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Age of smoke sampled by aircraft during FIREX-AQ: methods and critical evaluation

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Abstract. The age of smoke, meaning the time elapsed since it was produced in a fire, is an important parameter for interpreting measurements of evolving smoke composition. This study describes the smoke age estimates developed for large plumes sampled in the 2019 NASA-NOAA FIREX-AQ field experiment. Smoke ages are computed using two methods and applied to observations from two aircraft: the NASA DC-8 and a NOAA Twin Otter. The first method uses measurements of mean horizontal wind speed, as observed by the sampling aircraft, and distance to the fire to provide a single age estimate for each plume-crossing performed by the aircraft. While this "mean-wind method" uses accurate wind measurements, it can be systematically biased by assumptions that plume rise time is negligible and that winds are homogeneous horizontally and in time during the plume transport. Wind inhomogeneities due to terrain effects and day-to-night transition, among other factors, affected some plumes during FIREX-AQ. The mean-wind method therefore performs best for short-range transport over level terrain with steady winds. The second method relies on upwind air parcel trajectories and plume rise computed with multiple high-resolution meteorological datasets. This "trajectory-based method" quantifies age uncertainty from the meteorological ensemble, plume rise speed, wind speed errors, and fire location. The second method also resolves age

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differences from the center to edge of a transect. Still, it is susceptible to errors in the meteorological model. With careful comparison of the simulated trajectories to smoke transport observed from geostationary satellite imagery described here, we filter out many trajectory errors and improve the smoke age estimates. The two age methods are strongly correlated (R = 0.93) for the periods during FIREX-AQ when both ages are available. The mean-wind age is systematically 14% younger than the trajectory-based age and the median absolute difference between them is 19 % (23 % for mean). The favorable agreement between the two age methods reflects that the mean-wind method was selectively applied to plumes with little wind variability. Trajectory-based ages are available for more of the FIREX-AQ smoke observations than the mean-wind ages. The median trajectory-based age uncertainty during FIREX-AQ is 24 % and the mean uncertainty is 37 %, due to a long-tailed distribution. The main source of age uncertainty is spread within the meteorological ensemble, followed by discrepancy between measured and modeled wind speed, then other factors like plume rise. The age uncertainty variable enables the user to identify periods with high or low confidence in the age estimate, thereby informing studies of smoke aging.

1 Introduction

The NASA-NOAA Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) campaign extensively sampled smoke from wildfires and prescribed fires over the United States in July through September 2019 (Warneke et al., 2023). Two aircraft that participated in the campaign, the NASA DC-8 and a NOAA Twin Otter, focused on in situ smoke measurements. They contained multiple instruments for measuring the chemical, physical, and optical properties of trace gases and aerosol in smoke. Understanding the chemical and physical evolution of the smoke from these measurements requires knowing the physical age of the smoke, meaning time elapsed since its emission at the fire source.

Determining the time for air parcel transport from a source location to a measurement location is an old problem in atmospheric science (see reviews by Fleming et al., 2012; Stohl et al., 1998). Over short periods of time when winds are steady, the transport time from an upwind source to a downwind receptor can be determined from the wind speed and distance (e.g. Pueschel and Van Valin, 1978; Ryerson et al., 1998; Yokelson et al., 2003). When winds are variable, which almost inevitably occurs on time scales of hours and longer, Lagrangian air parcel trajectory calculations that account for the evolving wind field are needed. HYSPLIT and FLEXTRA are two widely used trajectory models (Stein et al., 2015; Stohl et al., 1995), among many others (Fleming et al., 2012; Stohl, 1998). Buoyant plume rise, as occurs in fires and some industrial sources (Briggs, 1969; Freitas et al., 2007), introduces additional complications to determining the transport time, as buoyant vertical motions are typically not resolved in large-scale meteorological datasets used to drive trajectory calculations.

This work describes the methods and resulting dataset of smoke age for the FIREX-AQ campaign. Section 2 explains two methods used for computing ages: one based on measured mean wind speed and another based on an ensemble of air parcel

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trajectories. Geostationary satellite imagery is used to screen the trajectory ensemble and exclude implausible trajectories from the smoke age calculation. Section 3 evaluates smoke age estimates from the two methods, examines the contribution of plume rise to smoke age, and analyzes uncertainties in the ages. Section 4 describes the data availability and Section 5 provides conclusions and implications.

2 Data and Methods

2.1 Aircraft data and smoke plume identification

This work examines the age of smoke sampled in situ by two aircraft during FIREX-AQ: the NASA DC-8 and a NOAA Chemistry Twin Otter (NOAA48). A second NOAA Twin Otter (NOAA46) that collected remote meteorological measurements will not be discussed here. Both the DC-8 and Twin Otter intercepted numerous smoke plumes at multiple distances and ages downwind of the source fires, as shown in Figure 1. Smoke encounters are identified by manually inspecting the time series of measured CO (both aircraft) and black carbon aerosol (DC-8 only) for periods of elevated concentrations above the local background. The DC-8 instruments used to identify smoke are DACOM for CO (Sachse et al., 1991) and SP2 for black carbon (Schwarz et al., 2008). For the Twin Otter, a near-infrared cavity ring down spectrometer is used for CO (Crosson, 2008; Karion et al., 2013). Each passage of an aircraft through a smoke plume is referred to as a transect. Most transects were cross-wind, meaning the aircraft flew nearly perpendicular to the local wind, while others were nearly parallel to the wind. The start and end times of each plume transect are determined to the nearest second.

Smoke age is estimated for all smoke sampled by the DC-8 and Twin Otter in the western U.S., nearly all of which were wildfires. This sampling occurred 24 July 2019 through 16 August 2019 for the DC-8 and 20 July 2019 through 5 September 2019 for the Twin Otter. Ages are also estimated for three plumes sampled by the DC-8 over the central and eastern US that were sampled multiple times downwind. These are a prescribed fire in the Blackwater River State Forest, Florida (30 August 2019) and timber slash pile fires in Alabama (30 August 2019) and Oklahoma (26 August 2019). These eastern fires have fire ID numbers 52, 64, and 37 respectively, in the FIREX-AQ data catalog. Other fires in the eastern US were sampled almost directly over the source fire, with little or no downwind plume sampling, so no ages are provided for them. Overall, there are 21 hours of in situ smoke sampling and 339 smoke transects by the DC-8 for which smoke ages are determined, plus nearly 19 hours of smoke sampling and 266 smoke transects by the Twin Otter.

2.2 Fire locations

Most smoke plumes sampled by the DC-8 and Twin Otter during FIREX-AQ were visually traceable to a single fire or fire complex by personnel on board the aircraft. These fires ranged in size from < 1 km across to about 15 km, with 1-4 km being common. For plumes sampled by the DC-8, precise locations of those source fires are determined from infrared imagery

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collected by the MODIS/ASTER Airborne Simulator instrument (MASTER; Hook et al., 2001). MASTER provides fire temperature and fire radiative power at a horizontal resolution that depends on aircraft altitude, typically ~10-meter-scale for the fires examined here. From the DC-8 overpass that provided the most complete MASTER image of each fire, the fire centroid (latitude, longitude, and altitude) is calculated using fire radiative power as an averaging weight. Smoke age calculations treat the fire as a point source at the centroid location, with special accommodations for the largest fires described below. The Twin Otter did not carry a thermal imaging instrument so precise source fire locations for smoke sampled by this aircraft are instead determined from MODIS and VIIRS active fire detections on the flight day. As with MASTER, the centroid of the active fire pixels is used as the source for smoke age calculations. On some days, the satellite instruments did not detect the fires that were sampled by aircraft, which can occur because of clouds, small fire size, or burning that did not coincide with a satellite overpass. In these cases, we take the fire location from satellite detections on surrounding days or, if those are also unavailable, from fire incident reports (Incident Information System, 2020).

The fire locations used in smoke age calculations are updated each flight day to account for fire movement over multiple days. For example, the flame front of the Castle Fire moved 1.8 km from August 13 to 14, when it was sampled by the DC-8, and 5 km by August 22, when it was sampled by the Twin Otter. The two largest fire complexes sampled during FIREX-AQ—the Williams Flats and Sheep Fires—had multiple centers of fire activity that produced multiple, distinct smoke plumes separated by over 10 km. For these very large fires, separate source locations are determined for each fire center and matched to downwind plume transects. A few plume transects contain mixtures of smoke from multiple fires or the source fire cannot be identified confidently. In these cases, all of the potential source fire locations are used and the uncertainty in smoke age accounts for ambiguity in the source location (Sect. 2.4). More generally, smoke from a mixture of sources can be considered to have a spectrum of ages, but FIREX-AQ aircraft rarely sampled such mixtures, so the approach of providing a single age with uncertainty is used here.

2.3 Smoke age from measured wind profiles: "mean-wind age"

The first method for calculating smoke age relies on in situ wind measurements from the aircraft, as a long-established approach (e.g. Akagi et al., 2012; Pueschel and Van Valin, 1978; Ryerson et al., 1998; Yokelson et al., 2003). We refer to this as the "mean-wind age." A vertical profile of mean wind speed is calculated from all in situ wind measurements during the flight within 3° (latitude and longitude) of the fire. These wind measurements are averaged into 1000 m vertical bins. A mean wind speed vertical profile is constructed for each fire sampled during each flight. The smoke age is then determined from the distance between the source fire and the downwind measurement location, divided by the mean wind speed interpolated to the measurement altitude. This assumes that upwind transport occurs at the measurement altitude and that the plume's vertical rise time is small; both assumptions will be critically evaluated in Section 3. For cross-plume transects (i.e. perpendicular to the wind), the distance and age are calculated at the center location of the transect and all measurements during that transect are assigned the same age. For transects parallel to the wind, the distance and hence age are calculated

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from the aircraft location each second. The wind measurements used in the mean wind age calculation come from the Meteorological Measurements System (MMS) instrument on the DC-8 (Scott et al., 1990). Wind measurements from the Twin Otter have quality issues that prevent their use, so mean wind age is provided only for DC-8 smoke samples. The mean-wind age is also not applied to smoke sampled by the DC-8 beyond about 200 km from a fire or for plumes with obvious wind shifts, as the assumption of constant wind profile would be violated. Table 2 lists the variables related to mean-wind age that are contained in the FIREX-AQ data archive.

2.4 Smoke age from wind trajectories: "trajectory-based age"

The second method for calculating smoke age uses upwind trajectories originating from the aircraft measurement locations and tracing back to the source fire. Trajectories are initialized from the aircraft location at 5 second intervals during smoke sampling and propagated upwind using the NOAA HYSPLIT model (Stein et al., 2015). Three upwind trajectories are computed from each aircraft location using three meteorological datasets (Sect. 2.5). All trajectories extend 60 hours upwind with intermediate trajectory positions recorded every 10 minutes.

We decompose the smoke age into two components: advection ($\tau_{adv,m}$) and buoyant plume rise ($\tau_{rise,m}$):

$$\tau_m = \tau_{adv,m} + \tau_{rise,m}. \quad (1)$$

Each of the meteorological datasets (m) provide an estimate of the age and its rise and advection components. The advection age ($\tau_{adv,m}$) is determined from the point when then the upwind trajectory is closest to the source fire, as illustrated in Figure 2. Plume rise is not always vertical, but this is reasonable for fires sampled in FIREX-AQ. In some cases, wind shifts cause the upwind trajectory to pass over the fire multiple times. In those cases, we assume that the youngest age is most likely. The buoyant rise component of plume age is determined by the altitude of the trajectory above ground at the point of closest approach ($z_{rise,m}$) and an empirical plume rise vertical speed (w_{rise}):

$$\tau_{rise,m} = z_{rise,m}/w_{rise}. \quad (2)$$

Measurements of updraft speeds in wildfire smoke plumes are limited to a few case studies, but nevertheless show that vertical velocities vary with altitude and fire conditions and often fluctuate rapidly (Clements et al., 2018; Lareau and Clements, 2017; Rodriguez et al., 2020). In a smoke column topped with pyrocumulus clouds, like those commonly observed during FIREX-AQ, updraft speeds have been observed decreasing from 13 to 7 m s^{-1} in the 2 km above a fire (Lareau and Clements, 2017). In a pyrocumulonimbus, median updraft speeds of 5-18 m s^{-1} have been observed, albeit with much larger extremes (Clements et al., 2018; Rodriguez et al., 2020). In a larger dataset of ordinary cumulonimbus, median updraft speeds of 4-7 m s^{-1} were observed and extremes (95th percentile) were about twice the median (Giangrande et al., 2013). In 1-D smoke plume models, updraft speeds around 3-8 m s^{-1} have been simulated for plumes extending to 3 km altitude and around 6-15 m s^{-1} for plumes that generate deep convection up to 8 km altitude (Freitas et al., 2007). Based on these studies, we compute plume rise time using an updraft speed of 7 ± 3.5 m s^{-1} for plumes without clouds or with

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pyrocumulus. For a few plumes that generated pyrocumulonimbus (Williams Flats Fire, 8 August 2019) an updraft speed of 12 ± 6 m s^{-1} is used in age calculations. For FIREX-AQ samples, a typical plume rise distance is around 2000 m and a typical rise time is thus around 5 minutes.

We plot and visually screen all simulated trajectories from all meteorological datasets for consistency with the plume transport seen in geostationary satellite imagery (Sect. 2.6). If one of the meteorological datasets produces trajectories that are grossly inconsistent with the satellite-observed transport for a particular smoke transect, the meteorological dataset is excluded from further age analysis of that transect. Trajectories from the remaining meteorological datasets are considered equally plausible and used to determine the age. Examples of gross trajectory problems include wind directions errors exceeding 45°, wind speed errors exceeding 50% of observed wind speed, and implausible wind shifts. One or more meteorological datasets is excluded for about 30 % of transects. A data variable named "smoke_age_method" indicates which meteorological datasets have been included or excluded for each time point in the smoke age dataset. Our best estimate of smoke age is

$$\tau = \langle \tau_m \rangle = \langle \tau_{adv,m} \rangle + \langle \tau_{rise,m} \rangle \quad (3)$$

where $\langle \ \rangle$ represents the ensemble mean of ages derived from meteorological datasets that produced plausible upwind trajectories. Since upwind trajectories are computed from the aircraft location every 5 seconds, the best smoke age is first calculated at this frequency, then linearly interpolated to 1 second time basis for consistency with other aircraft measurements.

Inferred smoke ages are susceptible to errors in the meteorological analysis datasets. To constrain the magnitude of this effect, we compare the wind speed observed by the aircraft (u_o) to the model (u_m) at the aircraft location. If the observed wind speed is slower than the model predicts ($u_m/u_o > 1$), then the smoke age may be greater than implied by the trajectory-based method. We therefore compute a second advection age $\tau'_{adv,m} = \tau_{adv,m}(u_m/u_o)$ and second smoke age $\tau'_m = \tau'_{adv,m} + \tau_{rise,m}$. We refer to this as a wind speed correction, which is performed for each meteorological dataset m. Since wind speed errors at the aircraft measurement point may not be representative of wind speed errors along the entire upwind trajectory, the wind speed corrected ages are not necessarily more accurate, but they are useful for quantifying age uncertainty, as discussed in the next paragraph.

Estimates of uncertainty in smoke age are provided with each age estimate. The factors that influence this uncertainty include spread in age among the meteorological datasets, differences between measured and modeled wind speed, convective vertical velocity, and sometimes multiple potential source fires. These individual uncertainties (δ_i), defined as follows, are assumed to be independent and are therefore summed in quadrature to determine the overall age uncertainty: $\delta\tau = \left(\sum_i {\delta_i}^2\right)^{1/2}$.

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1. Spread in advection age across the ensemble of meteorology datasets: $\delta_{adv,ens} = s\{\tau_{adv,m}\}$. Here, $s\{x_m\}$ represents the sample standard deviation of variable x derived from multiple meteorological datasets m.
2. Spread in plume rise time across the ensemble of meteorology datasets: $\delta_{rise,ens} = s\{\tau_{rise,m}\}$
3. Uncertainty in pyroconvective vertical velocity: $\delta_{rise,w} = \langle\tau_{rise,m}\rangle \frac{\delta w_{rise}}{w_{rise}}$. As described above, $w_{rise} \pm \delta w_{rise}$ is 12 ± 6 m s^{-1} for smoke lofted in pyrocumulonimbus and 7 ± 4 m s^{-1} otherwise.
4. Wind speed error in meteorological datasets: $\delta_{ws} = \frac{1}{2}\langle|\tau_{adv,m} - \tau'_{adv,m}|\rangle$. This term represents the spread between age estimates with and without wind speed correction, averaged across the ensemble of meteorological datasets.
5. Trajectory displacement from source fire: $\delta_{traj} = \langle d_{min,m}\rangle^2/(2d_o\langle u_m\rangle)$. An upwind trajectory that doesn't pass directly over the source fire could indicate an error in the smoke age derived from that trajectory. We use scale analysis to approximate the associated age uncertainty. At the point where the trajectory is closest to the fire, the minimum distance between them ($d_{min,m}$, Fig. 2) could be traversed in time $d_{min,m}/u_m$, where u_m is the wind speed along the trajectory. Long-distance upwind trajectories are always expected to accumulate more error than short trajectories, so the age error likely scales with the ratio $d_{min,m}/d_o$, where d_o is the aircraft distance from the fire when the observation was made, which is also where the trajectory was initialized. We multiply these two scaling terms. The result is divided by 2 out of analogy that in a normal distribution the standard deviation is half of a result at the 95% confidence interval.
6. Source fire ambiguity: $\delta_{source} = \langle s_m\{\tau_{m,f}\}\rangle$. For smoke plumes with more than one possible source fire (Sect 2.2), the smoke age $\tau_{m,f}$ was calculated for each possible source fire *f*. The quantity $s_m\{\tau_{m,f}\}$ represents the sample standard deviation of these possible ages within meteorology dataset m.

The smoke age uncertainty is quantified for each observation. As discussed in Sect. 3.4, the resulting uncertainty varies spatially and temporally between and within smoke plume transects, identifying observations where the age can be determined with greater or lesser confidence.

Table 2 lists the variables related to trajectory-based age and age uncertainty that are contained in the FIREX-AQ data archive. All age computations, apart from the HYSPLIT trajectory calculations are done in Python. Cartopy is used for great circle distance calculations and mapping (Elson et al., 2018). The GNU Parallel utility is used to parallelize computing tasks (Tange, 2011).

2.5 Meteorological data and HYSPLIT developments

We use three meteorological datasets from NOAA to drive HYSPLIT in this work. These are High Resolution Rapid Refresh (HRRR), North American Mesoscale Contiguous United States nest (NAM CONUS), and Global Forecast System (GFS). The HRRR and NAM models have 3 km horizontal resolution while GFS is 0.25°. In the vertical, winds and other

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meteorological variables are saved on the native grid of each model (not standard pressure levels). These are 36 levels for HRRR, 40 for NAM, and 55 for GFS, plus an additional layer of surface variables in each model. The NOAA Air Resources Laboratory (ARL) maintains a long-term archive of the of the HRRR and GFS products in the file format used by HYSPLIT. For NAM CONUS nest, we create our own archive by piecing together the first six forecast hours of four daily model initializations (0, 6, 12, 18Z). This is the same method that ARL uses for the HRRR, GFS and other archives that they maintain. On two days when the NAM CONUS nest was not archived (14 and 25 August 2019), we use the 12 km NAM in its place. The GFS and NAM data that we use are never more than 6 hours after meteorological forecast initialization and HRRR is never more than one hour after initialization.

Trajectories are computed with HYSPLIT version 4.2 with the following improvements and bug fix. The trajectory output frequency and precision are increased to every 10 minutes of advection time. Capabilities are added to output wind speed and direction along the trajectory, which enables evaluation against the in situ aircraft wind measurements. We also correct the radius of Earth that HYSPLIT uses when handling HRRR and NAM data to match the value used in those meteorological models (6370.0 km). This geolocation error shifts the meteorological grid by up to 1 km.

2.6 Geostationary satellite images

We process and use geostationary satellite imagery from GOES-East (GOES-16) and GOES-West (GOES-17) to provide context for the aircraft measurements and better understand smoke transport from the fire to the aircraft. True color images are derived from Advanced Baseline Imager (ABI) Level 2 Cloud and Moisture Imagery (CMIPC) blue (B, 0.47 µm), red (R, 0.64 µm), and near infrared (NIR, 0.86 µm) reflectance (GOES-R Algorithm Working Group and GOES-R Series Program, 2017). The blue and near infrared channels (1 km nadir resolution) are sharpened to the red channel resolution (0.5 km nadir resolution) using the method from Miller et al. (2020). Since ABI does not have a green channel, a simulated green channel is constructed from a weighted average of the blue, red, and near infrared ($G = 0.45R + 0.45B + 0.1NIR$) (Bah et al., 2018; Mosher et al., 2023). The three channels are then combined into a true color image and contrast is increased in the dark to moderate values to brighten surfaces and accentuate differences between smoke and clouds (Bah et al., 2018). The resulting images are similar to other daytime true color products derived from ABI data (Mosher et al., 2023), while enabling easier distinction between clouds and smoke and providing more accurate surface locations, as described next. GOES images are available at 5-minute time intervals over the contiguous United States.

Most software packages provide geolocations for GOES data by projecting the satellite image onto Earth's ellipsoid. While this provides the correct latitude and longitude for features at sea level, anything above sea level—including elevated land, clouds, and smoke—appears displaced from its true latitude and longitude (e.g. Akagi et al., 2012). This satellite parallax effect produces geolocation errors that increase with altitude and with distance from the sub-satellite point (Figure 3). For terrain in the western US imaged by GOES-East, the naively projected locations are frequently 2-8 km north and west of the true location. In this work, the GOES images and image data provided in the FIREX-AQ data archive correct for the terrain parallax effect. Surface elevation data from a 30 arc second (~1 km) resolution dataset (GTOPO30; Gesch et al., 1999) are projected into the ABI geostationary perspective, which provides an interpolation map from the image pixel coordinates to accurate latitude-longitude geolocations on Earth's surface. Figure 3c illustrates a smoke plume in the uncorrected images that appears to originate from locations where there were no fires. With parallax correction (Fig. 3d), however, the smoke plumes begin over the fire locations. Clouds and smoke, which are above ground level, are still affected by the parallax effect, however. GOES-East and GOES-West images and movies (mp4 format) of all fires sampled during FIREX-AQ are available in the FIREX-AQ data archive. RGB image data on a regular latitude-longitude grid are also provided in netCDF format to enable users to combine these images with data of their choice.

3 Results

3.1 Meteorological dataset evaluation

Table 1 evaluates the accuracy of the three meteorological datasets used in this work against wind and temperature measurements (10-second averages) from the DC-8 aircraft. The evaluation focuses on periods and locations where the aircraft sampled smoke. In all three meteorological datasets, the mean biases are 0.25 m s^{-1} or less for wind speed and 5° or less for wind direction. The median absolute differences are larger, but still 1.4 m s^{-1} or less for wind speed and under 13° for wind direction. For comparison, two separate measurement systems on board the DC-8 (MMS and Navigational Management System) have median absolute differences of 0.34 m s^{-1} in wind speed, 2.5° in wind direction. None of the meteorological datasets consistently outperformed the others across all wind performance metrics. For temperature, the high-resolution datasets (HRRR, NAM CONUS nest) have smaller mean and median errors than the lower-resolution GFS, but temperature is less relevant than wind for transport and smoke age calculations. In other circumstances, such as in the boundary layer or near frontal boundaries or convection, winds from the high-resolution models would likely perform better than GFS, but smoke plume sampling during FIREX-AQ primarily occurred in the lower free troposphere and avoided severe weather. On the basis of their comparable overall wind representation, the trajectories computed with all three meteorological datasets are treated as an ensemble with equal weight for purposes of determining smoke age.

3.2 Smoke age evaluation: comparison of methods

Figure 4 illustrates the difference between smoke ages from the mean-wind and trajectory-based methods using observations from the Shady Fire, Idaho, as an example. This fire was sampled by the NASA DC-8 on 25 July 2019 with 48 transects extending up to 160 km downwind of the fire. The mean-wind method produces a single age for each smoke transect, while the trajectory-based method allows the smoke age and its uncertainty to vary across each transect. For comparison between the methods, the trajectory-based ages are averaged across each transect and compared to the single mean-wind age for that

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transect. Age uncertainties (trajectory-based method only) are also averaged across each transect because the age errors in a single transect are expected to be highly correlated.

Overall, there is strong consistency between the age estimates from the mean-wind and trajectory-based methods for the Shady Fire. The two ages have strong linear correlation (Pearson $R = 0.95$) as well as rank correlation (Spearman $\rho = 0.97$). The mean relative difference between the two methods is 17% for this fire, with the trajectory-based ages being older, which is comparable to the 20% mean uncertainty in the trajectory-based ages for this day of sampling. Despite the overall consistency, however, the trajectory-based ages are systematically older than the mean-wind ages.

For smoke transects closest to the Shady Fire (< 40 km, age < 60 minutes; Fig. 4c), the two age estimates are within 10 minutes of each other, but the trajectory-based ages are systematically older than the mean-wind ages. For example, the two smoke transects closest to the Shady Fire had ages of 8 and 18 minutes according to the mean-wind method versus 16 ± 4 and 23 ± 4 minutes according to the trajectory-based method. The difference is almost entirely due to aging during buoyant plume rise, which is included in the trajectory-based age but not in the mean-wind age. The plume rise time for these transects close to the fire is about 6 minutes. If this plume rise time were added to the mean-wind age, the difference between the two methods would be less than 2 minutes, which is less than the uncertainty in the trajectory-based method. Thus, neglecting plume rise time in the mean-wind method is the cause of its systematic bias for young plumes. In future applications, a plume rise component could be added to the mean-wind method.

At further distances (> 80 km, age > 100 minutes) additional differences between the two age methods appear. The oldest smoke, at the eastern end of sampling, is older according to the trajectory-based method than the mean-wind method by more than 1 hour for some transects. The difference is primarily explained by the oldest samples being collected in the evening as winds slowed around sunset, a common meteorological phenomenon in the lower troposphere. The evening wind slowdown was recorded in the aircraft's wind measurements and visible in sequences of GOES images of the smoke plume, so it is a real effect that is represented in the trajectory-based age. Trajectories with high-resolution meteorology (HRRR, NAM CONUS nest) also suggest that the smoke plume ascended and descended by about 1 km when passing over mountains and valleys (Fig. 2). The mean-wind age, however, assumes constant winds at each altitude and that upwind transport occurred at the same altitude as the aircraft measurement. An additional difference between the two age methods that can be seen in maps (Figs. 4a, 4b) is that the trajectory-based ages are older on the north side of the plume than the south side during some transects. The slower smoke transport on the north side of the plume also appears in GOES image sequences. Thus, the age differences in the far field smoke samples are due to temporal and horizontal wind shifts that are not accounted for in the mean-wind method.

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Figure 5 compares the two age methods for a second example plume from the Sheridan Fire, Arizona. Terrain surrounding the Sheridan Fire has less topographic variation than the Shady Fire, which should make the winds more horizontally homogeneous and provide a better environment for the mean-wind age to perform well. Indeed, the two ages are very strongly correlated for the Sheridan Fire (Pearson R = 0.99). The mean-wind age is again systematically younger than the trajectory-based age for the first hour downwind of the fire, with the difference explained by the plume rise time (~ 5 minutes). After about one hour downwind, the trajectory-based ages are younger than the mean-wind ages, as the meteorological datasets slightly overestimate the wind speed for this plume. The largest age differences between the two methods occur in the five most distant cross-wind transects, which coincide with the plume passing over terrain on the edge of the Colorado Plateau in central Arizona. The high-resolution meteorological datasets have better capability to resolve winds around such topography, although their accuracy is not always guaranteed. The widths of these distant transects also increase to about 120 km, making the assumption of constant age across a transect less plausible. Evidence from Sheridan Fire and Shady Fire together supports that the two age methods having better agreement over flatter terrain.

Figure 6 expands the age comparison to all smoke plume transects sampled by the DC-8 during FIREX-AQ. There are 262 smoke plume transects with ages provided by the mean-wind method. The trajectory-based method provides ages for an additional 75 plume transects where the mean-wind method was not used because the winds were especially variable or the transport distance was exceeded 200 km. As described in Sect. 2.1, the large majority of the DC-8 transects were smoke from western wildfires. The mean-wind age could not be calculated for the Twin Otter, so the comparison in Fig. 6 only shows DC-8 data. The age comparison across all FIREX-AQ transects is similar to the results for the Shady plume already discussed. The linear correlation between the two methods is very strong (Pearson R = 0.93) and the mean relative difference is 14 %, with the trajectory-based ages being the older of the two. At the youngest ages (<60 minutes), we again see especially tight correlation between the two ages, with the trajectory-based age being systematically older because it accounts for aging during plume rise. The level of agreement between the two methods also reflects that the mean-wind method is not used for plumes with variable winds or beyond about 200 km, when age errors would likely be larger in this method.

3.3 Plume rise

The trajectory-based smoke ages here account for time elapsed during buoyant plume rise, as smoke ascends from the surface fire to its level of neutral buoyancy, after which plume transport becomes nearly horizontal. Figure 7 shows the distribution of plume rise heights for smoke sampled during FIREX-AQ, which are determined from the upwind trajectory altitudes where they pass over the fire (Sect. 2.4). For DC-8 observations, the mean smoke rise is 2700 m, with 95% of the values in the range 700-5300 m. The Twin Otter generally sampled smoke at lower altitudes than the DC-8 so the mean smoke rise is lower at 1700 m, with 95% of the values being in the range 600-2700 m. The mean plume rise time is 6.4 min (95% range: 1.8-12.2 min) for the DC-8 and 4.2 min (95% range: 1.4-6.3 min) for the Twin Otter. Both the DC-8 and Twin

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Otter sampled smoke with less than 20 minutes of aging, so these observations, plume rise time is 30-50% of the total age. Most smoke sampling was done farther downwind, however, so plume rise is less than 14% of the smoke age for 95% of the smoke measurements by the two aircraft. The mean fraction of smoke age coming from plume rise is 5%. Thus, plume rise is small fraction of the age for most smoke samples collected during FIREX-AQ, but significant for accurate ages of the young smoke samples.

The plume rise contribution to smoke age is sensitive to the plume vertical speed, which is assumed to be 7 ± 4 m s^{-1} in most plumes and 12 ± 6 m s^{-1} in pyrocumulonimbus (Sect. 2.4). The limited literature on pyroconvective vertical velocities suggests that there is considerable variability in these speeds (Lareau and Clements, 2017; Rodriguez et al., 2020), which is the basis for the assumed 50% relative uncertainty in vertical speed. The ensemble of meteorological models also provides a range of plume rise altitudes for each smoke observation, which is a second source of plume rise age uncertainty. However, mean uncertainty in plume rise height is 20% of the height, so this has less impact on the results than uncertainty in rise speed. Figure 7b shows the distribution of plume rise age uncertainty. Values are slightly greater than 50% of the rise time, due to the rise speed being the dominant contributor to rise time uncertainty.

For 11 smoke plume transects (n =1443 s) collected by the DC-8 in pyrocumulonimbus outflow (Peterson et al., 2022), the plume rise is about 3 times greater than the campaign average. For these samples, the mean plume rise is 7900 m (95% range: 5800-9100 m) and these form a small, separate population in Figure 7a. Despite the greater plume rise height, the plume rise time is within the range of other samples (Fig. 7b), because the vertical speed in pyrocumulonimbus convection is greater than the vertical speed in other pyroconvection (Sect 2.4). The mean rise time for the pyrocumulonimbus is 11 min (95% range: 8.1-12.6 min). Since the DC-8 measured pyrocumulonibus outflow 19-170 min after it detrained at the cloud top, the plume rise comprises 13 % of the smoke age on average and up to 40% of the smoke age for some samples.

3.4 Smoke age uncertainty

The dataset presented here provides two ways of assessing the uncertainty in smoke age, both of which are shown in Figure 8. The trajectory-based age method internally quantifies the uncertainty in each smoke age value. From this method, the median smoke age uncertainty was 24% of the smoke age for DC-8 observations and 16% for Twin Otter observations. The leading factor contributing to this uncertainty is the spread in upwind advection ages in the ensemble of meteorological datasets (term 1 in Sect. 2.4, Fig. 8). This age uncertainty from the advection ensemble alone is 13-15% of smoke age for both the DC-8 and Twin Otter observations. The second-largest factor contributing to age uncertainty is wind speed errors in the meteorological datasets (term 4), which contributes 11 % uncertainty for the DC-8 smoke ages and could not be assessed for the Twin Otter. Plume rise and other terms in the trajectory-based age analysis contribute much less to smoke age uncertainty for both aircraft (≤ 5%). Figure 8 thus shows that the component uncertainty terms are similar for the DC-8 and Twin Otter, with the exception of the wind speed term that could only be estimated for the DC-8. The lack of a wind speed

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uncertainty term for the Twin Otter therefore likely explains the apparently higher median total uncertainty for the DC-8 (24% vs. 16%). The larger mean and median uncertainty statistics for the DC-8, therefore, should be considered representative for both aircraft during FIREX-AQ.

Comparison between the mean-wind and trajectory-based ages provides a second way of assessing smoke age uncertainty. This comparison is only possible for the subset of DC-8 smoke observations in which the mean-wind method provides an age estimate. The median absolute difference between the two methods is 19% and the mean is slightly larger at 23%. As reported in Sect. 3.2, the mean-wind age is systematically 14% younger than the trajectory-based age on average. Thus, the absolute differences between the two age methods are mainly systematic, not random. The slightly lower median uncertainty suggested by the comparison between two age methods may be because the mean-wind method was not used in cases with long-range transport or shifting winds, where ages may be inherently more uncertain. Moreover, the trajectory-based method provides an uncertainty for each age estimate. These estimates can be used to identify periods where smoke age is known with particularly high or low confidence or used as weighting factors in statistical models of smoke aging.

4 Data availability

The data described and used in this paper are contained in the NASA-NOAA FIREX-AQ data archive, which is housed at the NASA Atmospheric Science Data Center (ASDC): http://doi.org/10.5067/SUBORBITAL/FIREXAQ2019/DATA001 (FIREX-AQ Science Team, 2019). The specific data products used in this work are:

- Smoke age (mean-wind and trajectory-based methods) and meteorological measurements for the NASA DC-8: https://doi.org/10.5067/ASDC/FIREXAQ_MetNav_AircraftInSitu_DC8_Data_1 (Chen, 2020a)
- Smoke age (trajectory-based method) for the NOAA Twin Otter: https://doi.org/10.5067/ASDC/SUBORBITAL/FIREXAQ_Analysis_N48_Data_1 (FIREX-AQ Science Team, 2021)
- GOES ABI true color imagery (png, mp4, and netCDF4 formats): https://doi.org/10.5067/ASDC/FIREXAQ_Satellite_Data_2 (Chen, 2020b)

Key smoke age variables from both the mean-wind and trajectory-based methods (age, plume rise, uncertainty) are also contained in aircraft "merge" files that combine measurements from multiple instruments into a single file for each flight (https://doi.org/10.5067/ASDC/FIREXAQ_Merge_Data_2).

The HYSPLIT model is available from https://www.ready.noaa.gov/HYSPLIT.php. Meteorology data for HYSPLIT (GFS, NAM CONUS nest, HRRR) are available from https://www.ready.noaa.gov/data/archives/.

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5 Conclusions

Two methods for determining smoke age have been applied to aircraft observations from the NASA-NOAA FIREX-AQ field campaign. The mean-wind method infers the age from the mean vertical profile of measured winds near the fire and the downwind distance from the fire to the observation point. The trajectory-based method uses an ensemble of upwind trajectories from the observation location, accounts for plume rise time, and provides an internal uncertainty estimate. Both methods are used to estimate the age of smoke observed by the NASA DC-8. The trajectory-based method is used to estimate age of smoke observed by the NOAA Chemistry Twin Otter.

This work also describes true color imagery and movies created from the ABI instrument on GOES-East and GOES-West satellites. The satellite imagery includes a terrain parallax correction, so that surface features appear at the correct latitude and longitude. For fires in mountainous western US, the parallax correction shifts the apparent locations by 2-8 km. As a result, smoke plumes in the terrain-corrected images appear over the true fire locations, rather than appearing displaced from the fires by many kilometers. 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. The age estimate is then based on the remaining trajectories that are consistent with the actual plume transport.

The main strength of the mean-wind method is that it does not depend on the availability or accuracy of meteorological analysis datasets. Therefore, the mean-wind method is best suited for short-range transport under steady wind conditions with minimal terrain effects on the wind. Indeed, the mean-wind method was not used during FIREX-AQ for cases of long-range plume transport or days with especially variable winds. The strengths of the trajectory-based method are that it includes plume rise, accounts for spatial and temporal wind variation, works when wind measurements are not available (e.g. Twin Otter), and provides an uncertainty estimate. The trajectory-based age method is sensitive to errors in meteorological datasets. While the three meteorological datasets used (HRRR, NAM CONUS nest, GFS) here have small mean biases in wind speed (<0.25 m s^{-1}) and wind direction (<5 °) during FIREX-AQ smoke sampling, errors are intermittently larger. In the trajectory-based method, the difference between measured and modeled wind speed informs the age uncertainty estimate, so the user can identify intermittent periods of greater age uncertainty.

Age estimates from the two methods can be compared for 262 smoke plume transects collected by the DC-8 during FIREX-AQ. While the two ages are strongly correlated ($R = 0.93$), the mean-wind age is 14% younger than the trajectory-based age on average. This systematic difference is most noticeable for young smoke observations (< 60 min) due to the buoyant plume rise time being included in the trajectory-based age but not in the mean-wind age. In future applications, the mean-wind method could be adapted to include plume rise time. Some of the older smoke observations (>100 min) were collected in the evening as wind speeds in the boundary layer decayed. By assuming constant wind speeds, the mean-wind method

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underestimates the age of these evening smoke samples, while the meteorological datasets and trajectory-based age have the capability to resolve these wind changes.

The uncertainty in smoke age can be obtained from the trajectory-based method, which provides the uncertainty for each age value. The uncertainty can be used identify periods with high and low confidence in the age or as weighting factors in statistical models of smoke aging. The median age uncertainty for FIREX-AQ smoke observations is 24% of the smoke age. The distribution of uncertainty values has a long tail, however, so the mean age uncertainty is larger 37%. The main source of uncertainty is ensemble spread between the three meteorological models used to compute trajectories (13-15%) and the second-largest source of uncertainty is due to disagreement between measured and modeled wind speed (~11%). Other factors, like plume rise and ambiguity in the source fire contribute much less to age uncertainty during FIREX-AQ (< 5%).

The smoke age products described here provide a basis of interpreting measurements of chemical and physical aging in the smoke observations during FIREX-AQ. These analyses have been applied to composition and optical properties of aerosols (Adachi et al., 2024; Azzarello et al., 2023; Pagonis et al., 2023; Saide et al., 2022; Washenfelder et al., 2022) and trace gases (Decker et al., 2021a, b, 2024; Robinson et al., 2021; Xu et al., 2021). The techniques for assessing uncertainty in the trajectory-based ages may be useful for other applications where age estimates are needed, including other studies of smoke and long-range plume transport more generally.

Author contributions

CDH and JPS conceived the research goals, performed data analysis, and curated data. CDH, JPS, and RY formulated the smoke age methods with input from DAP. CDH, CHF, HKN, and AA developed software. RAW, MAR, ZCJD, KB, EMG, AJS, TPB, JD, SK, CX, JPD, JBN, HH and GSD provided data used in the analysis. CDH prepared the manuscript with contributions from all co-authors.

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Table 1. Statistical comparison of meteorological models to in situ measurements during smoke sampling in the Western US by the NASA DC-8. [a]

	NAM CONUS nest			HRRR			GFS (0.25°)			MetNav[b]		
Variable	Bias	MAD	*R*	Bias	MAD	*R*	Bias	MAD	*R*	Bias	MAD	*R*
Wind speed, m/s	–0.02	1.28	0.89	0.25	1.40	0.87	0.02	1.23	0.90	0.04	0.35	0.99
Wind direction, °	4.46	12.26	0.65	–0.35	12.67	0.75	3.43	13.33	0.71	–0.30	2.55	0.96
Temperature, °C	0.09	0.41	0.997	–0.10	0.41	0.997	–1.74	1.84	0.997	–0.01	0.08	0.9998

[a] All comparisons are against MMS measurements (10 second averages, n = 7749). Bias is the mean difference from MMS measurements. MAD is median absolute difference. R is the Pearson correlation coefficient.

[b] The Navigational Management System (MetNav) contains a second, independent meteorological measurement suite on board the aircraft.

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Table 2. Smoke age variables contained in ICARTT files for FIREX-AQ

Name	Description, units
Mean-wind age method	
transect_smoke_age	Age of smoke at center of transect, s
fire_distance_estimate	Distance from fire to center of transect, m
Trajectory-based age method[a]	
smoke_age (τ)	Age of smoke, s
smoke_age_unc ($\delta\tau$)	Uncertainty in age of smoke, s
smoke_age_corr (τ')	Age of smoke after scaling trajectory to match observed wind speed, s
smoke_age_rise (τ_{rise})	Age of smoke due to plume rise to trajectory altitude, s
smoke_rise (z_{rise})	Plume rise height from surface to trajectory altitude, m
fire_distance	Distance from fire to aircraft, m
smoke_age_method	Indicator for which meteorological datasets are used in the best age estimate; all datasets are used for uncertainties; 1=HRRR,NAM,GFS (default); 2=HRRR,NAM; 3=HRRR,GFS; 4=NAM,GFS; 5=HRRR; 6=NAM; 7=GFS

[a] Symbols in parentheses are used in Sect. 2.4.

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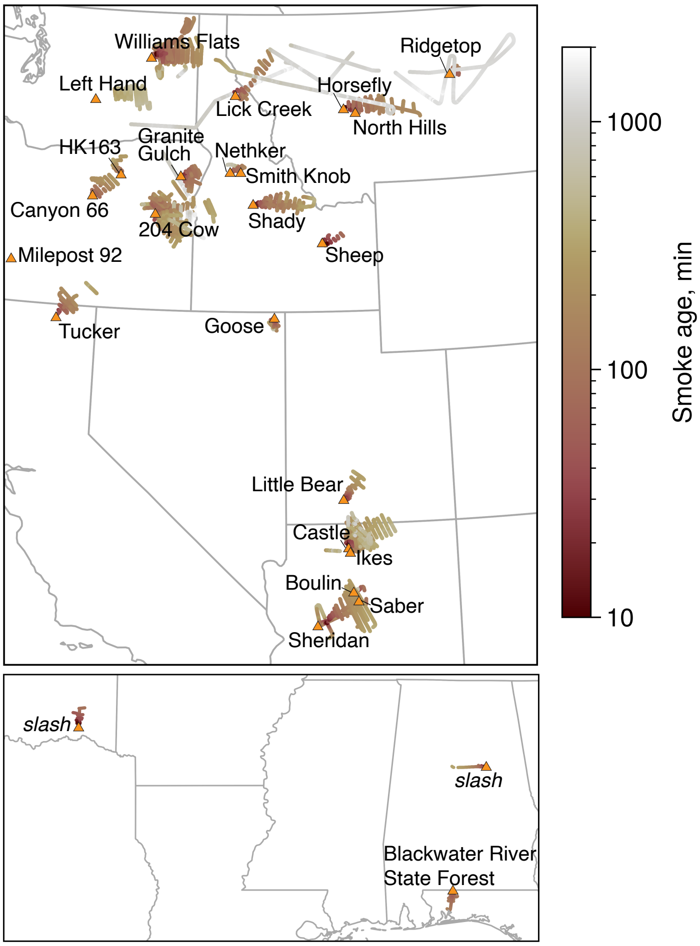

495 **Figure 1: Map of fires (triangles) and smoke age (colored shading) sampled by the NASA DC-8 and NOAA Twin Otter during FIREX-AQ. Smoke samples without ages are not shown; these occurred in the eastern US, where measurements occurred almost directly over the source fire, at low altitude, with little or no downwind plume sampling.**

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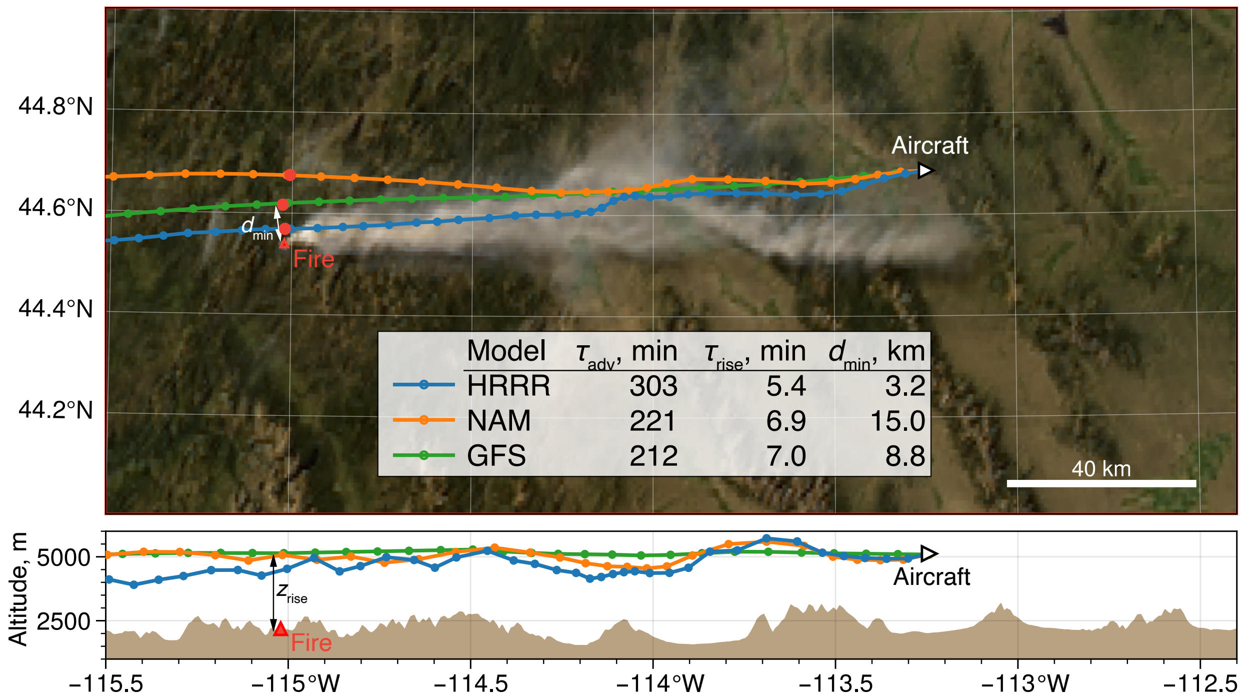

500 **Figure 2: Example trajectories used for smoke age calculation, based on the Shady Fire, Idaho. Lines show upwind trajectories in three meteorological datasets, with dots marking 10-minute intervals and a red dot marking the closest trajectory approach to the fire where the advection age is determined. The inset table gives the age contributions from advection (τ_{adv}) and plume rise (τ_{rise}), as well as the minimum separation between the trajectory and fire (d_{min}) for this example. The background image is a true color image from GOES-West (26 July 2019 00:21UTC), including terrain parallax correction (Sect. 2.6). For the example shown,**
505 **$\langle\tau_{adv,m}\rangle$ = 245 min and $\langle\tau_{rise,m}\rangle$ = 6.4 min, so the trajectory-based age estimate is τ = 251.4 min.**

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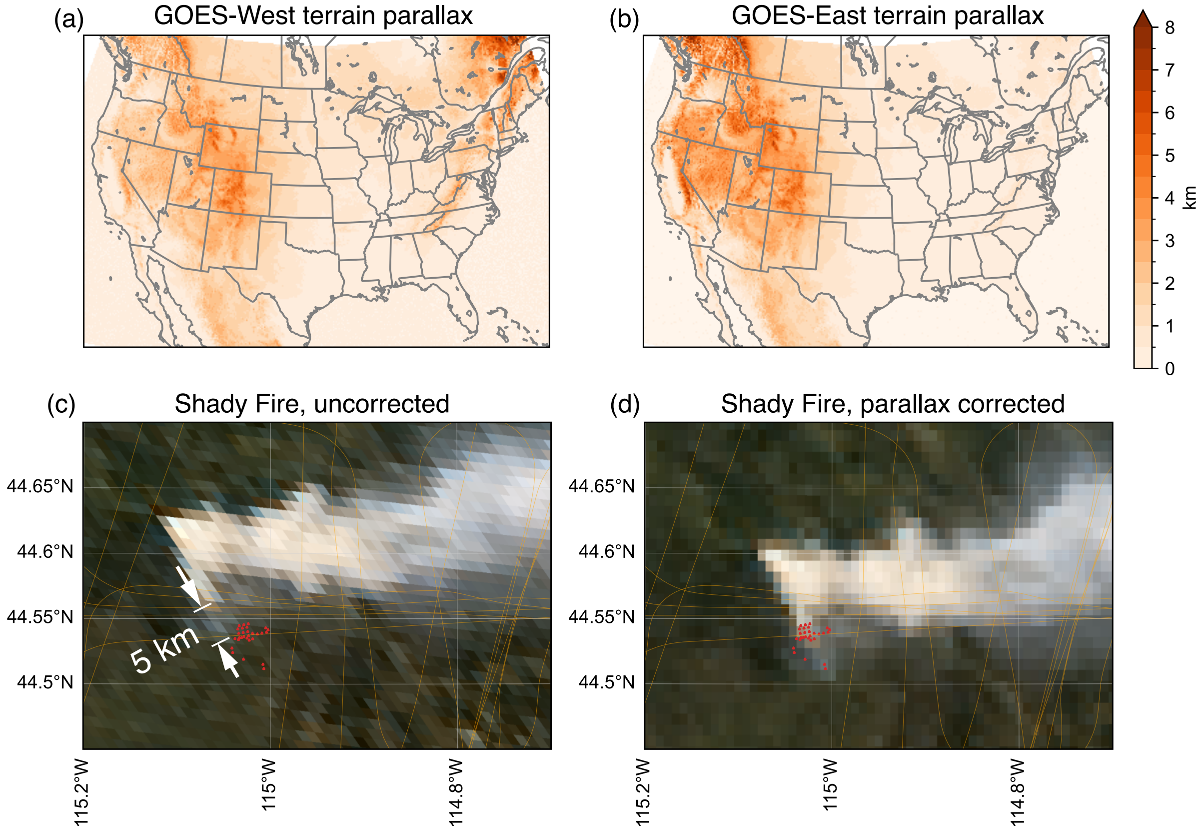

510 **Figure 3: Terrain parallax effect for GOES-West (a) and GOES-East (b) over the contiguous United States with comparison of uncorrected (c) and corrected (d) images of the Shady Fire from GOES-East. The parallax effect in panels a and b is the offset distance between actual and apparent locations of surface features. The apparent smoke plume source in panel (c) is displaced (white arrow) by nearly 5 km from the active fires (red dots, VIIRS active fires), while the two coincide in the corrected image in panel d. The GOES-East image was collected at 22:11 UTC on 25 July 2019.**

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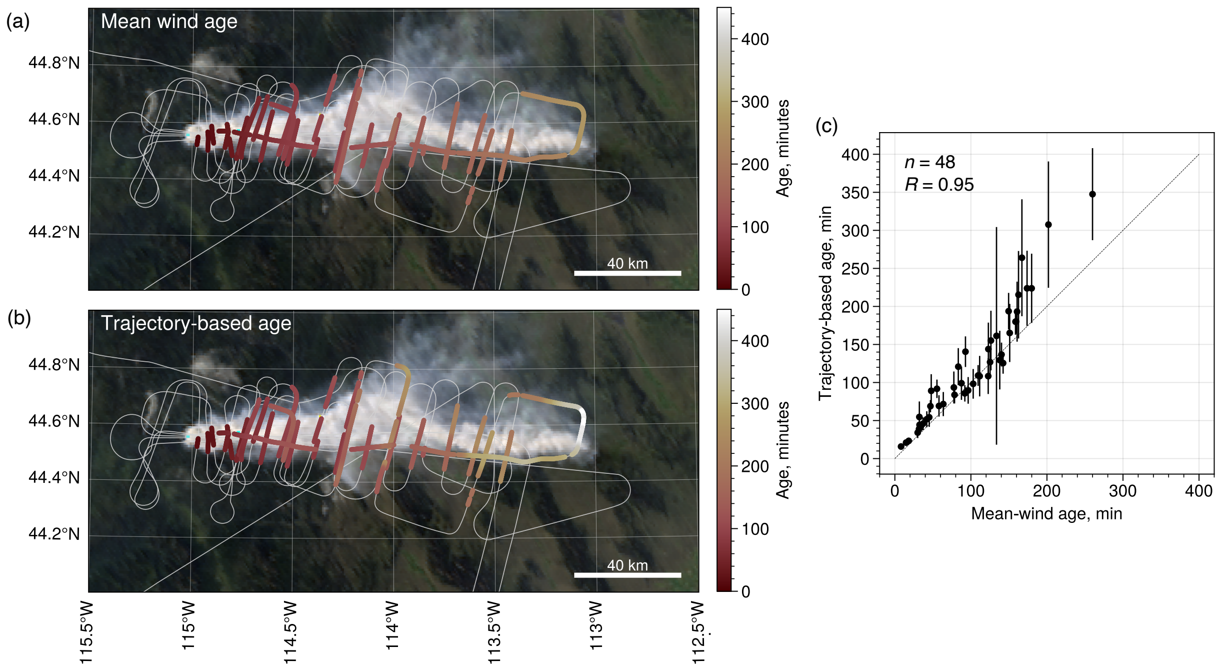

515 **Figure 4: Smoke age for the Shady Fire, Idaho sampled by the NASA DC-8 on 25 July 2019, as determined by the mean-wind method (a), trajectory-based method (b), and comparison of the two methods (c). Data in panels a and b are overlaid on true color imagery from GOES-East (26 July 2019 00:36 UTC). Each dot in panel c represents one transect. For the trajectory-based age, the mean age of the transect is shown, with a vertical line for the age uncertainty, while a single age is given for the entire transect in the mean-wind age.**

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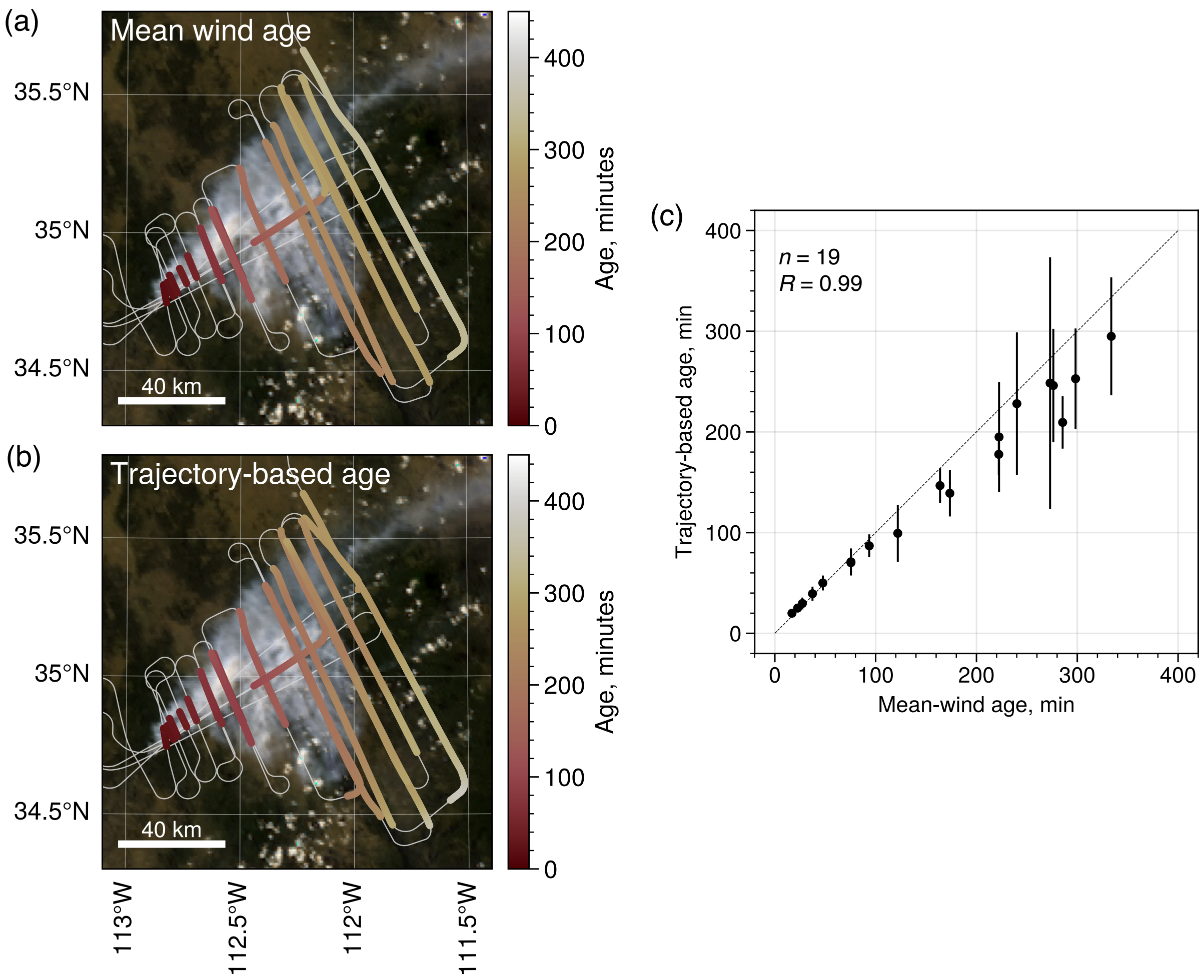

525 **Figure 5: Smoke age for the Sheridan Fire, Arizona sampled by the NASA DC-8 on 16 August 2019, as determined by the mean-wind method (a), trajectory-based method (b), and comparison of the two methods (c). Data in panels a and b are overlaid on true color imagery from GOES-East (17 August 2019 00:21 UTC). Each dot in panel c represents one transect. For the trajectory-based age, the mean age of the transect is shown, with a vertical line for the age uncertainty, while a single age is given for the entire transect in the mean-wind age.**

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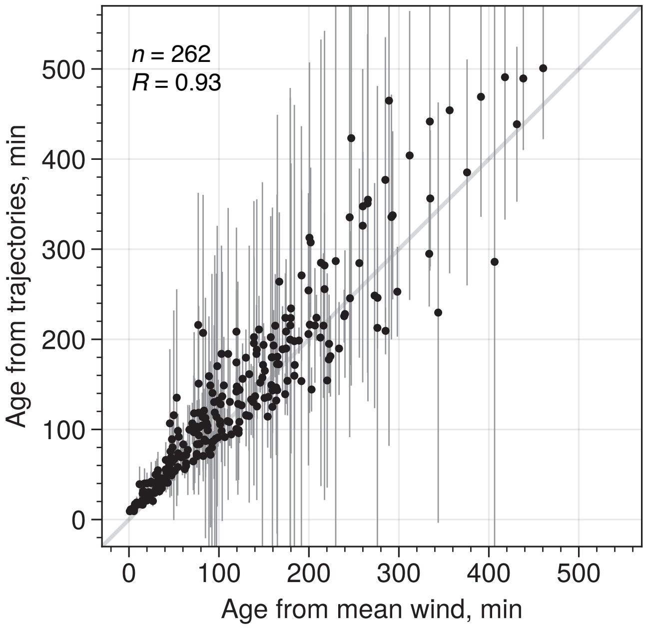

Figure 6: Comparison of smoke ages from the mean-wind and trajectory-based methods for all NASA DC-8 smoke transects during FIREX-AQ. Each dot represents one transect. For the trajectory-based age, the mean age of the transect is shown, with a vertical line for the age uncertainty, while a single age is given for the entire transect in the mean-wind age.

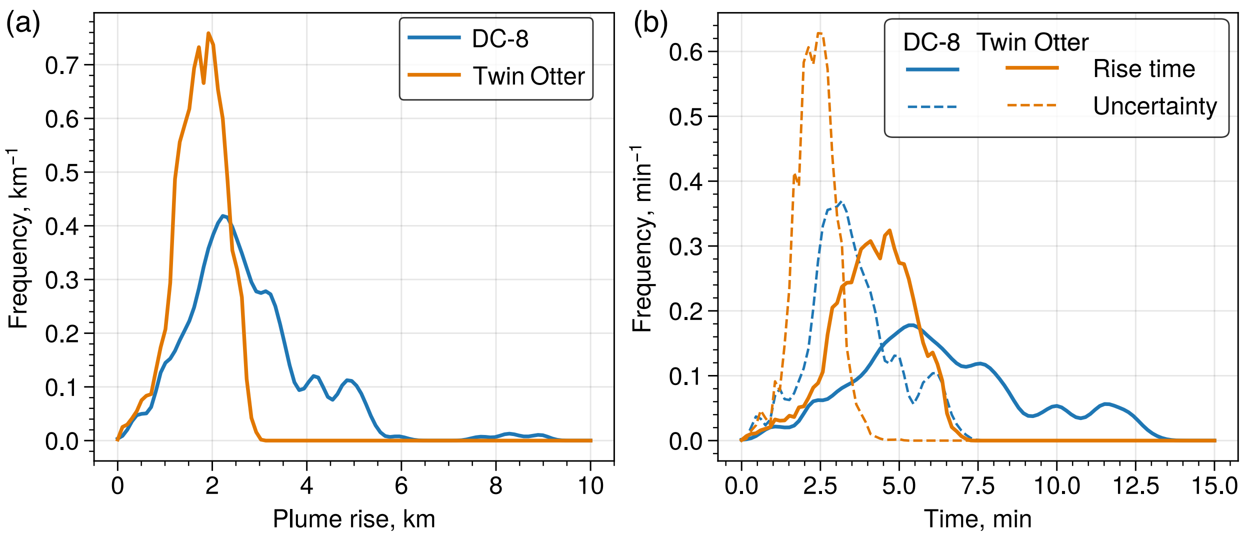

Figure 7: Distribution of plume rise heights (a) and plume rise times (b) for smoke measured during FIREX-AQ (n = 76,000 s for the DC-8 and n = 68,000 s for the Twin Otter). Plume rise heights are determined from the trajectories (Fig. 2, Sect. 2.4). The rise time uncertainty (panel b) accounts for uncertainty in the plume rise height and plume rise speed (Sect. 2.4). All probability density functions are normalized to a unit integral.

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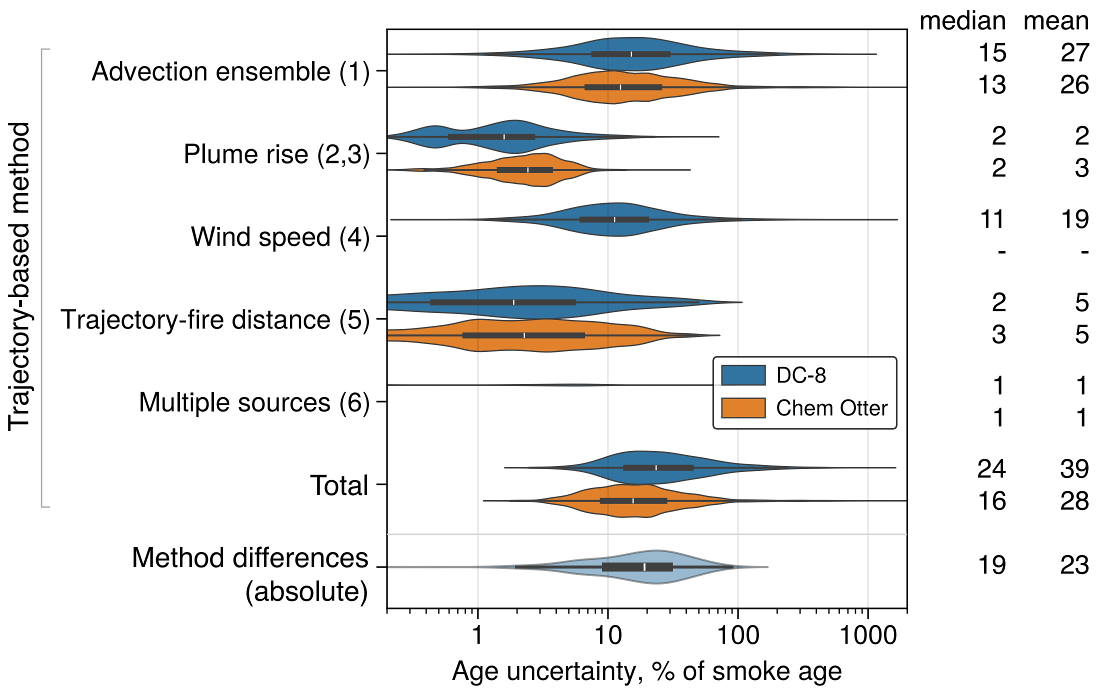

Figure 8: Distribution of smoke age uncertainty and factors contributing to the uncertainty during FIREX-AQ. The width of each violin shape represents the relative frequency of data values (n = 76,000 s for DC-8 and n = 68,000 s for Twin Otter); black bars and white dots within each violin show the interquartile range and median, respectively. Parenthetical numbers in the left axis group labels specify the uncertainty components listed in Sect. 2.4. The median and mean of each distribution are provided by the right axis.

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