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Wildfire Smoke Injection Heights – Two Perspectives from Space

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Smoke injection heights are key inputs for aerosol transport modeling, as they are critical for determining the distance and direction the smoke will travel [e.g., *Westphal and Toon,* 1991; *Ginoux et al*., 2001; *Colarco et al.,* 2003]. A recent paper in the *Journal of Geophysical Research, Atmospheres* analyzed the injection heights of wildfire smoke and other aerosol plumes near their sources, using stereo-derived plume heights from the Multi-angle Imaging SpectroRadiometer (MISR) that flies aboard the NASA Earth Observing System's Terra satellite [*Kahn et al*., 2007]. This study reported smoke from major wildfires injected into layers of relative stability above the atmospheric boundary layer (ABL) in the immediate vicinity of the sources themselves, and concluded that the buoyancy generated by the fires studied could account for these observations, within the limitations of a crude plume entrainment model, and the uncertainty of assumed fire radiant emissivity. However, the analysis made no attempt to characterize the frequency with which above-boundary-layer injection occurs on a regional or global basis.

An independent study of smoke aerosol height, performed using data from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) that flies aboard the joint US (NASA) and French (Centre National d'Etudes Spatiales/CNES) CALIPSO satellite, found that wildfire smoke remains in the boundary layer, and is not observed aloft in a sampling of the CALIPSO global record, except in rare cases far from sources, after other atmospheric processes have had time to lift the smoke to higher elevations [*Labonne et al.,* 2007].

The combination of MISR and CALIOP sampling and sensitivity differences may account for these seemingly disparate, qualitative conclusions about the frequency with which smoke is injected above the ABL. CALIOP is part of the A-Train constellation, having a dayside equator crossing at about 1:30 PM local time, and a field-of-view, before averaging, of 100 m [*Winker et al*., 2004]. The MISR dayside equator crossing is at about 10:30 AM local time (about an hour later, local time, over most longitudes of Alaska), and its swath is nearly a factor of 4×10^3 wider. Over the 16-day ground-track repeat cycle of both satellites, the lidar samples less than 0.2% of the total surface area of the planet ($< 9.3 \times 10^5$ km^2), including day and night, ocean, land, and polar regions, whereas MISR views the equivalent of the entire Earth surface about 3.5 times ($\sim 1.8 \times 10^9$ km^2) on the dayside, where it observes reflected visible light. So, ignoring spatial coverage pattern biases that affect primarily the narrow-swath instrument, and diurnal variations in fire intensity that favor the early afternoon CALIPSO over the late morning Terra

and especially over the late night CALIPSO observing times, MISR is nearly 4,000 times more likely to observe buoyant plume cores than CALIOP.

On the other hand, the active lidar sensor can measure layer heights of optically very thin aerosol (aerosol optical thickness (AOT) ~0.02, D. Winker, personal communication, 2007), whereas the MISR stereo height technique relies on identifying aerosol or cloud contrast features in multiple, angular views, having AOT of at least a few tenths. Since smaller fires deposit all their aerosol in the ABL, and even the most energetic fires leave some smoke there, CALIOP is much more likely to detect horizontally extensive, but optically thin, boundary layer smoke that the MISR Stereo Height algorithm misses. As such, the MISR and CALIOP measurements are essentially complementary.

We take an initial step toward assessing the contribution wildfires make to above-boundary-layer smoke by calculating the distribution of differences between aerosol source plume height derived from MISR, and ABL height obtained from the Goddard Earth Observing System Model – Version 4 (GEOS-4) [*Bloom et al.,* 2005]. Early work at locating smoke plumes in the MISR data was performed by *Mazzoni et al.* [2007]. In the current analysis, smoke plumes were identified by first using the MODerate resolution Imaging Spectroradiometer (MODIS) MOD-14 fire pixels to find candidate plume locations in the MISR field-of-view, and then visually inspecting the MISR images to determine where smoke plumes were apparent in the data. Plume shapes and wind directions were digitized manually with the help of an interactive analysis tool. Wind-corrected height above the geoid was calculated to approximately ±200 m accuracy by stereo-matching images from MISR's nadir camera with images from six of MISR's oblique-viewing cameras (all but the 70˚ views).

The plume height measurement approach adopted here represents a refinement, in several respects, of that developed for the MISR Standard Stereo Height product by *Moroney et al.* [2002] and *Muller et al.* [2002]: (1) Plume occurrence, extent, and wind direction are verified by visual inspection. (2) Taking advantage of the visual inspection step, wind speed and plume height are derived simultaneously and at the same high spatial resolution of 275 m, rather than retrieving wind direction along with wind speed first, at 70.4 km resolution. (3) Parallaxes from the 46˚ and 60˚ forward and aft cameras compared to nadir are included with the 26˚ comparisons, which improves vertical resolution. ABL height is reported in the GEOS-4 model on a 1˚ latitude x 1.5˚ longitude grid, for 55 vertical levels from the surface to 0.01 hPa, at 3-hour intervals, with an uncertainty estimated at ±500 m [GMAO, 2004].

We found 664 smoke plumes over central Alaska and the Yukon between mid-June and mid-September 2004. The search region extended from ~130˚ to ~170˚ W longitude, north of ~50˚ N latitude. Plume heights were assessed in two ways: (1) once for each pixel falling within the plume area, and (2) once for each plume event, where the elevation was determined by fitting a plane through the heights of all pixel in that plume, but discarding heights more than 1.5 standard deviations from the plane, and finding the median of the remaining heights. The more conservative median plane estimate de-emphasizes the larger plumes, and at the same time, helps remove possible contributions from convective overshoot or isolated pyrocumulus and other cloud that might appear as above-boundary-layer smoke. The extent of each plume itself is defined visually, and for the purpose of this analysis, covers the coherent smoke cloud emanating from the apparent source, but not any diffuse aerosol in the surroundings. Obvious clouds are also eliminated from the height maps.

Plume-ABL height results are presented in Figure 1, and are summarized in Table 1. The total area covered by digitized plumes amounts to about 1.7 x 10^5 km^2, acquired during 79 MISR orbits. Calculated either by event or by area, the peak of the distribution is -0.25 km, essentially within the ABL. As expected, the Median Plane method produced fewer above-boundary-layer counts. But from the population under study, nearly a third of pixels and more than a quarter of plumes overall appear to contribute smoke to the free troposphere, which in this case could be especially important for aerosol transport to high latitudes, including snow and ice-covered surfaces. Also given in Table 1 is the percent of counts for which the Plume-ABL height difference is >0.5 km, which captures cases having height differences that exceed the *sum* of expected uncertainties in both the plume and ABL heights. Something between 8% and 10% of cases meet this criterion, and the events that do inject smoke to these heights are expected to be the larger ones.

However, the data presented here do not provide a precise measure of plume "size." There is only a very weak correlation between plume area, as produced by our method, and [Plume-ABL height], to which ambiguities in the way plume area is defined contribute. The correlation between MODIS fire radiant energy flux and [Plume-ABL height] is also weak, most likely caused by a combination of varying fire emissivity and varying smoke opacity above the fire pixels, both of which affect the satellite signal, along with the influence of the atmospheric stability structure on smoke plume elevation [e.g., *Kahn et al.,* 2007]. None of these effects are included in the present analysis. So estimating the *amount* of smoke injected above the ABL will require additional data; this is beyond the scope of the current note, but is a subject ripe for further study.

Table 1. Summary of 664 Alaska-Yukon Smoke Plume Statistics for Summer 2004

	All smoke pixel heights by Area	Median Plane heights
[Plume-ABL] Height >0	31.0%	26.2%
[Plume-ABL] Height > 0.5 km	9.5%	7.5%

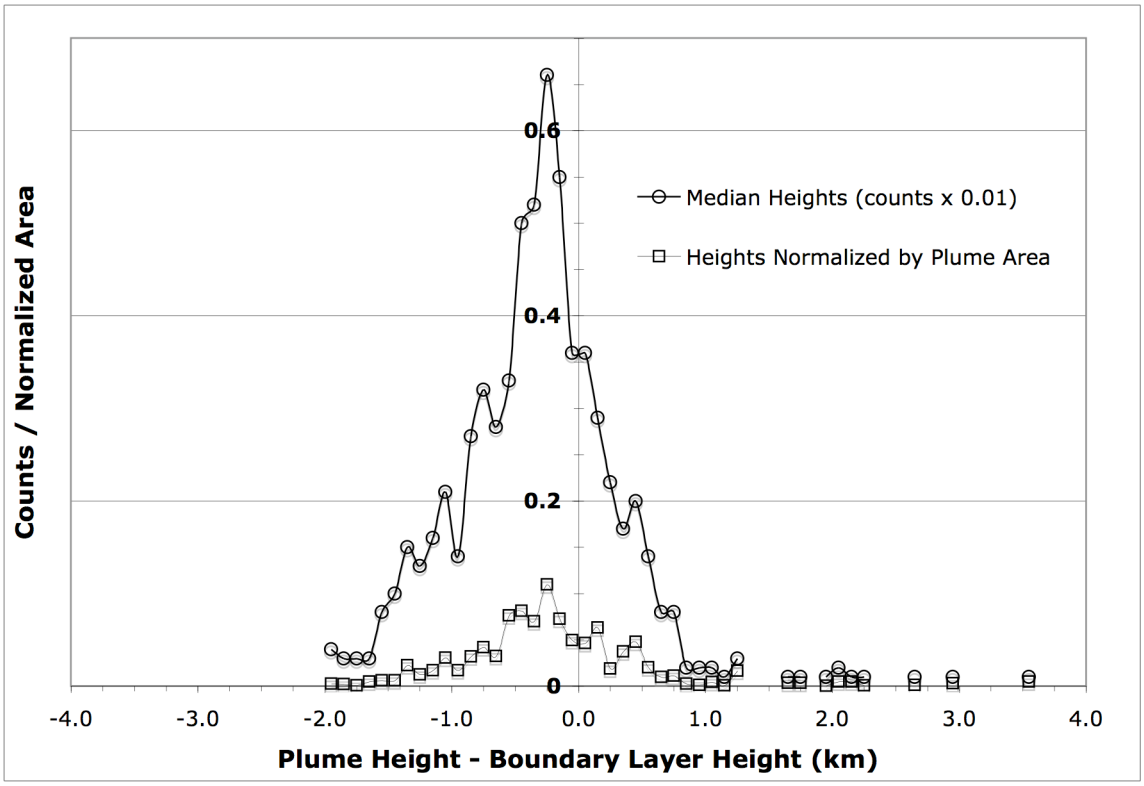

Figure 1. Histograms of plume elevation relative to the nominal ABL, both by plume count and by fraction of total plume area, for 664 plumes in the Alaska-Yukon region, Summer 2004. The Normalized Heights were calculated as a count of all pixels from all plumes that fall in a given height difference bin, divided by the total number of pixels from all plumes. For this figure, the number of counts, for plumes classified by median height, has been multiplied by 0.01 to fit on the vertical scale.

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