Satellite Multi-angle Observations of Wildfire Smoke Plumes During the CalFiDE Field Campaign: Aerosol Plume Heights, Particle Property Evolution, and Aging Timescales

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Key Points:

• NASA's MISR multi-angle imagery allows aerosol plume-height, associated motion vector, and particle property retrievals from space

• Typically, field data are acquired to validate satellite data, but MISR data is mature enough to contribute directly to the CalFiDE campaign

• Aircraft and MISR overflights were coordinated twice, so MISR aerosol context and detail for joint smoke-plume dynamics and chemistry study

Abstract

Wildfire-related aircraft field campaigns frequently offer opportunities to validate remote-sensing retrievals of aerosol properties and other quantities derived from satellite-borne-instrument observations. Satellite instruments often provide regional context-imagery for more sparsely sampled aircraft and surface-based measurements. However, aerosol amount, particle type, aerosol plume height and the associated wind vector products retrieved from the NASA Earth Observing System's Multi-angle Imaging SpectroRadiometer (MISR) instrument have matured sufficiently that these quantities can also contribute substantially to a campaign dataset, in regional context. This is especially useful when such measurements are not acquired at all from the suborbital platforms. During NOAA's California Fire Dynamics Experiment (CalFiDE), aircraft operations were coordinated with MISR overpasses on two occasions, for the Rum Creek fire on 30 August 2022, and for the Mosquito fire on 08 September. MISR-retrieved aerosol properties show distinctly different patterns of black and brown smoke particle distributions and inferred plume evolution in the two cases. This paper describes the satellite data analysis techniques and presents the satellite-retrieved results, demonstrating what such measurements can offer, and contributing material for detailed fire dynamics and chemistry studies when combined with the CalFiDE suborbital observations and models.

Plain Language Summary

A common use of aircraft field campaigns is to validate the radiances measured by space-based instruments and the geophysical quantities derived from the satellite observations. However, satellite aerosol amount and properties derived from the NASA Earth Observing System's Multi-angle Imaging SpectroRadiometer (MISR) instrument are sufficiently mature that they can also contribute directly to field-campaign datasets. During NOAA's CalFiDE campaign is summer 2022, on two occasions the aircraft observed wildfire smoke plumes coordinated with MISR overpasses: for the Rum Creek fire on 30 August 2022, and for the Mosquito fire on 08 September. In addition to providing broad spatial context to the much more spatially limited aircraft measurements, the MISR results offer geometrically-derived smoke-plume height, plume-level motion vectors from which smoke age can be estimated downwind along the plume. From MISR-retrieved constraints on particle size, shape, and light-absorption properties, the distribution of black and brown smoke can be inferred, along with the underlying processes responsible for plume-particle evolution. This paper describes the MISR data analysis techniques and presents the satellite-retrieved results for the CalFiDE campaign observations.

1 Introduction

The California Fire Dynamics Experiment (CalFiDE) featured the NOAA Chemistry Twin Otter Aircraft, along with NOAA ground-based mobile assets, sampling wildfires in northern California and southern Oregon from late August to late September 2022 (Carroll et al., 2023). The campaign aimed at investigating key science questions related to fire-plume dynamics and the impact wildfire plumes have on air quality. To this end, the aircraft carried a Micro-pulse Doppler lidar retrieving wind field and aerosol backscatter profiles, along with a robust payload of meteorological and atmospheric gas chemistry instruments. The aircraft obtained high-resolution infrared imaging measurements of fire radiative power (FRP, an indication of fire intensity), along with NO, NO_2, NO_y, O_3, CO, CO_2, CH_4, and H_20 trace gas concentrations, context cameras, downward-looking radiation-field instruments, and *in situ* temperature, pressure, and wind from the Aircraft-Integrated Meteorological Measurement System (AIMMS-20). A second wind and aerosol-backscatter Doppler lidar as well as local temperature and wind sensors were deployed on their Pick-Up based Mobile Atmospheric Sounder (PUMAS) truck.

Although the CalFiDE suborbital platforms did not include instruments to measure aerosol properties in the smoke plumes, field operations were coordinated with overpasses of the NASA Earth Observing System's Terra satellite on two occasions, 30 August and 08 September. On these dates, the space-based Multi-angle Imaging SpectroRadiometer (MISR) instrument obtained regional-scale snapshots of the Rum Creek and Mosquito fire plumes, respectively.

From the multi-angle, multi-spectral MISR imagery acquired on these days, we retrieved aerosol plume heights, plume horizontal motion vectors at plume elevation, and aerosol optical depth (AOD), as well as constraints on particle size, shape, and light-absorption properties, complementing the aircraft gas chemistry, meteorology, and wind-profile payload. Also on the Terra satellite, the MODerate resolution Imaging Spectroradiometer (MODIS) acquired broad-scale context imagery and FRP measurements at 1 km horizontal resolution. This paper reports the key MISR results along with the associated MODIS observations, and demonstrates the contribution satellite observations from such instruments can make during field campaigns, by providing aerosol amount and property mapping as well as context for the individual transects and point measurements acquired by the suborbital instruments.

2 Satellite Data and Methods

The MISR instrument aboard the NASA Earth Observing System's polar-orbiting Terra satellite acquires imagery in each of four wavelengths (centered at 446, 558, 672, and 866 nm), at nine angles ranging from 70˚ in the forward direction, through nadir, to 70˚ in the aft direction, capturing air mass factors ranging from 1 to 3, and scattering angles in mid-latitudes from about 60˚ to 160˚ (Diner et al., 1998). The MISR swath width is about 380 km, offering global coverage about once per week. The pixel size is 1.1 km in all channels except for those of the nadir camera and the eight red-band off-nadir views, where the pixel resolution is about 275 m. Terra satellite equator crossing on the day side is in the mid-late morning at about 10:30 AM local time, so the typical diurnal peak of fire activity is missed. However, major fire activity is often observed for fires at high latitudes and everywhere for major fires that remain active through the night, making comprehensive, statistically based regional studies of wildfire plume properties and evolution possible (e.g., Zhu et al., 2018; Val Martin et al., 2018; Gonzalez-Alonso et al., 2019; Junghenn Noyes et al., 2020).

From the MISR data, aerosol plume height can be derived geometrically using the parallax in the multi-angle views; this is accomplished at vertical precision of between 250 and 500 m with the MISR Interactive Explorer (MINX) software (Nelson et al., 2013). A user must outline the plume boundary to capture a region where the aerosol is sufficiently optically thick, so plume contrast features can be matched in the multi-angle views, and must specify the plume source location and apparent wind direction interactively, on a case-by-case basis. As it takes about seven minutes for all nine MISR cameras to view a given location on Earth, the proper motion of plume contrast elements over this period is used to derive the wind speed at plume elevation, allowing wind-corrected plume height to be derived, and the age of aerosol progressively downwind from the source to be estimated (e.g., Junghenn Noyes et al., 2020a, 2020b).

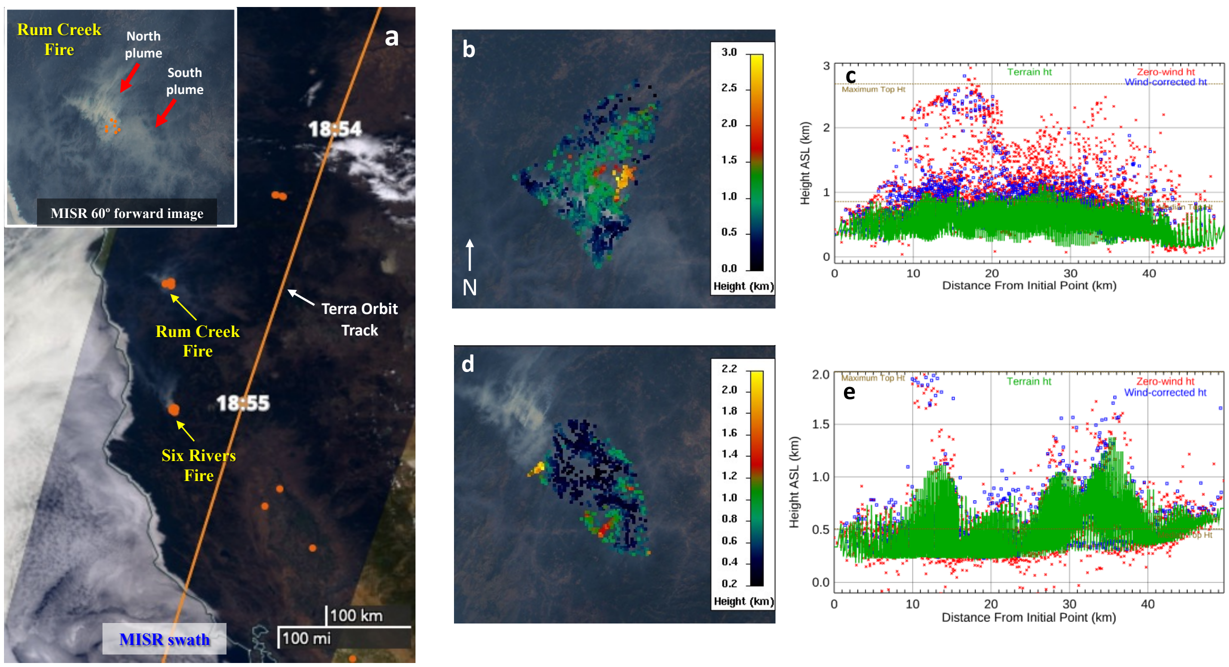

Figure 1. (a) MODIS/Terra context image of the Rum Creek fire on 30 August 2022, with the MISR nadir RGB image superposed, as well as the MODIS 4-micron thermal anomalies (red dots) and the Terra Orbit 120744 track with UTC time stamps. The Six Rivers fire also appears to the south in this image, though it was not sampled by the CalFiDE aircraft or ground platforms. (NASA WorldView, http://worldview.earthdata.nasa.gov; last accessed January 2023). The inset provides a detail of the Rum Creek plume geometry with the MISR 60˚ forward view, Block 57, highlighting the north and south components. MISR-MINX plume-height maps and profiles for the Rum Creek north (b,c), and south (d,e) plumes, respectively. In the profile views, the zero-wind heights are shown in red, the wind-corrected heights in blue, and the surface elevation in green. (Tables S6 and S7 in Supplemental Material provide the numerical plume-height values for the North and South Plumes, respectively.)

Given the range of scattering angles sampled by MISR, aerosol column optical depth (AOD) and qualitative constraints on particle size, shape, and single-scattering albedo (SSA) can be derived, provided the AOD and the range of observed scattering angles are sufficiently high (Kahn & Gaitley, 2015). This usually favors particle property retrieval for wildfire smoke, desert dust, and volcanic plumes. Based on cluster analysis, about three-to-five bins in particle size over the range of about 0.1 to 2 microns effective radius, two-to-four bins in mid-visible SSA between about 0.7 and 1.0, and spherical vs. randomly oriented non-spherical particles can be distinguished under good but not necessarily ideal retrieval conditions (Kahn et al., 2001).

However, we can usually observe more subtle differences in retrieved effective particle size (REPS), retrieved effective light absorption (REPA), and flat or steep light absorption spectral slope along aerosol plumes. For the current study, the MISR Research Aerosol retrieval algorithm (RA) was used (Limbacher et al., 2022), which systematically compares the observed top-of-atmosphere (TOA) radiances to a look-up table and selects the best-fitting mixture of candidate aerosol optical models for each MISR pixel. For wildfires, a key strength of the algorithm is its ability to separate black smoke (BlS) and brown smoke (BrS) aerosol types, where BlS displays little to no variation in SSA across the MISR wavelengths (spectrally flat), whereas SSA increases with wavelength for BrS. We use the terms BlS and BrS to distinguish our remote-sensing aerosol type retrieval results from “black carbon” and “brown carbon,” which in the atmospheric chemistry community refer to specific particle constituents rather than observed whole-particle radiative properties observed from space. Compared to the MISR operational aerosol retrieval algorithm (e.g., Garay et al., 2020), the RA code includes a range of adaptations that optimize particle property retrievals over land as well as water, at the cost of running each case individually (Limbacher & Kahn, 2014; Limbacher et al., 2022). Surface properties are retrieved self-consistently for low AOD cases, whereas they are prescribed from MODIS at high AOD, and a range of radiometric calibration, radiance filtering, algorithm particle property climatology options, and other refinements are included in the RA. For further details on the specific aerosol components included in the RA climatology for this and other wildfire studies, see Junghenn Noyes et al. (2020a).

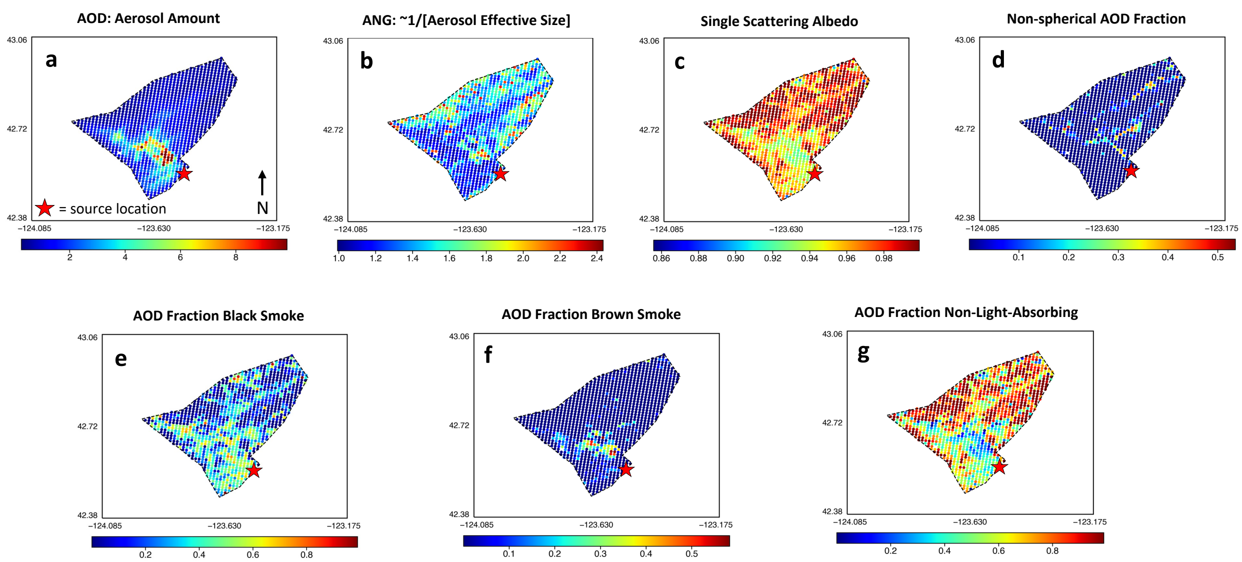

Figure 2. MISR Research Aerosol retrieval algorithm results for the North Plume of the Rum Creek Fire, 30 August 2022, ~18:54 UTC. (a) Aerosol mid-visible optical depth (AOD_{558}). (b) Ångström Exponent (i.e., the negative logarithm of the spectral AOD_{558} divided by logarithm of the wavelength range, assessed in a least-squares fit over the four MISR spectral bands). (c) Mid-visible single-scattering albedo. (d) Fraction AOD_{558} non-spherical. (e) Fraction AOD_{558} interpreted as black smoke (spectrally flat SSA, generally < 0.95). (f) Fraction AOD_{558} interpreted as brown smoke (spectrally steep SSA, more absorbing at shorter wavelengths). (g) Fraction AOD_{558} non-light-absorbing. (Table S3 in Supplemental Material provides numerical summaries of the particle properties plotted in this figure.)

We identified the active fire hotspot locations and assessed fire intensity from the MODIS 4-micron brightness temperature anomalies, which are reported quantitatively as the FRP in the MOD14 product (Giglio et al., 2003; Giglio & Justice, 2015). (FRP is often reported in MW/pixel; in the region close to the sub-spacecraft point where MISR and MODIS have coincident data, the MODIS pixel area is about 1 km^2, so the physical units of FRP are W/m^2). Note that FRP is often a severe underestimate of the sensible heat flux generated by a fire, due to overlying smoke, active fire only partly filling the MODIS pixel, and/or emissivity at 4 microns that is less than unity, e.g., for smoldering fire (Kahn et al., 2008).

3 Results of the MISR CalFIDE Observations

In this section, we summarize the key features of the Rum Creek and Mosquito fire smoke plumes as retrieved from the MISR multi-angle, multi-spectral imagery. The Supplementary Material elaborates on these observations quantitatively: Tables S1 and S2 contain the MODIS Terra fire pixel information for the Rum Creek and Mosquito fires, respectively, Tables S3-S5 contain statistical summaries of key RA-retrieved particle properties for each plume, and Tables S6-S8 display MINX plume height data.

3.1 **The Rum Creek Fire, 30 August 2022**

MISR imaged the Rum Creek fire plume in southwest Oregon over seven minutes beginning at about 18:53 UTC (near local noon) on 30 August 2022. Figure 1a is a MODIS/Terra context image showing the location of the fire plume, with the MISR nadir image and the MODIS 4-micron thermal anomalies superposed. At overpass time, the fire had generated a north plume that extended roughly to the west and northeast from the source region, and a south plume that advected toward the southeast. Peak plume elevation of about 2.7 km ASL (roughly 2 km above the terrain) was reached over the north plume hotspots (Fig. 1b and 1c). The mean, median, and maximum derived wind speeds for this plume are 1.25, 0.9, and 11.0 m/s, respectively, yielding a maximum estimated smoke age of between 8 and 12 hours for the observed smoke. Contrast features in the much thinner south plume remained within a few hundred meters of the surface (Fig. 1d and 1e), and the mean and median wind speeds derived for this plume were 0.9 and 0.5 m/s, respectively.

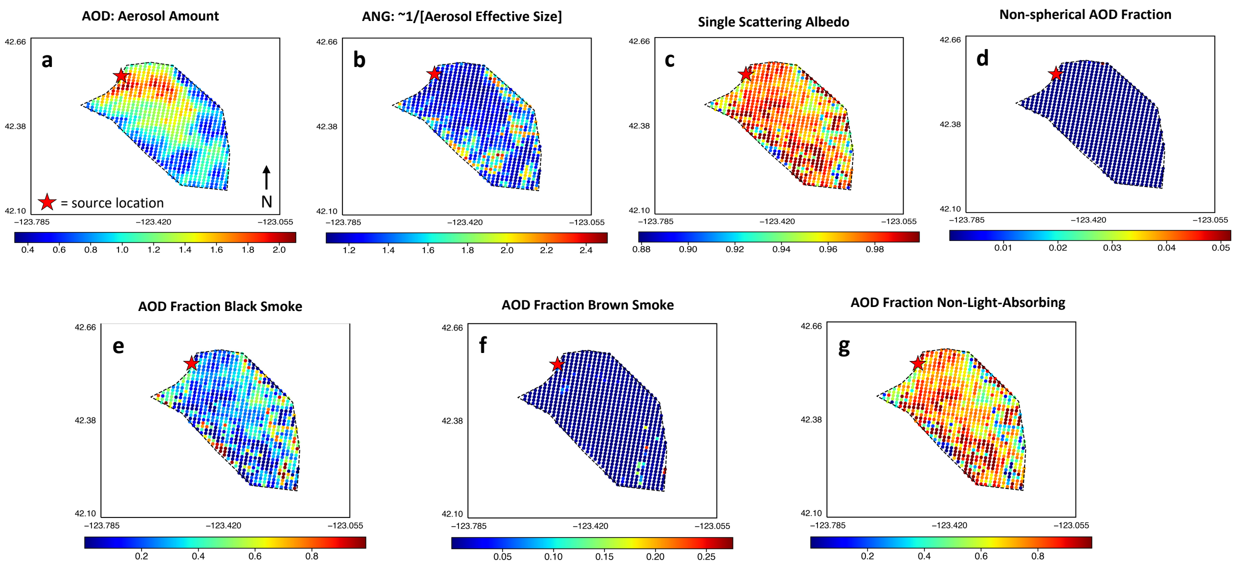

Figure 3. Same as Figure 2, but for the South Plume of the Rum Creek Fire on 30 August 2022. (Table S4 in Supplemental Material provides numerical summaries of the particle properties plotted in this figure.)

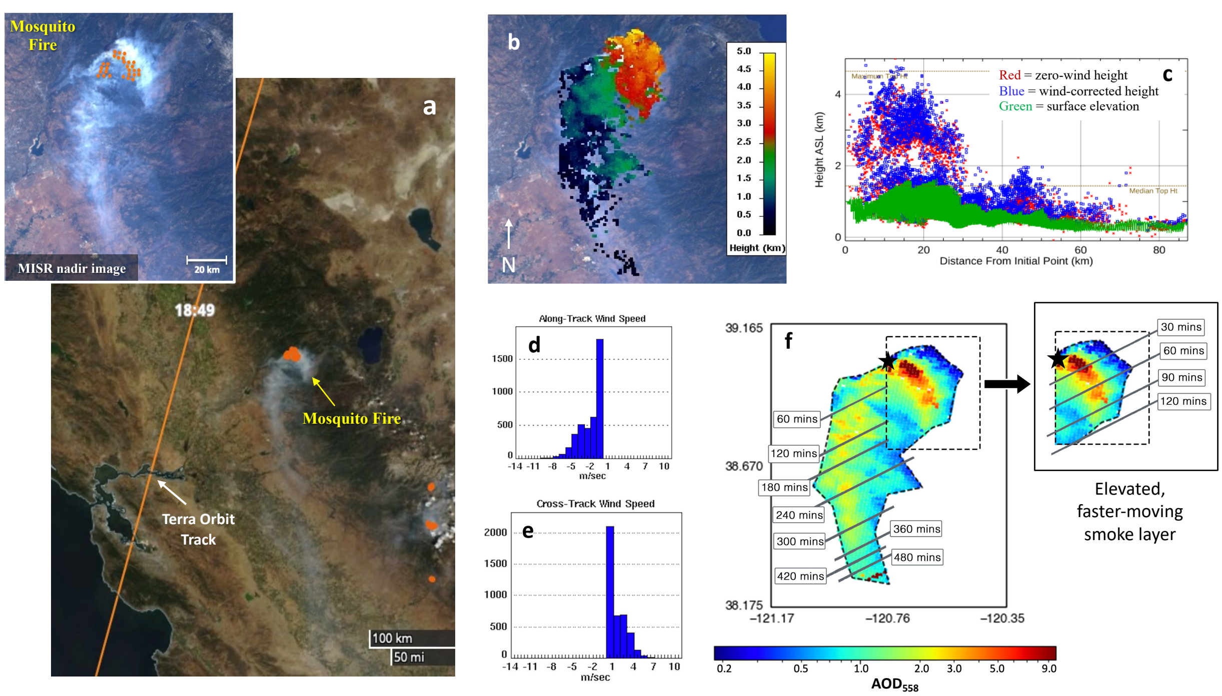

Figure 4. (a) MODIS/Terra context image of the Mosquito fire on 08 September 2022, with the MODIS 4-micron thermal anomalies (red dots) and the Terra Orbit 120875 track with UTC time

stamp superposed. (NASA WorldView, http://worldview.earthdata.nasa.gov; last accessed January 2023). The inset provides a detail of the Mosquito fire plume geometry from the MISR nadir view, Blocks 59-60, highlighting about 80 km of downwind extent. The MISR-MINX plume-height map and profile for the Mosquito plume are given in (b) and (c), respectively. In the profile view, the zero-wind heights are shown in red, the wind-corrected heights in blue, and the surface elevation in green. (d, e) Histograms of MISR-MINX along- and across-track wind speeds, respectively, derived at plume elevation. (f) Map of MISR-retrieved AOD_{558}, with inferred plume age markers superposed. The inset shows estimated smoke age over the elevated, faster-moving smoke layer from this fire. Black asterisks indicate the location of the presumed source. (Table S8 in Supplemental Material provides the numerical plume-height values for the Mosquito Fire.)

MISR-retrieved aerosol amount and particle properties for the north plume are shown in Figure 2. The retrieved mid-visible AOD (AOD_{558}) reaches a maximum exceeding 8 near the southeast corner of the plume. These values are about the highest that can be derived with this remote-sensing technique, as the method saturates when the top-of-atmosphere radiances no longer contain sufficient signal from the surface. High smoke opacity in the vicinity of the fire blocking much of the upward-emanating radiance could account for the low FRP values reported by MODIS, which do not exceed 26 W/m^2 (Table S1 in Supplemental material). There is a concentration of brown smoke in the immediate vicinity of the source (Fig. 2f), and black smoke extending over the southeast and south parts of the plume (Fig. 2e). AOD falls off rapidly within a few tens of kilometers from the active fire. The particles are small-medium (Ångström Exponent or ANG > ~1.2) and ranged from moderately dark (SSA ~0.94) to quite bright (SSA ~0.99). Essentially only spherical particles were detected (Fig. 2d). A more detailed interpretation of REPS is given in Figure S1 in Supplemental Material. The qualitative size categories shown here indicate that there are essentially no “very small” or “large” particles within the range of sizes to which MISR is sensitive; medium particles tend to dominate, with substantial small particle concentrations on the northwest and southeast flanks of the plume.

MISR-retrieved particle properties for the south plume are given in Figure 3. This plume was optically thinner, with peak AOD_{558} around 2.0. The particles were mostly medium (Fig. S2) and spherical (Fig. 3d), ranging in SSA between about 0.94 and 0.99 (Fig. 3c). One aspect of the Rum Creek fire plume at MISR observation time is a significant fraction of black smoke (Fig. 3e), which typically concentrates near-source for wildfires (e.g., see Section 3.2 below). However, in the optically thickest part of the Rum Creek fire South Plume, near the fire source, the MISR retrievals identify primarily non-light-absorbing particles (Fig. 3g); black smoke concentrated primarily all along the northeast plume edge. Under the low-wind, near-surface conditions here, the visible Rum Creek plumes apparently extended no more than ~50 km in any direction, so particle evolution is more difficult to discern than it is when the smoke is more rapidly advected downwind.

3.2 **The Mosquito Fire, 08 September 2022**

The Mosquito fire northeast of Sacramento, California was captured by MISR on 08 September 2022 around 18:49 UTC. Figure 4 provides a MODIS context image, the MISR plume geometry relative to the MODIS 4-micron thermal anomalies, as well as the MISR-MINX plume-height map and profile. In this case the near-source plume resides about 3 km above the surface (just over 4 km ASL), whereas ~30 km downwind the smoke approaches the surface, as can be seen in the profile plot (Fig. 4c). The plume-height map shows that the elevated, near-source part of the plume is located to the northeast in the scene, mainly above the MODIS hotspots. Of the two distinct layers, the downwind part was emitted earlier in the morning, when the fire might have been less energetic, and this part probably fills the near-surface boundary layer. The elevated smoke observed in the near-source region was emitted around local noon, and is not only spreading south but likely also a bit to the northeast within a layer of relative atmospheric stability in the free troposphere.

MISR-retrieved median wind speed for the pixels above 2 km ASL is ~4.7 m/s, whereas for pixels below 2 km ASL, retrieved winds are slower, at ~2.8 m/s. Over the ~80 km for which the AOD was sufficiently optically thick to obtain good particle property constraints from MISR, estimated plume age extends over about 6 hours (Fig. 4f). The MISR RA particle property retrievals are given in Figure 5. AOD_{558} reached the upper limit of the retrieval technique (>8) in the source region, where dark (SSA < ~0.85, Fig. 5b), nearly all spherical particles, were concentrated. ANG achieved values exceeding 2.5 here (Fig. 5b), indicating predominantly very small particles (Fig. S3 in Supplemental Material). These particles are identified as spectrally "flat" black smoke immediately over the source region, typical of intense fire plumes, and brown smoke to the northeast (Fig. 5f), possibly formed as secondary organic aerosol by the condensation of volatiles during plume evolution. MODIS FRP reached as high as 230 W/m^2 in this region (Table S2 in Supplemental Material), supporting the interpretation of an intense fire with a well-developed plume. About 15-20 km downwind of the source, at an estimated plume age of 1-2 hr., the particles appear brighter (Fig. 5c), though the SSA varies between about 0.93 and unity. Particles identified as brown smoke comprise about 30% of the mid-visible AOD near the center along the downwind plume core, whereas those retrieved as black smoke concentrate along the downwind west flank of the plume, where the REPS is medium; small particles were retrieved along the east flank (Fig. S3). However, the dominant downwind plume aerosol component is spherical, non-light-absorbing particles (Fig. 5g), likely some combination of sulfate and water particles that might form as the smoke ages and/or be contributed by background aerosol.

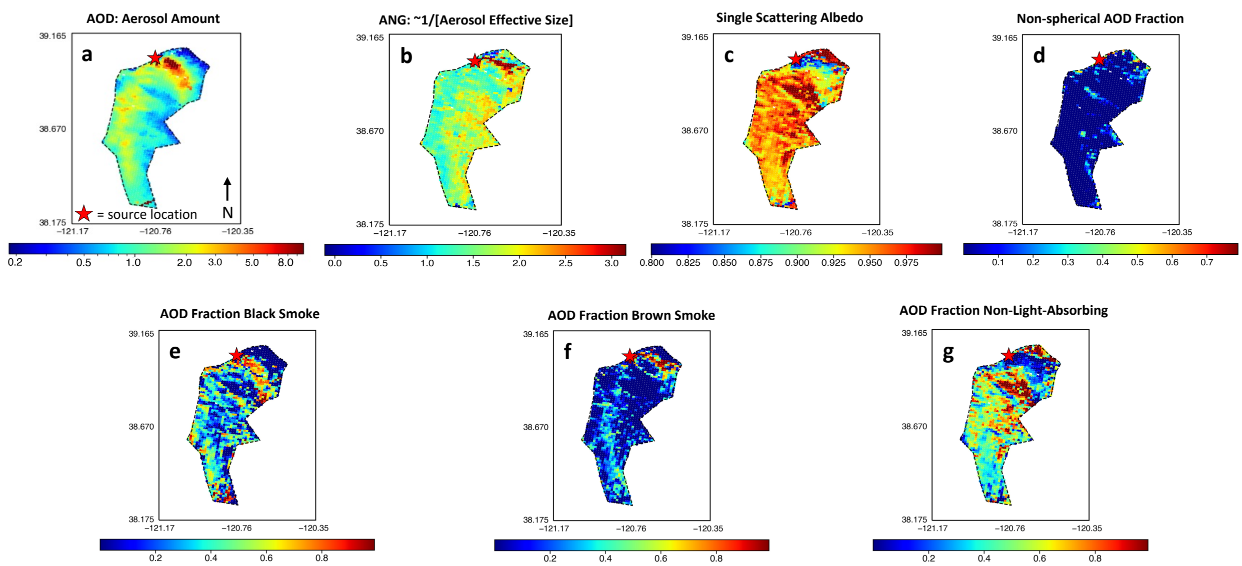

Figure 5. Same as Figure 2, but for the Mosquito Fire, 08 September 2022, ~18:49 UTC. (Table S5 in Supplemental Material provides numerical summaries of the particle properties plotted in this figure.)

4 Conclusions

On two occasions during NOAA's 2022 CalFiDE field campaign, NOAA Twin Otter aircraft measurements were coordinated with overpasses of NASA's Terra satellite, within the fields-of-view of the space-based MISR and MODIS instruments. At satellite overpass time, the

Rum Creek fire on 30 August had produced a compact smoke plume, where particles of different ages probably mixed, making assessment of systematic particle property changes difficult and any inferences about particle evolution uncertain. For the Mosquito fire on 08 September, however, the plume-particle evolution inferred from MISR Research Algorithm particle property retrieval results show consistent spherical particle shape and distinct patterns in REPS, REPA, and particle light-absorption spectral dependence, from which we infer black smoke near the fire source, brown smoke near but away from the source, likely formed as secondary particles due to especially small REPS, and increasing AOD fractions of non-light-absorbing particles ~1.5 to 2 hours downwind. As the Twin Otter was not equipped with aerosol-measuring instruments, the MISR-derived particle property information makes a unique contribution to the CalFiDE dataset. Ongoing smoke plume dynamics work led by other CalFiDE investigators can explore the relationships between fire-source characteristics, the 3-D wind structure associated with the smoke plumes, and the concentrations of fire-emitted trace gases, all obtained from the aircraft and surface platforms, and the satellite-retrieved FRP and spatial distribution of smoke particle amount, properties, and their inferred downwind evolution.

Field campaigns often provide opportunities to validate Level 2 geophysical products derived from satellite remote sensing, However, the satellite products also provide information that can be helpful in interpreting the suborbital observations, such as placing individual, disjoint aircraft transects in the context of the larger pattern of smoke plume aerosol properties. Given the complex ways in which airborne particles can impact regional-scale air quality and climate, the combination of satellite and suborbital data with models is often required to advance our understanding of the processes involved (e.g., Kahn et al., 2023). As such, the CalFiDE field campaign also offers us one opportunity to achieve such advances.

Open Research

MISR data are freely available for download from NASA's MISR data repository (https://l0dup05.larc.nasa.gov/MISR/cgi-bin/MISR/main.cgi), maintained by NASA's Langley Research Center (LaRC) Atmospheric Science Data Center (ASDC). The MISR INteractive eXplorer (MINX) program, for determining the altitude of plumes, is a stand-alone software package developed at the NASA Jet Propulsion Laboratory (JPL) and distributed through Github (https://github.com/nasa/MINX/releases). MISR RA and MINX results generated in this work can be accessed through the NASA Langley DAAC (Link TBD). MODIS true color imagery and thermal anomalies derived from MODIS data, are accessed through the NASA Worldview application (https://worldview.earthdata.nasa.gov), part of the NASA Earth Observing System Data and Information System (EOSDIS). The key data associated with this study are also included in supplemental tables.

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