and modified combustion efficiency (MCE). The strong linear relationship indicates that periods with more smoldering combustion (and a lower MCE) produce significantly higher levels of CH_4 emissions. The relationship was defined by a slope of -46.77 ± 4.70, a Y intercept of 46.37 ± 4.13 g kg^{-1} dry biomass burned, an r^2 of 0.54, and a significance value of $p < 0.01$



Deleted:

Moved up [32]: **Figure 5.**

Moved (insertion) [33]

Deleted: with

Deleted: smaller

Deleted: -

Deleted: 0.XX±0.YY g CH_4 per kg dry biomass per MCE, an X intercept of XX±0.YY g CH_4 per kg dry biomass, an R^2 of 0.XX…

Deleted: 0X

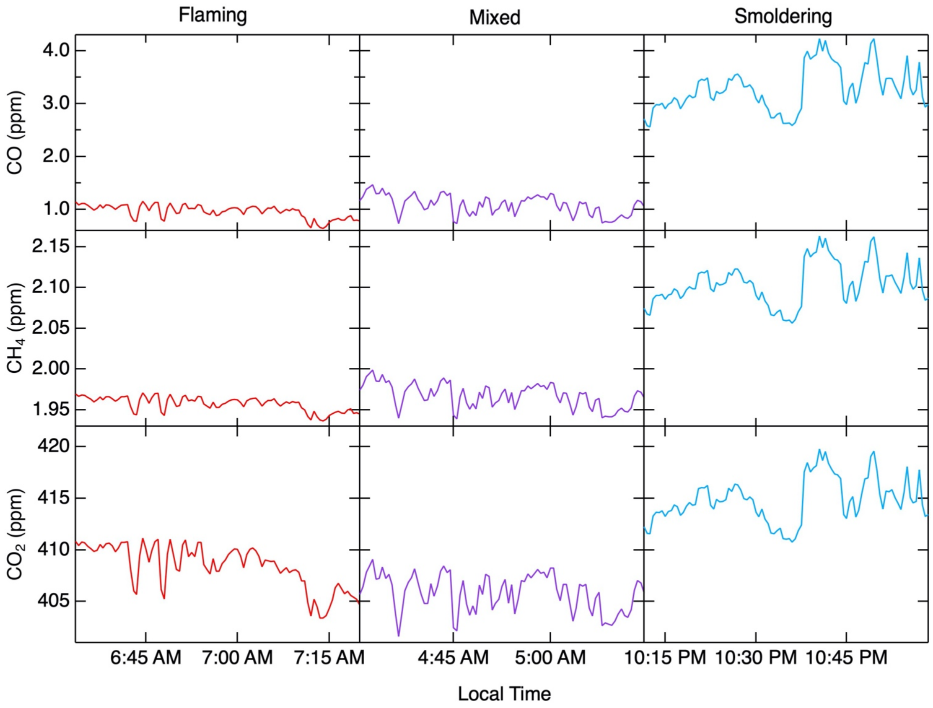
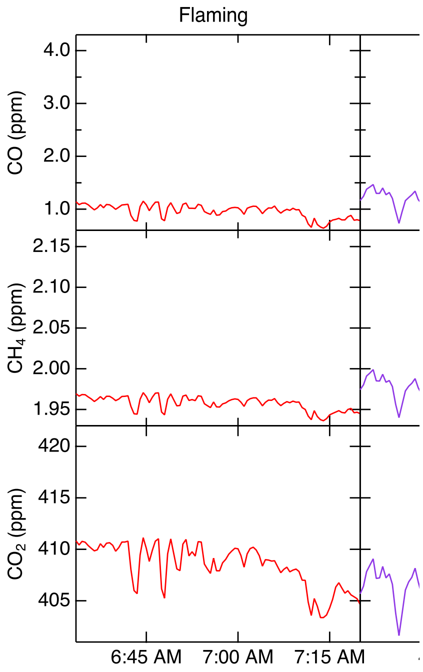


Figure 7. Examples of intervals used to calculate emission ratios. The flaming combustion example is from DOY 177, the mixed example is from DOY 177, and smoldering example is from DOY 175. These intervals correspond to events 27, 25, and 19 in Table 2. The trace gas measurements are shown at a 30 s temporal resolution.

Deleted: ¶



Moved up [33]: **Figure 6.**

Formatted: Not Highlight

Moved (insertion) [34]

Deleted:

Deleted: 30 s trace gas observations

Deleted: . All dates are from 2015 and in local time. The flaming …

Deleted: factors for smoldering (blue), mixed (purple), and flaming (red) dominated

Deleted: X

Deleted: Y

Deleted: Z

Deleted: X, Y

Deleted: Z

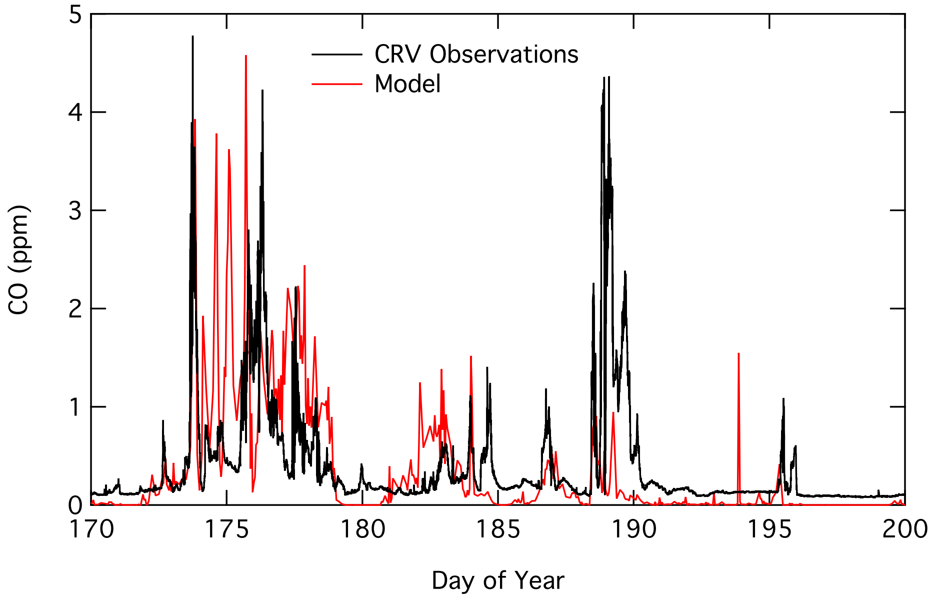
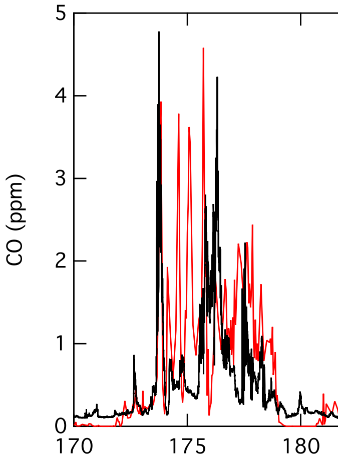


Figure 8. CRV observations of CO (black) compared with the modeled CO anomaly from fires (red) derived from the PWRF-STILT atmospheric model driven by AKFED fire emissions. The trace gas observations and model predictions are shown at 1 hr temporal

Moved up [34]: **Figure 7.**

Moved (insertion) [35]



Deleted:

Deleted: a

Deleted: X hour?

Deleted: resolution

Deleted: during the day and a Y hour resolution at night.

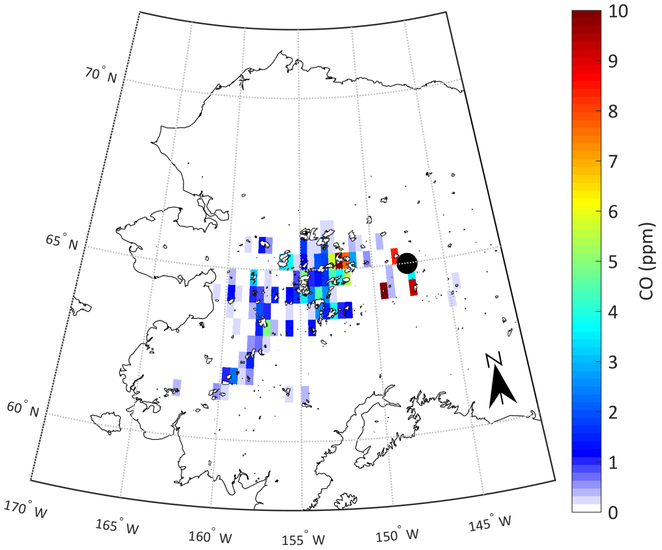
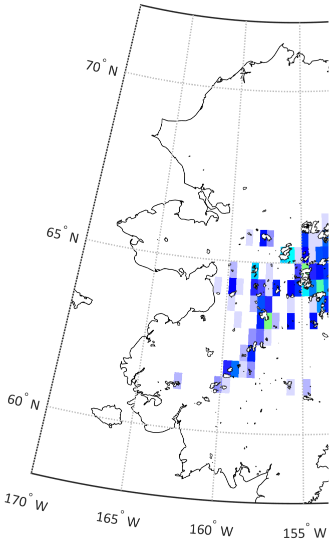


Figure 9. Individual fire contributions to the total fire season integral of CO anomalies measured at the CRV tower, as determined by convolving footprints from PWRF-STILT with fire emissions from AKFED. The location of CRV is shown as a black dot. Fire perimeters are shown in black.

Moved up [35]: **Figure 8.**

Deleted: ¶
¶
¶
¶



Deleted: Total individual

Deleted: anomaly

Deleted: tower

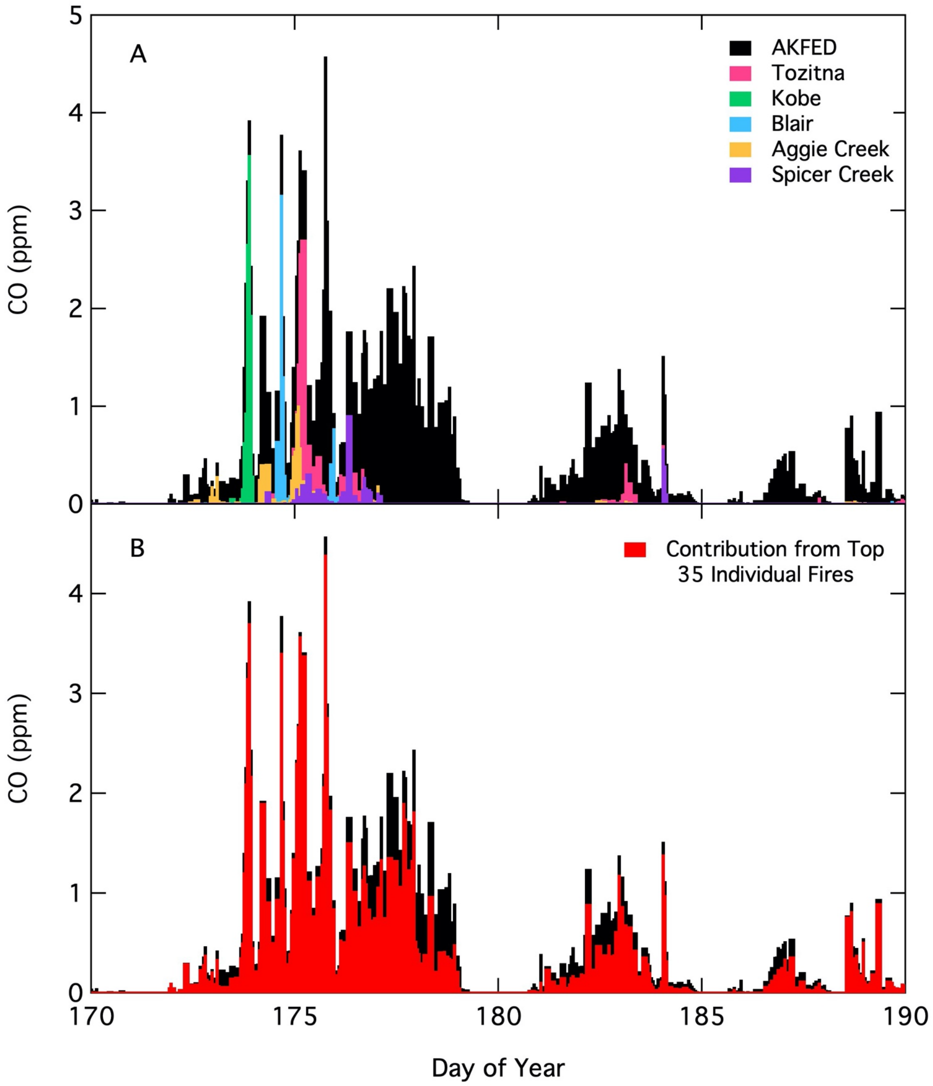


Figure 10. A) Top 5 individual fire contributions to the CO anomalies simulated at the CRV tower. The black line shows original PWRF-STILT × AKFED model, pink denotes contributions from the Tozitna fire, green from the Kobe fire, blue from the Blair fire, gold from the Aggie Creek fire, and purple from the Spicer Creek fire. B) The total CO anomaly from the 34 fires that contributed to at least 1% of the modeled CO anomaly at CRV tower (red) compared to sum of all fire shown in black derived from original PWRF-STILT × AKFED simulation (black).

Deleted: ¶ ... [47]

Deleted: anomaly

Formatted: Space Before: 0 pt, After: 0 pt

Deleted: 9

Deleted: Black

Deleted: red depicts

Deleted: 35

Deleted: the

Deleted: model

Deleted: ¶ ... [48]

Moved up [30]: when CO was emitted by a fire and the time the CO anomaly reached the CRV tower, as estimated by multiplying footprints from PWRF-STILT with fire

Deleted: ¶
¶
¶
¶ ... [49]

Formatted: Font: Not Bold

Tables

Table 1. Comparison of CO emission ratio and modified combustion efficiency (MCE) from previous studies that sampled emissions from boreal forest fires. The studies are organized according to wildfire domain (North America or Siberia), management practice (wildfire or management fire), and sampling approach (aircraft, laboratory, or surface tower). Siberian studies are indicated as aircraft studies (A), surface based studies (S), or a combination of the two (A & S). The CO emission ratio column has units of ppmv ppmv^{-1} and uses CO_2 as the reference gas. MCE was calculated as $1/(1 + \Delta CO/\Delta CO_2)$ when not directly reported in the study. The weighted mean of emission ratios and MCE for all previous studies is shown in the row labeled fire-weighted mean, with each study weighted according to the number of fires sampled.

Study	$\Delta CO/\Delta CO_2$ Emission Ratio	Modified Combustion Efficiency	Number of fires sampled
North American wildfires sampled by aircraft			
Cofer et al., 1989	0.069 ± 0.004	0.935 ± 0.004	1
Cofer et al., 1998	0.140 ± 0.012	0.878 ± 0.009	1
Friedli et al., 2003	0.100 ± 0.020	0.909 ± 0.017	1
Goode et al., 2000	0.085 ± 0.008	0.922 ± 0.007	4
Laursen et al., 1992	0.050 ± 0.007	0.953 ± 0.006	1
Nance et al., 1993	0.078 ± 0.012	0.928 ± 0.011	1
O'Shea et al., 2013	0.150 ± 0.024	0.871 ± 0.012	4
Radke et al., 1991	0.116 ± 0.087	0.896 ± 0.075	1
Simpson et al., 2011	0.110 ± 0.070	0.901 ± 0.061	5
Fire-weighted mean	**0.102 ± 0.033**	**0.908 ± 0.027**	**19**
North American management fires sampled by aircraft			
Cofer et al., 1990	0.086 ± 0.008	0.921 ± 0.007	2
Cofer et al., 1998	0.095 ± 0.016	0.913 ± 0.013	7
Radke et al., 1991	0.047 ± 0.032	0.956 ± 0.030	4
Susott et al., 1991	0.060 ± 0.061	0.943 ± 0.058	1
Fire-weighted mean	**0.077 ± 0.022**	**0.929 ± 0.020**	**14**
North American fuels sampled in the laboratory			
Yokelson **et al.,** 1997[a]	0.208 ± 0.039	0.827 ± 0.083	-
Yokelson **et al.,** 1997[b]	0.231 ± 0.068	0.813 ± 0.167	-
Yokelson et al., 1997[c]	0.162	0.860	-
Bertschi **et al.,** 2003[d]	0.151 ± 0.040	0.870 ± 0.030	-
Burling et al., 2010[e]	0.209	0.827	-
Mc**Meeking** et al., 2009[e]	0.153 ± 0.032	0.867 ± 0.074	-
McMeeking et al., 2009[f]	0.045 ± 0.005	0.957 ± 0.012	-
McMeeking et al., 2009[c]	0.030	0.971	-
Stockwell et al., 2014[f]	0.043 ± 0.004	0.959 ± 0.008	-
Stockwell et al., 2014[g]	0.245 ± 0.005	0.803 ± 0.009	-
Mean	**0.143 ± 0.028**	**0.875 ± 0.053**	
Siberian wildfires – sampled by aircraft or surface tower			
Cofer et al., 1998 (A)	0.224 ± 0.036	0.817 ± 0.025	1
McRae **et al., 2006** (A & S)	0.249 ± 0.064	0.800 ± 0.043	6
Vasileva et al., 2017 (S)	0.126 ± 0.007	0.888 ± 0.005	2
Fire-weighted mean	**0.219 ± 0.048**	**0.822 ± 0.033**	**9**
North American wildfires sampled by surface tower			
Wiggins et al., 2016	0.128 ± 0.023	0.887 ± 0.018	3
This study	0.142 ± 0.051	0.878 ± 0.039	34

Formatted ... [50]
Moved (insertion) [36] ... [51]
Formatted ... [52]
Deleted: ¶ ... [53]
Formatted ... [54]
Formatted ... [55]
Formatted ... [57]
Formatted Table ... [56]
Formatted ... [58]
Formatted ... [59]
Formatted ... [60]
Formatted ... [61]
Formatted ... [62]
Formatted ... [63]
Formatted ... [64]
Formatted ... [66]
Formatted ... [67]
Formatted ... [68]
Formatted ... [69]
Formatted ... [65]
Formatted ... [70]
Formatted ... [71]
Formatted ... [72]
Formatted ... [73]
Formatted ... [74]
Formatted ... [75]
Formatted ... [76]
Formatted ... [77]
Formatted ... [78]
Formatted ... [79]
Formatted ... [80]
Formatted ... [81]
Formatted ... [82]
Formatted ... [83]
Formatted ... [84]
Formatted ... [85]
Formatted ... [86]
Formatted ... [87]
Formatted ... [88]
Formatted ... [89]
Formatted ... [90]
Formatted ... [91]
Formatted ... [92]
Formatted ... [93]
Formatted ... [94]
Formatted ... [95]
Formatted ... [96]
Formatted ... [97]
Formatted ... [98]
Formatted ... [99]
Formatted ... [100]
Formatted ... [101]
Formatted ... [102]
Formatted ... [103]
Formatted ... [104]
Formatted ... [105]
Formatted ... [106]
Formatted ... [107]
Formatted ... [108]

Fire-weighted mean	**0.141 ± 0.049**	**0.879 ± 0.027**	**37**

[a] Moss (Alaska), [b] Peat (Alaska), [c] White Spruce (Alaska), [d] Duff Jack Pine/Black Spruce (Canada), [e] Duff Black Spruce (Alaska), [f] Black Spruce (Alaska), and [g] Peat (Canada).

Formatted: Font color: Auto

Formatted: Font color: Black

Formatted: Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Deleted: **38**

Formatted: Font color: Auto

Formatted: Font color: Black

Formatted: Font color: Auto

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Deleted: ¶
¶
¶
¶
¶
¶
¶
¶
¶
¶
¶
¶
¶
¶
¶

Moved up [36]: **Table 1**. Comparison of CO emission ratio and modified combustion efficiency (MCE) from previous studies that sampled emissions from boreal forest fires. The studies are organized according to wildfire domain (North America or Siberia), management practice (wildfire or management fire), and sampling approach (aircraft, laboratory, or surface tower). Siberian studies are indicated as aircraft studies (A), surface based studies (S), or a combination of the two (A & S). The CO emission ratio column has units of ppmv ppmv^{-1} and uses CO$_2$ as the reference gas.

Deleted: MCE was calculated as 1/(1+CO emission ratio) when not directly reported in the study.

Moved up [37]: The weighted mean of emission ratios and MCE for all previous studies is shown in the row labeled fire-weighted mean, with each study weighted according to the number of fires sampled. ¶

Formatted: Font: Bold

Table 2. Intervals with elevated trace gas mole fractions at CRV associated with fire emissions. Columns show the number of 30 s measurements used to calculate emission factors for each interval (N), the time of the interval (units of day of year (DOY)), emission ratios (ppmv ppmv^{-1}), emission factor (g kg^{-1} dry biomass burned), and modified combustion efficiency (MCE). The primary combustion process is denoted as flaming, mixed, or smoldering using thresholds on MCE defined in the text.

Interval number	N	Time of Event (DOY)	CO Emission Ratio	CO Emission Factor	CH_4 Emission Ratio	CH_4 Emission Factor	MCE	Combustion Phase
1	82	173.27 - 173.30	0.161 ± 0.004	144 ± 4	0.012 ± 0.0003	6.1 ± 0.2	0.861 ± 0.004	Mixed
2	95	173.32 - 173.35	0.151 ± 0.004	136 ± 4	0.011 ± 0.0002	5.8 ± 0.2	0.869 ± 0.004	Mixed
3	95	173.36 - 173.39	0.141 ± 0.003	128 ± 3	0.010 ± 0.0002	5.5 ± 0.1	0.877 ± 0.003	Mixed
4	83	173.40 - 173.43	0.149 ± 0.008	135 ± 8	0.011 ± 0.0005	5.5 ± 0.3	0.870 ± 0.008	Mixed
5	95	173.45 - 173.48	0.130 ± 0.006	120 ± 6	0.009 ± 0.0004	5.0 ± 0.3	0.885 ± 0.006	Mixed
6	95	173.84 - 173.87	0.136 ± 0.008	124 ± 8	0.014 ± 0.0009	7.3 ± 0.5	0.880 ± 0.008	Mixed
7	85	174.27 - 174.30	0.170 ± 0.008	152 ± 8	0.008 ± 0.0003	4.3 ± 0.2	0.855 ± 0.008	Mixed
8	95	175.15 - 175.18	0.08 ± <0.001	78 ± 0.3	0.004 ± <1e4	2.3 ± <0.1	0.926 ± 1e4	Flaming
9	95	175.19 - 175.22	0.143 ± 0.007	131 ± 7	0.008 ± 0.0004	4.2 ± 0.3	0.875 ± 0.007	Mixed
10	58	175.23 - 175.25	0.091 ± 0.002	87 ± 2	0.005 ± 0.0002	2.5 ± 0.1	0.916 ± 0.002	Mixed
11	88	175.27 - 175.30	0.091 ± 0.001	87 ± 1	0.005 ± 0.0001	2.9 ± <0.1	0.917 ± 0.001	Mixed
12	95	175.32 - 175.35	0.153 ± 0.003	138 ± 4	0.009 ± 0.0002	4.5 ± 0.1	0.867 ± 0.003	Mixed
13	89	175.40 - 175.44	0.187 ± 0.012	164 ± 12	0.013 ± 0.0008	6.4 ± 0.5	0.842 ± 0.012	Smoldering
14	95	175.66 - 175.70	0.060 ± 0.003	59 ± 3	0.005 ± 0.0002	2.6 ± 0.1	0.943 ± 0.003	Flaming
15	55	175.75 - 175.77	0.129 ± 0.001	119 ± 1	0.009 ± 0.0001	4.5 ± 0.1	0.886 ± 0.001	Mixed
16	35	175.77 - 175.79	0.237 ± 0.015	198 ± 15	0.017 ± 0.0010	8.1 ± 0.6	0.809 ± 0.014	Smoldering
17	95	175.80 - 175.83	0.147 ± 0.002	133 ± 2	0.011 ± 0.0001	5.5 ± 0.1	0.872 ± 0.002	Mixed
18	95	175.88 - 175.91	0.155 ± 0.003	139 ± 3	0.009 ± 0.0002	4.9 ± 0.2	0.866 ± 0.003	Mixed
19	95	175.92 - 175.96	0.198 ± 0.004	172 ± 4	0.012 ± 0.0001	6.1 ± 0.1	0.835 ± 0.004	Smoldering
20	80	175.98 - 176.00	0.193 ± 0.003	169 ± 3	0.011 ± 0.0001	5.4 ± 0.1	0.838 ± 0.003	Smoldering
21	95	176.06 - 176.09	0.119 ± 0.007	111 ± 7	0.008 ± 0.0004	4.4 ± 0.3	0.893 ± 0.007	Mixed
22	85	177.06 - 177.09	0.108 ± 0.001	102 ± 1	0.010 ± 0.0001	5.3 ± <0.1	0.902 ± 0.001	Mixed
23	75	177.11 - 177.14	0.122 ± 0.002	113 ± 2	0.011 ± 0.0001	5.6 ± 0.1	0.892 ± 0.002	Mixed
24	95	177.15 - 177.18	0.129 ± 0.001	119 ± 1	0.010 ± 0.0001	5.5 ± 0.1	0.886 ± 0.001	Mixed
25	95	177.19 - 177.22	0.102 ± 0.002	96 ± 2	0.008 ± 0.0002	4.4 ± 0.1	0.908 ± 0.002	Mixed
26	58	177.23 - 177.25	0.148 ± 0.011	134 ± 12	0.012 ± 0.0009	6.0 ± 0.5	0.871 ± 0.011	Mixed
27	94	177.27 - 177.31	0.060 ± 0.002	59 ± 2	0.004 ± 0.0001	2.3 ± 0.1	0.944 ± 0.002	Flaming
28	95	177.80 - 177.83	0.094 ± 0.002	89 ± 2	0.008 ± 0.0001	4.1 ± 0.1	0.914 ± 0.002	Mixed
29	95	177.88 - 177.91	0.120 ± 0.006	111 ± 6	0.020 ± 0.0012	10.7 ± 0.7	0.893 ± 0.006	Mixed
30	93	177.92 - 177.96	0.164 ± 0.006	146 ± 7	0.018 ± 0.0007	8.9 ± 0.4	0.859 ± 0.006	Mixed
31	95	184.23 - 184.26	0.232 ± 0.014	196 ± 15	0.013 ± 0.0007	6.5 ± 0.4	0.811 ± 0.014	Smoldering
32	80	186.49 - 186.52	0.025 ± 0.002	25 ± 2	0.002 ± 0.0001	1.2 ± 0.1	0.976 ± 0.002	Flaming
33	64	188.07 - 188.09	0.188 ± 0.012	165 ± 13	0.013 ± 0.0008	6.6 ± 0.5	0.842 ± 0.012	Smoldering
34	95	188.10 - 188.13	0.106 ± 0.002	100 ± 2	0.008 ± 0.0002	4.5 ± 0.1	0.904 ± 0.002	Mixed
35	54	188.14 - 188.16	0.109 ± 0.001	102 ± 1	0.008 ± 0.0001	4.3 ± <0.1	0.902 ± 0.001	Mixed
36	64	188.20 - 188.22	0.104 ± 0.004	99 ± 4	0.008 ± 0.0003	4.2 ± 0.2	0.906 ± 0.004	Mixed
37	52	188.23 - 188.25	0.080 ± 0.007	77 ± 7	0.006 ± 0.0004	3.2 ± 0.2	0.926 ± 0.007	Flaming
38	95	188.40 - 188.44	0.194 ± 0.003	169 ± 3	0.012 ± 0.0002	6.1 ± 0.1	0.837 ± 0.003	Smoldering
39	95	188.45 - 188.48	0.131 ± 0.004	120 ± 4	0.013 ± 0.0006	6.9 ± 0.3	0.884 ± 0.004	Mixed
40	36	188.53 - 188.55	0.146 ± 0.002	132 ± 2	0.012 ± 0.0001	6.0 ± 0.1	0.873 ± 0.002	Mixed
41	54	188.59 - 188.61	0.163 ± 0.002	145 ± 2	0.012 ± 0.0001	6.3 ± 0.1	0.860 ± 0.002	Mixed
42	95	188.62 - 188.65	0.179 ± 0.002	158 ± 2	0.014 ± 0.0002	6.9 ± 0.1	0.848 ± 0.002	Smoldering
43	74	188.66 - 188.69	0.214 ± 0.011	183 ± 12	0.015 ± 0.0008	7.4 ± 0.5	0.824 ± 0.011	Smoldering
44	95	188.71 - 188.74	0.138 ± 0.005	126 ± 5	0.010 ± 0.0004	5.1 ± 0.2	0.879 ± 0.005	Mixed
45	95	188.75 - 188.78	0.055 ± 0.003	54 ± 3	0.006 ± 0.0002	3.3 ± 0.1	0.948 ± 0.003	Flaming
46	95	188.79 - 188.83	0.272 ± 0.009	223 ± 10	0.012 ± 0.0005	5.7 ± 0.3	0.786 ± 0.009	Smoldering
47	52	188.84 - 188.85	0.120 ± 0.002	112 ± 2	0.009 ± 0.0001	4.9 ± 0.1	0.893 ± 0.002	Mixed
48	39	188.86 - 188.87	0.091 ± 0.002	87 ± 2	0.007 ± 0.0001	4.0 ± 0.1	0.916 ± 0.002	Mixed
49	59	189.03 - 189.05	0.154 ± 0.012	139 ± 13	0.010 ± 0.0008	5.3 ± 0.5	0.867 ± 0.012	Mixed
50	95	189.27 - 189.31	0.149 ± 0.008	135 ± 9	0.011 ± 0.0005	5.6 ± 0.3	0.871 ± 0.008	Mixed
51	30	189.34 - 189.35	0.090 ± 0.009	86 ± 9	0.006 ± 0.0005	3.2 ± 0.3	0.917 ± 0.009	Mixed
52	89	189.49 - 189.52	0.165 ± 0.009	147 ± 9	0.012 ± 0.0007	6.1 ± 0.4	0.858 ± 0.009	Mixed
53	48	195.10 - 195.12	0.212 ± 0.019	181 ± 20	0.016 ± 0.0014	8.0 ± 0.9	0.825 ± 0.018	Smoldering
54	37	195.12 - 195.13	0.262 ± 0.027	215 ± 28	0.020 ± 0.0020	9.5 ± 1.2	0.792 ± 0.026	Smoldering
55	95	195.14 - 195.17	0.140 ± 0.007	128 ± 8	0.010 ± 0.0006	5.5 ± 0.3	0.877 ± 0.007	Mixed
Mean			0.142 ± 0.051	127 ± 40	0.010 ± 0.0038	5.3 ± 1.8	0.878 ± 0.039	

Deleted: ¶
¶ ... [235]

Deleted: Events of

Formatted: Left

Deleted: concentrations

Deleted: the

Deleted: tower due to

Deleted: event

Deleted: event,

Deleted: factors

Deleted: per

Deleted: of

Deleted: combusted

Deleted: Dominant

Deleted: (CP)

Deleted: described

Deleted: .

Table 3. All fires that contributed to at least 1% of the total CO anomaly observed at CRV, in order from largest CO contribution to smallest CO contribution. The distance column represents the distance of the center of the fire perimeter to CRV tower. Contribution is the percent contribution to the total integral of fire CO at CRV for the entire 2015 fire season. Some fires were grouped together if they were inside the same 0.5° grid cell during model coupling. For those cases, individual fire contribution to the CO anomaly observed at CRV tower was weighted based on fire size.

	Fire Name	**Distance (km)**	**Contribution (%)**	**Total Hectares**	**Fuel Type**	**Ignition Source**
1	Tozitna	229	10.74	31652	Black Spruce	Lightning
2	Kobe	119	7.20	3444	Black Spruce	Lightning
3	Blair	82	6.31	15217	Black Spruce	Lightning
4	Aggie Creek	41	5.63	12829	Black Spruce	Lightning
5	Spicer Creek	195	5.30	39761	Black Spruce	Lightning
6	Blind River	252	3.87	24608	Black Spruce	Lightning
7	Holtnakatna	404	3.44	90308	Mixed	Lightning
8	Blazo	514	3.39	49106	Black Spruce	Lightning
9	Big Creek 2	351	3.23	126637	Black Spruce	Lightning
10	Chitanana River	241	3.12	17483	Black Spruce	Lightning
11	Sea	309	3.06	172	Black Spruce	Human
12	Sushgitit Hills	276	2.92	111712	Black Spruce	Lightning
13	Big Mud River 1	254	2.72	42076	Black Spruce	Lightning
14	Lost River	347	2.58	21088	Black Spruce	Lightning
15	Munsatli 2	302	2.36	40682	Black Spruce	Lightning
16	FWA Small Arms Complex	19	2.31	740	Black Spruce	Prescribed
17	Tobatokh	280	2.24	21868	Black Spruce	Lightning
18	Trail Creek	363	2.24	11939	Black Spruce	Lightning
19	Lloyd	201	2.22	26818	Black Spruce	Lightning
20	Isahultila	342	2.17	60445	Black Spruce	Lightning
21	Nulato	499	2.17	449	Black Spruce	Lightning
22	Three Day	472	2.17	39378	Black Spruce	Lightning
23	Hay Slough	188	1.90	37007	Black Spruce	Lightning
24	Rock	316	1.83	3714	Other	Lightning
25	Sulukna	329	1.77	6760	Black Spruce	Lightning
26	Titna	273	1.77	12415	Black Spruce	Lightning
27	Quinn Creek	657	1.49	2002	Other	Lightning
28	Harper Bend	188	1.45	17555	Black Spruce	Lightning
29	Hard Luck	328	1.43	5230	Black Spruce	Lightning
30	Fox Creek	369	1.42	2346	Black Spruce	Lightning
31	Bering Creek	280	1.36	45654	Black Spruce	Lightning
32	Eden Creek	324	1.16	18614	Black Spruce	Lightning
33	Falco	390	1.10	1817	Mixed	Lightning
34	Jackson	202	1.00	2969	Black Spruce	Lightning

Moved (insertion) [38]
Deleted:
Formatted: Font: Bold
Formatted ... [236]
Formatted Table
Formatted ... [237]
Formatted ... [238]
Formatted ... [239]
Formatted ... [240]
Formatted ... [241]
Formatted ... [242]
Formatted ... [243]
Formatted ... [244]
Formatted ... [245]
Formatted ... [246]
Formatted ... [247]
Formatted ... [248]
Formatted ... [249]
Formatted ... [250]
Formatted ... [251]
Formatted ... [252]
Formatted ... [253]
Formatted ... [254]
Formatted ... [255]
Formatted ... [256]
Formatted ... [257]
Formatted ... [258]
Formatted ... [259]
Formatted ... [260]
Formatted ... [261]
Formatted ... [262]
Formatted ... [263]
Formatted ... [264]
Formatted ... [265]
Formatted ... [266]
Formatted ... [267]
Formatted ... [268]
Formatted ... [269]
Formatted ... [270]
Deleted: 35 ... [271]
Moved up [38]: The distance column represents the
Formatted: Font: 12 pt
Deleted: ¶ ... [272]

Page 26: [1] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 26: [2] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 33: [3] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 33: [4] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [5] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [6] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [7] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [8] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [9] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 34: [10] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 34: [11] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Page 34: [12] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Add space between paragraphs of the same style

Page 34: [13] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Default Paragraph Font, Font: 12 pt, Font color: Blue, Check spelling and grammar

Page 35: [14] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [15] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Add space between paragraphs of the same style

Page 35: [16] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [17] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Normal, Add space between paragraphs of the same style, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Page 35: [18] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [18] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [19] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 35: [19] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 35: [19] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 35: [19] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 35: [20] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [21] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [22] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [23] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [24] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [25] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [25] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 35: [26] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [27] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Page 35: [28] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Custom Color(RGB(28,29,30)), Pattern: Clear (White)

Page 35: [29] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [30] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Page 35: [31] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Custom Color(RGB(34,34,34)), Pattern: Clear (White)

Page 35: [32] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 35: [33] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 8/3/20 3:34:00 PM

Page 37: [34] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [35] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [36] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [37] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [38] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: (Default) Times New Roman, Font color: Black, Check spelling and grammar

Page 37: [39] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [40] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: (Default) Times New Roman, Font color: Black, Check spelling and grammar

Page 37: [41] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black, Check spelling and grammar

Page 37: [42] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 37: [43] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Custom Color(RGB(28,29,30)), Pattern: Clear (White)

Page 37: [44] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 37: [45] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 47: [46] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 52: [47] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 52: [48] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 52: [49] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 53: [50] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Left

Page 53: [51] Moved from page 54 (Move #36) Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Table 1. Comparison of CO emission ratio and modified combustion efficiency (MCE) from previous studies that sampled emissions from boreal forest fires. The studies are organized according to wildfire domain (North America or Siberia), management practice (wildfire or management fire), and sampling approach (aircraft, laboratory, or surface tower). Siberian studies are indicated as aircraft studies (A), surface based studies (S), or a combination of the two (A & S). The CO emission ratio column has units of ppmv ppmv^{-1} and uses CO$_2$ as the reference gas.

Page 53: [51] Moved from page 54 (Move #36) Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Table 1. Comparison of CO emission ratio and modified combustion efficiency (MCE) from previous studies that sampled emissions from boreal forest fires. The studies are organized according to wildfire domain (North America or Siberia), management practice (wildfire or management fire), and sampling approach (aircraft, laboratory, or surface tower). Siberian studies are indicated as aircraft studies (A), surface based studies (S), or a combination of the two (A & S). The CO emission ratio column has units of ppmv ppmv^{-1} and uses CO$_2$ as the reference gas.

Page 53: [52] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Bold

Page 53: [53] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 53: [54] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [55] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [56] Formatted Table Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Formatted Table

Page 53: [57] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [58] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [59] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [60] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [61] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [61] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [62] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [62] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [63] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [63] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [64] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [65] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [66] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [67] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [67] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [68] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [68] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [69] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [69] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [70] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [71] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [72] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [73] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [73] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [74] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [74] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [75] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [75] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [76] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [77] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [78] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [79] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [79] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [80] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [80] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [81] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [81] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [82] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [83] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [84] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [85] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [85] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [86] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [86] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [87] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [87] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [88] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [89] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [90] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [91] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [91] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [92] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [92] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [93] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [93] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [94] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [95] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [96] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [97] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [97] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [98] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [98] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [99] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [99] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [100] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [101] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [102] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [103] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [103] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [104] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [104] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [105] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [105] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [106] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [107] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [108] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [109] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [109] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [110] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [110] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [111] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [111] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [112] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [113] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [114] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [115] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [115] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [116] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [116] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [117] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [117] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [118] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [119] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [120] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [121] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [122] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [123] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [124] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [124] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [125] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [125] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [126] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [126] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [127] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [128] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [129] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [130] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [130] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [131] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [131] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [132] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [132] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [133] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [134] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [135] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [136] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [136] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [137] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [137] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [138] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [138] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [139] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [140] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [141] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [142] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [142] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [143] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [143] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [144] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [144] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [145] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [146] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [147] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [148] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [148] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [149] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [149] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [150] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [150] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [151] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [152] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [153] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [154] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [155] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [156] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [157] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [158] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [159] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [160] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [161] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [162] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [163] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [163] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [164] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [165] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [166] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [167] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [168] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [169] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [170] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [171] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [171] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [172] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [173] Formatted Table Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Formatted Table

Page 53: [174] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [175] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [176] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [177] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [178] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [179] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [180] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [181] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [182] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [182] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [183] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [184] Formatted Table Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Formatted Table

Page 53: [185] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [186] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Auto

Page 53: [187] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Auto

Page 53: [188] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [189] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Auto

Page 53: [190] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Auto

Page 53: [191] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [192] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font: Not Bold, Font color: Black

Page 53: [193] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [194] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [195] Formatted Table Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Formatted Table

Page 53: [196] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [197] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [198] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [199] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [200] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [200] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [201] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [201] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [202] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [202] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [203] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [204] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [204] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [205] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [205] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [206] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [206] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [207] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [207] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [208] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [209] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [210] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [211] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [211] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [212] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [212] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [213] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [213] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [214] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [215] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [216] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [217] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [217] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [218] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [218] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [219] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [219] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [220] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [221] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [222] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [223] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [224] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [225] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [226] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [226] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [227] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [227] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [228] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [228] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [229] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [230] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 53: [231] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 53: [232] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [232] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [233] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [233] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Auto

Page 53: [234] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Font color: Black

Page 55: [235] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 56: [236] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [237] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [238] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [239] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [240] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [241] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [242] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [243] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [244] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [245] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [246] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [247] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [248] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [249] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [250] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [251] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [252] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [253] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [254] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [255] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [256] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [257] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [258] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [259] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [260] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [261] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [262] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [263] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [264] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [265] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [266] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [267] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [268] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [269] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [270] Formatted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Position: Horizontal: Left, Relative to: Column, Vertical: In line, Relative to: Margin, Horizontal: 0", Wrap Around

Page 56: [271] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM

Page 56: [272] Deleted Wiggins, Elizabeth B. (LARC-E3)[UNIVERSITIES SPACE RESEARCH ASSOCIATION] 2/3/21 1:00:00 PM