Dear Editor –

Thank you for overseeing the progress of this paper through ESSD. We were pleased with the helpful and supportive comments. We have addressed them all, as presented, point-by-point below. Reviewer comments in normal text, our response in bold font. The changes to the manuscript largely amount to text additions to share deeper information for the reader about details of the techniques and comparison to other possible approaches. We believe that the updated manuscript is more clear and compelling, and resubmit it for your assessment.

Citations for three datasets have been updated in the manuscript to be consistent with NASA's updated recommendation of how to cite these datasets.

REVIEWER 1

Thank you for your comments and suggestions. We address them individually in the bold text below and explain changes that we will make to the manuscript. We believe that the revisions will clarify and strengthen the manuscript.

This paper develops two methods to estimate the age of smoke plume particles downwind from the source, and applies them to fires during the FIREX-AQ campaign. One uses the mean wind speed measured downstream combined with the distance from the source, the other is based on plume rise and trajectory transport modeling. Given the inherent uncertainties in these approaches, the authors are clear about the limitations of each, and they critically assess the results. Their dataset includes 339 plume transects for the NASA DC8 and 266 transects for the NOAA Twin Otter, so robust statistics were obtained for assessing these methods. This is valuable work, and deserves publication in ESSD.

Below are a few suggestions, for your consideration:

Introduction and/or Conclusions Sections. Regarding plume-age estimation generally, it might be helpful to provide some context by discussing 'how good is good enough' for different applications. This would provide an important perspective on the overall results, for example on how much accuracy you really need in the plume-rise time estimate part of the trajectory method, and also on the value of any of the method-related suggestions I've included below. For plume chemical evolution, I'm thinking plume age *as a function of distance from the source* might be of particular interest. (Such data are implicit in your work, at least with the trajectory method, but they don't seem to be reported explicitly.)

As recognized by the reviewer, the criteria for "good enough" depend on the specific application, so we will add some general discussion of this topic to the manuscript.

Specifically, we will add to the introduction, "The level of accuracy required for plume age estimates depends on the application, as age uncertainties propagate to inferred rates and timescales of chemical processing. Studies of rapid chemical evolution in young plumes (< 1 h) may require age uncertainties below ~5-10 min, whereas analyses of more aged plumes or broader trends in composition may tolerate larger uncertainties. Studies linking downwind smoke properties to fuel and fire conditions at the source may need accuracy around 1-3 h, reflecting the timescale over which fire behavior often evolves across the diurnal cycle."

In section 3.4, we will add, "In applications that derive chemical rates from samples spanning a range of plume ages, age uncertainties translate directly to uncertainties in inferred rates or timescales. For a first-order process (e.g. exponential growth or decay), a ~20% age uncertainty implies a similar relative uncertainty in the fitted rate, though combining multiple observations reduces this when age errors are not strongly correlated."

In the conclusions paragraph discussing uncertainty, we will add, "The level of accuracy required of age data depends on the application. In analyses that quantify chemical transformations, age uncertainty limits how tightly rates can be constrained, although this limitation diminishes when multiple observations with largely independent errors are combined."

Lines 141-145. I assume you chose to use only upwind trajectories with HYSPLIT because they are guaranteed to "end" at the plume observation point. However, because these age estimates are at the heart of the current study, and especially with HYSPLIT, it might be interesting to run the model again in the forward direction from the fire source location to see how the result compares, at least in some representative cases. (The comparison might be most interpretable where HYSPLIT identifies a source that is clearly associated with the downwind observation point.)

There are other reasons why upwind trajectories from the observation point are preferrable and downwind trajectories beginning at the source fire are unfeasible. Due to vertical wind shear, the trajectory age depends on the altitude at which plume transport occurred. Upwind trajectories enable us to determine the plume injection height and the plume altitude at all points upwind of the aircraft. Trajectories that start at the fire would require prior knowledge of the time-varying plume injection height. Remote sensing measurements of smoke height can be unavailable due to cloud cover or mismatched satellite overpass time and often identify the top of the plume, rather than the altitude at which the aircraft sampled. Upwind trajectories also enable us, in some cases, to compute the mix of ages from multiple source fires or multiple flame fronts within a large fire.

To reflect some of these issues for the reader, we will add a sentence at the line cited, "Using upwind trajectories from the aircraft allows plume rise ($z_{rise,m}$) to be inferred from the trajectories, whereas downwind trajectories from the fire require prior information about plume rise."

Lines 185-188. Similar to the note on Line 141, the variability in the aircraft-derived wind speed across a transect, or among several nearby transects of the same plume at similar points along the plume cross-section, might yield further confidence in the aircraft-derived values. I'm thinking these uncertainties might make a larger contribution to the overall plume age estimates than the uncertainty in the plume-rise time (~5 min) that are assessed so carefully, as discussed toward the end of Section 2.4.

The wind variability within transects is already accounted for in the uncertainty analysis, through the difference between wind speed corrected and uncorrected ages. Indeed, the wind speed is almost always a larger source of age uncertainty than plume rise, as shown in Fig 8 and discussed in Sect. 3.4.

We will clarify that the wind speed correction and uncertainty is computed for each observation point rather than each transect, by adding "for each observation within a transect" to the sentence "We therefore compute a second advection age $\tau'_{adv,m} = \tau_{adv,m}(u_m/u_o)$ and second smoke age $\tau'_m = \tau'_{adv,m} + \tau_{rise,m}$ for each observation within a transect."

Lines 206 ff. Another thought on procedure, in case it is of use. For very long trajectories, there might be some value in assessing the "mean-wind" advection time by dividing the plume into at least a couple of segments, making age assessments for each individual segment, adding them together, and comparing with the trajectory advection-time estimates, especially if the plume curves or has otherwise complex downwind horizontal structure. (This approach might be helpful, for example, in addressing the issues raised on Lines 314-315 and Lines 319-320.) Similarly, for long plumes that change direction along the way, you might obtain different results from the trajectory method by running the model separately for significantly different segments.

It may be possible to compute two, three, or more segment trajectories from wind measurements in some special cases, but that is a major task beyond the scope of what we are able to do in this manuscript. In general, considerable manual effort is required to identify appropriate spatio-temporal break points in the wind field and trajectories.

We will add a sentence to the identified paragraph noting this possibility: "Future work could perhaps mitigate this limitation by computing the mean-wind age in a few segments where there are sufficient observations to characterize distinct wind regimes."

Lines 268-269. You do a careful job of accounting for parallax related to surface topography in the GOES ABI imagery. Would a further correction be needed for plume elevation, especially for plumes that reside in the free troposphere, much above the boundary layer? (I know there are relatively few of those in your dataset.)

Correct. The smoke in the images also appears displaced from its true location, particularly for smoke above the boundary layer. Adjusting the smoke plumes within the image would require information about the smoke height, which is often lacking. This is noted in the manuscript: "Clouds and smoke, which are above ground level, are still affected by the parallax effect, however."

Lines 305-310. This seems important. As I understand, the plume-rise times are explicitly not included in the statistics for the mean-wind method. (The distance used is from the fire horizontal location, not the surface, and besides, the vertical velocity is governed by factors other than the mean wind at plume elevation.) So, when comparing with the trajectory approach, I'd think adding the plume-rise time from the trajectory estimate would be appropriate (as highlighted by the issue raised on Lines 345-348). I see you were thinking about this by Line 309...

Yes. We discuss this possibility in Sect 3.2 and again in the Conclusions. We will also add, "Users may, if desired, add the plume rise time from the trajectory method to the mean-wind age to mitigate this bias."

Another note: If your data set happens to include the Williams Flats fire plume on August 09, 2019, you might consider comparing your results with plume ages estimated based on motion vectors at plume elevation, assessed along the entire plume, that were derived from MISR multi-angle imagery (Junghenn *Noyes et al*., 2020, doi:10.3390/rs12223823). You obviously won't get statistics from a single case (there are many others, though not during FIREX, e.g., doi:10.5194/acp-22-10267-2022), but the method is entirely different and quite robust, as it is based on the geometry of the observations.

This is a nice suggestion, but it appears that this particular Williams Flats case is not suitable for this comparison. Noyes et al. (2020) point out that the MISR observations, on which the motion vector age is based, occurred 2-3 hours before the aircraft observations (their Fig 1a vs 1b). The smoke ages used by Noyes et al. (2020) during the aircraft sampling are the mean-wind ages described in this work, so comparing to them would not provide additional information. We are not aware of other MISR wind vector age data that would provide independent evaluation.

REVIEWER 2

Thank you for your comments and suggestions. We address them individually in the bold text below and explain changes that we will make to the manuscript. We believe that the revisions will clarify and strengthen the manuscript.

This manuscript presents two complementary approaches to estimate the age of wildfire smoke sampled during the 2019 FIREX-AQ campaign: (1) a mean-wind method that converts fire–receptor distance and in-situ wind speed into a single age, and (2) a trajectory-based method that back-propagates air parcels with an ensemble of high-resolution meteorological datasets and adds buoyant plume rise time. The results show a strong correlation between methods, and a systematic ~14% younger bias of mean-wind ages relative to trajectory ages.

The work is carefully conducted, and the dataset is valuable. It fits well within the scope of the ESSD journal. Here, only a few comments are suggested to further improve the manuscript.

Specific Comments

(1) Section 2.3

For the uncertainty analysis, can you please explain why the mean-wind age method does not provide an uncertainty estimate?

This may be possible in future work. We note that we believe that the comparison between our very detailed wind-field advection scheme approach and the simple mean-air approach is likely the strongest manner in which to assess the uncertainty. Generating an "internal" estimate of uncertainty from the mean-wind approach (i.e. developing a quantification based on observed variability in the wind fields averaged for the approach) is not clearly of value because of the potential complexities in the wind field. For example, regions of high-shear may or may not influence either the uncertainty estimate or the actual advection of the smoke We will add a sentence, "Observed wind variability within the domain used to construct the mean vertical profile might help constrain age uncertainty; however, this remains for future work."

(2) Section 3.2

For the case of the Shady Fire, it is suggested that "neglecting plume rise time in the mean-wind method is the cause of its systematic bias for young plumes". Would this conclusion hold for the whole dataset, i.e., "the mean-wind age is systematically 14% younger than the trajectory-based age on average", and the 14% would be attributed to plume rise time? Please clarify.

Indeed, the inclusion of plume rise time contributes to the bias. We will add a sentence "Plume rise accounts for about half of the mean difference between methods."

(3) Page 12, Line 365/Page 7, Line 207

"plume vertical speed, which is assumed to be 7 +/- 4 m s-1 in most plumes". On Line 165, it writes "plume rise time using an updraft speed of 7 +/- 3.5 m s-1". Please check the number.

Some values in the text were rounded. Calculations used 7 ± 3.5 m/s and the revised text will say this throughout.

(4) The label in Figure 8; here, "Chem Otter" should be "Twin Otter" for consistency.

Agreed

(5) Line 434:

“This satellite imagery is used to filter out upwind trajectories from the trajectory-based age analysis when a model is grossly inconsistent with the smoke plume transport visible is the satellite data.” What does the sentence mean? Please check.

We will revise this sentence to “Satellite imagery is used to exclude upwind trajectories from the trajectory-based age analysis when a meteorological dataset shows large inconsistencies in wind direction or speed relative to the observed smoke plume transport.”

The criteria are spelled out in greater detail in section 2.4: “Examples of gross trajectory problems include wind directions errors exceeding 45°, wind speed errors exceeding 50% of observed wind speed, and implausible wind shifts.”
