Characteristics of fire plume heights and smoke clouds on Borneo and Sumatra

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Objective and Approach

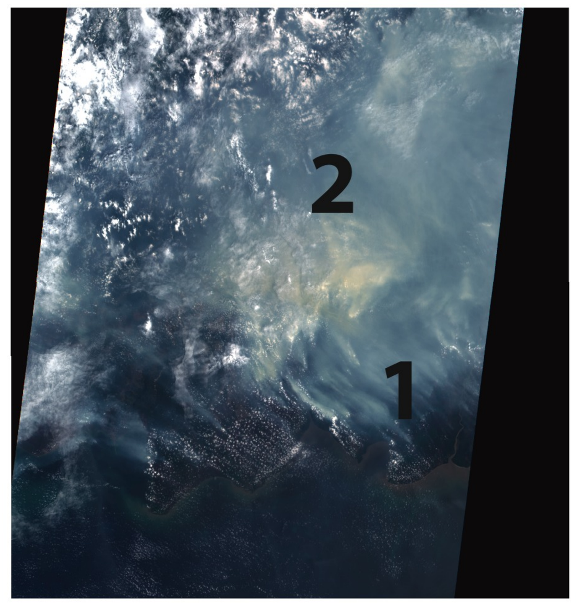


Figure 1. Visible MISR image of smoke over Borneo observed on 28 October 2006. Region (1) indicates smoke "plumes." Region (2) indicates a smoke "cloud."

Long range transport of smoke has important consequences for atmospheric chemistry, climate, and air quality. Some chemical transport models that incorporate fire assume that no smoke escapes the atmospheric boundary layer (BL). Val Martin et al. (2009) observe that between 5 and 12% of North American plumes are injected above the BL.

In this project we analyzed smoke plume and smoke cloud heights on the islands of Borneo and Sumatra from 2001-2008.

Smoke altitudes were obtained from stereo-derived height estimates using the MISR Interactive eXplorer (MINX) software (Nelson, et al., 2008).

We identified all visible plumes between 2001 and 2008 for Borneo and Sumatra. MISR images were selected using the MODIS fire pixel product. Images were chosen if they contained at least one MODIS fire pixel. The plume source, boundaries and direction were then identified by visual inspection.

The total sample size of plumes observed in this study was 405: 294 on Borneo and 121 on Sumatra. There was statistically significant correlation between annual fire count and observed plume number on both Borneo and Sumatra (Fig. 2; r^2=0.98, 0.92), suggesting consistency in the digitization process.

Smoke plumes are defined as any smoke features in the high-resolution MISR images that have a discernable surface source point (Figure 1, **(1)**).

Smoke clouds are defined as smoke features that are not visibly associated with a source, and are generally larger and thicker than plumes (Figure 1, **(2)**).

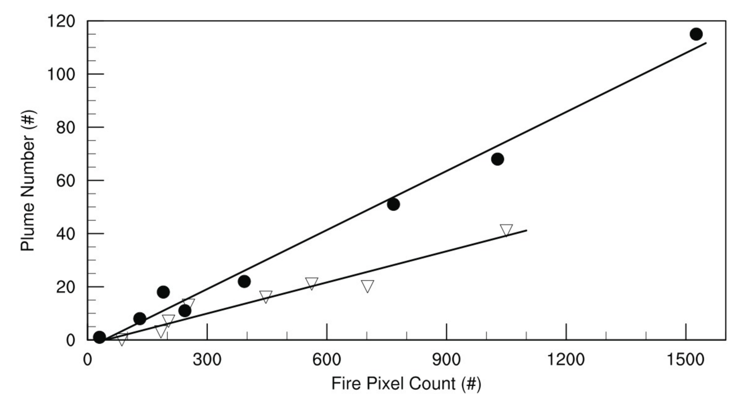


Figure 2. Linear relationships between the number of annually observed (MODIS) fire pixels and (MISR) smoke plumes on **(a)** Borneo (black dots) and **(b)** Sumatra (triangles)

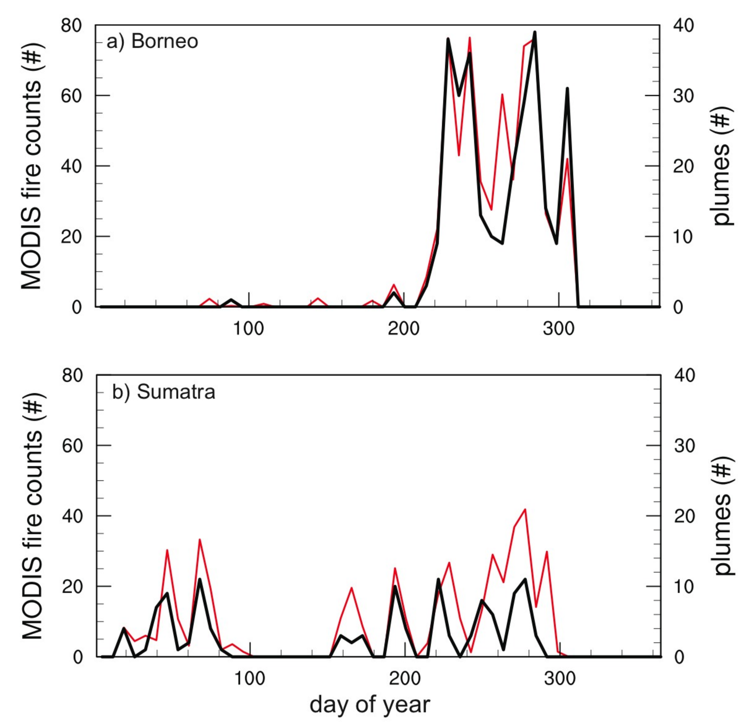


Figure 3. Seasonal time series of the number of observed (MODIS) fire counts (red line) and number of observed (MISR) smoke plumes (black line) for Borneo (a) and Sumatra (b).

Plume height distributions

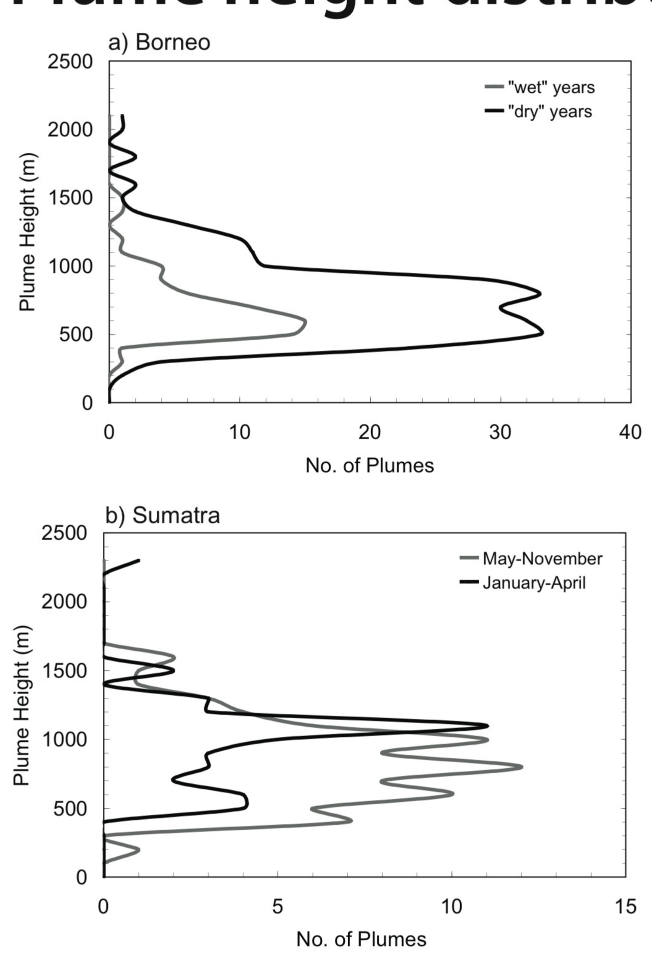


Table 1. Plume height summary

	No. of Plumes	Mean height ± S.E. (m)
BORNEO		
total	294	757.3 ± 16.8
"dry" [1]	235	765.8 ± 19.7
"wet" [2]	60	711.4 ± 28.7
SUMATRA		
total	121	887.4 ± 29.2
Jan-Apr	41	997.5 ± 53.2
May-Nov	80	830.9 ± 33.2

[1] "dry" years = 2002, 2004, 2006 (El Niño)
[2] "wet" years = 2001, 2003, 2005, 2007

Figure 4. (a) Histogram of Borneo mean plume injection heights (m) binned into 'dry' years (those associated with El Niño; 2002, 2004, 2006) and 'wet' years (2001, 2003, 2005, 2007). **(b)** Histogram of Sumatra mean plume injection heights (m) binned into either a winter/spring (January-April) or summer/fall (May-November) burning season.

Plume height analysis

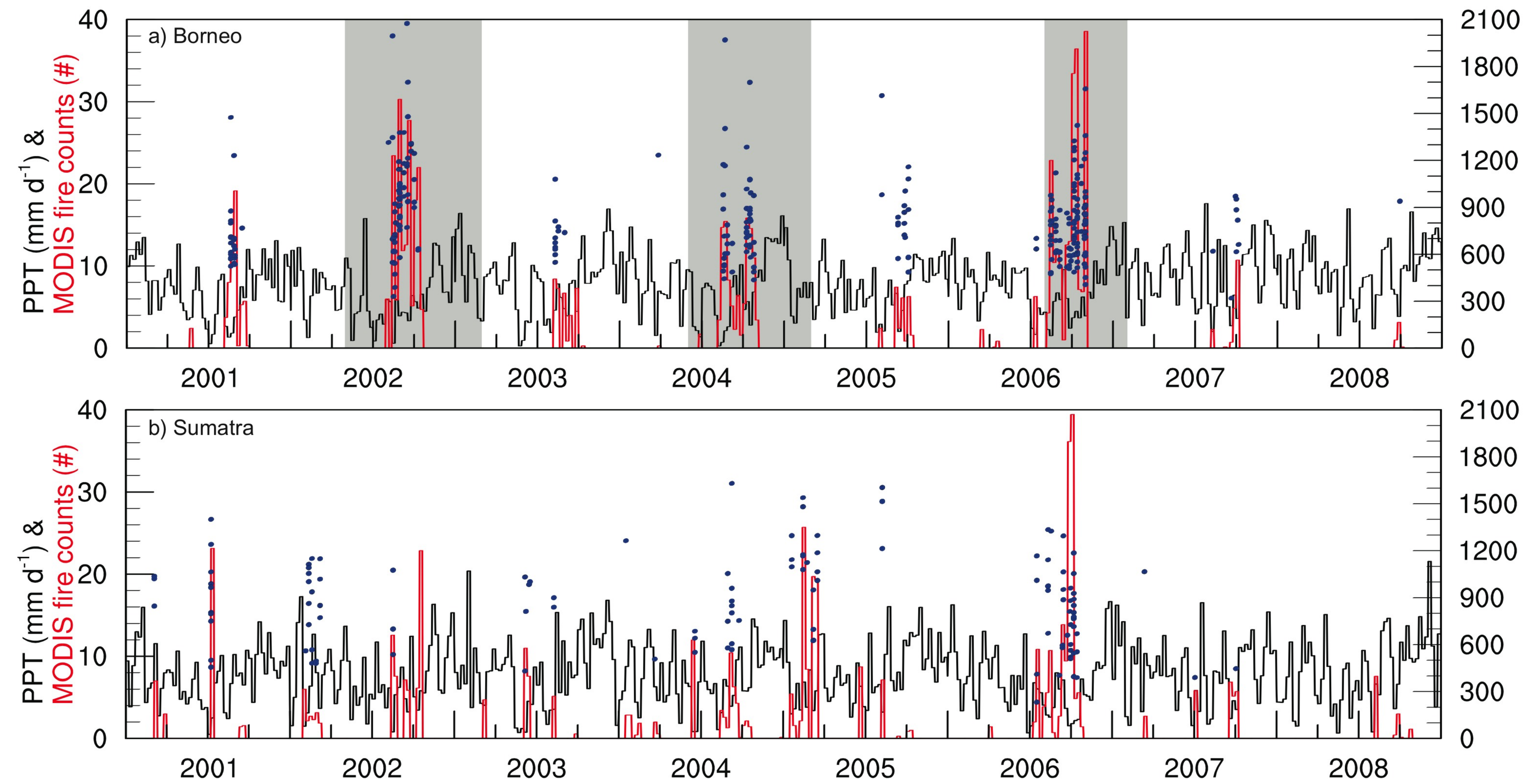


Figure 5. The 2001-2008 time series of 8-day averaged number of observed (MODIS) fire pixels (red line), precipitation (TRMM; black line), and mean plume height (blue dots) for **(a)** Borneo and **(b)** Sumatra. Gray regions designate periods with Oceanic Niño Index values >0.5, indicating El Niño conditions in the Eastern Pacific.

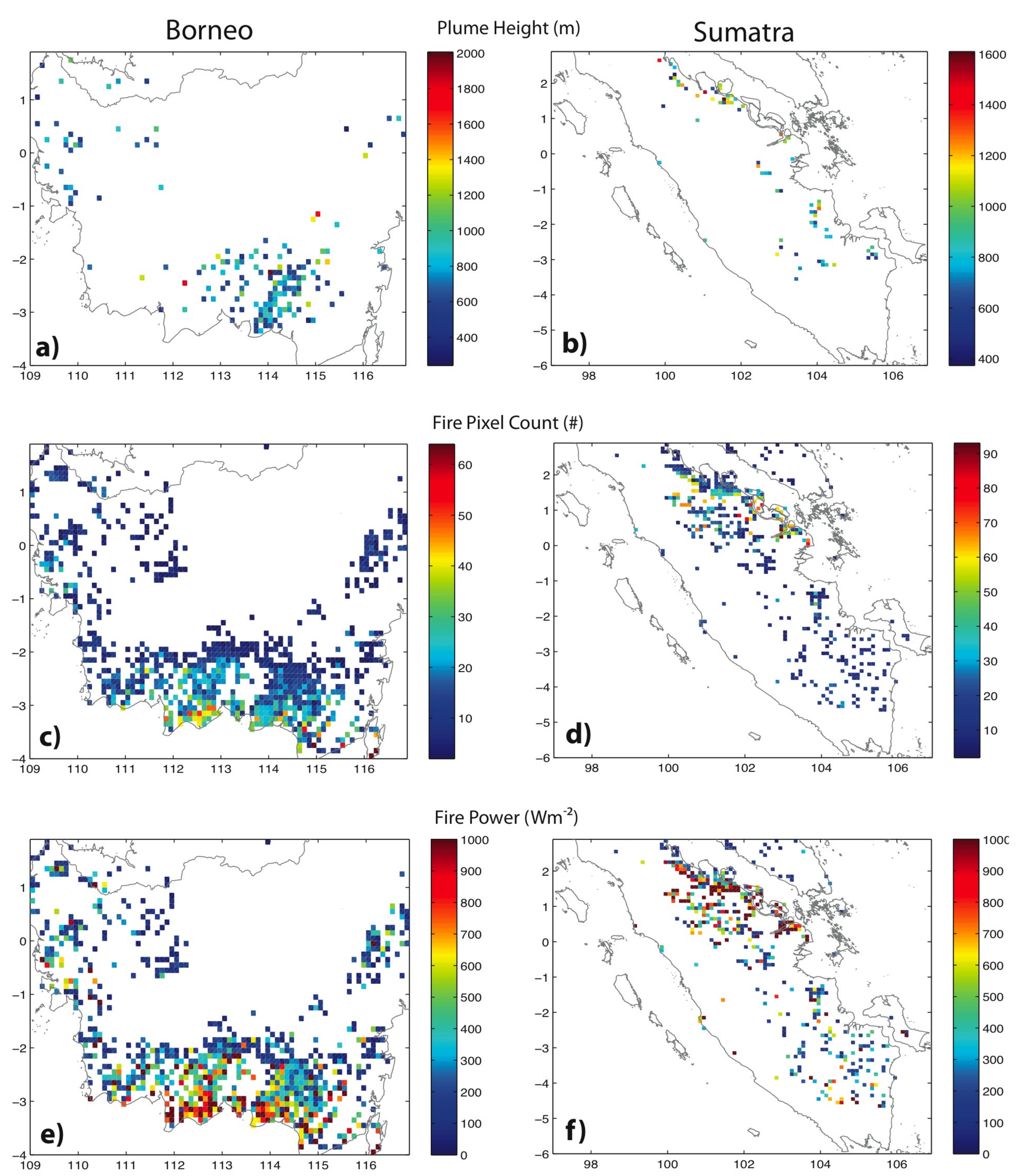


Figure 6. Borneo (left) and Sumatra (right) mean plume injection heights (a,b), total number of fire pixels (c,d) and total fire power (e,f) for each 0.1 x 0.1 degree grid cell.

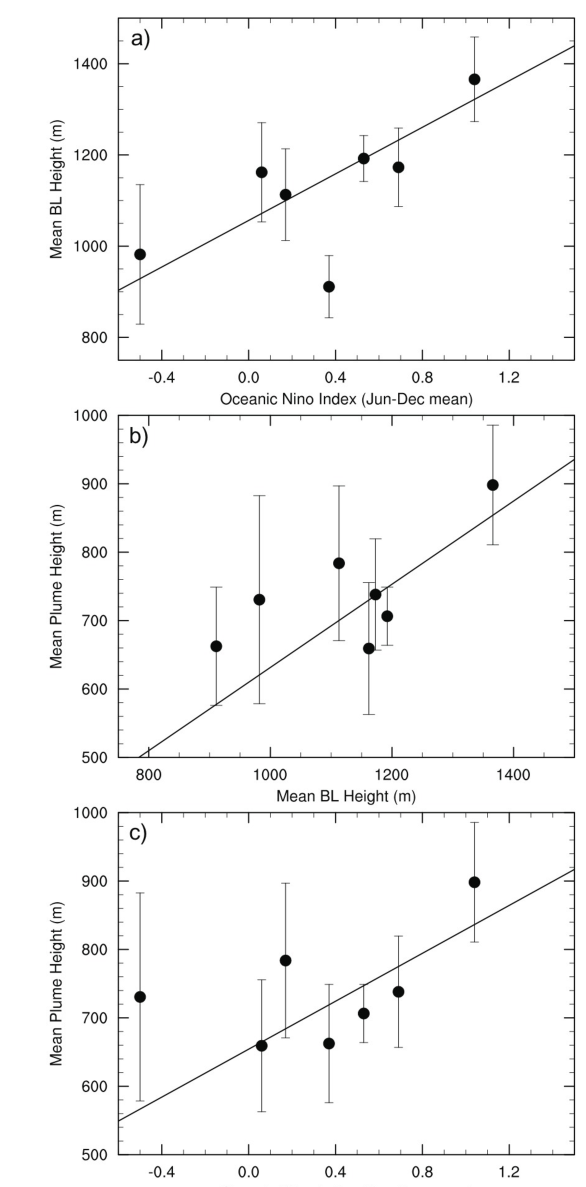


Figure 7. Seasonally averaged linear relationships. **(a)** The June-December mean Oceanic Niño Index (ONI), an indicator of El Niño, vs. mean plume boundary layer (BL) height (r^2 = 0.66), **(b)** mean BL height vs. mean plume injection height (r^2 = 0.63), **(c)** mean ONI vs. mean plume injection height (r^2 = 0.52). All regressions are weighted by the number of observed plumes per year and are fit with 95% confidence (p = 0.04, 0.02, <0.01, respectively).

Most observed smoke plumes on Borneo were located in Central Kalimantan, Indonesia (Fig. 6). A smaller cluster of plumes was observed further west, in Western Kalimantan, Indonesia and Sarawak, Malaysia.

The majority of Sumatra plumes were observed on the east coast of the island in Riau, Jambi and South Sumatra provinces (Fig. 6). Plumes north of 0° in northwest Riau and southeast North Sumatra province were substantially higher than plumes south of the equator. High fire power and fire counts in this region suggest that plume heights in northern Sumatra were tangentially linked to fire strength.

Annual mean plume heights on Borneo were positively correlated with the Oceanic Niño Index, a measure of El Niño strength (Fig. 7); r^2=0.52. This is partly due to a positive correlation between boundary layer heights and ONI and boundary layer heights and plume heights.

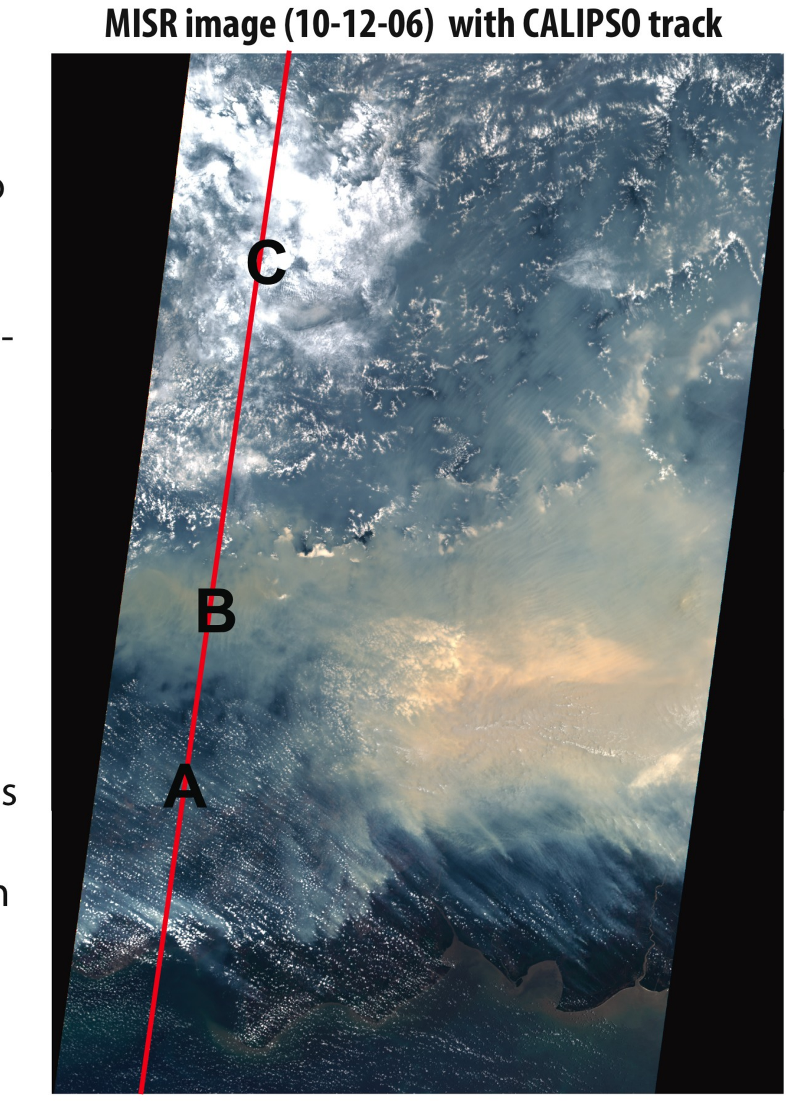
Smoke cloud altitudes and CALIPSO case-study

Weighted by the total number of smoke grid cells, the mean altitude of 2006 smoke clouds was 1374m, compared with 836.1m for all 2006 Borneo plumes (Figure 8).

Only 5% of all plume pixels had an altitude of 1468m and above. For smoke clouds, this value was almost 1000m higher (2378m).

Only 0.8% of all plume grid cells were higher than 2000m, compared with 14.3% of all cloud grid cells. However, only 5% of all cloud cells were below 518m, compared to 17% of plume cells below 547m. This suggests that the variability of cloud altitudes was much higher than that of plume altitudes.

MISR image (10-12-06) with CALIPSO track



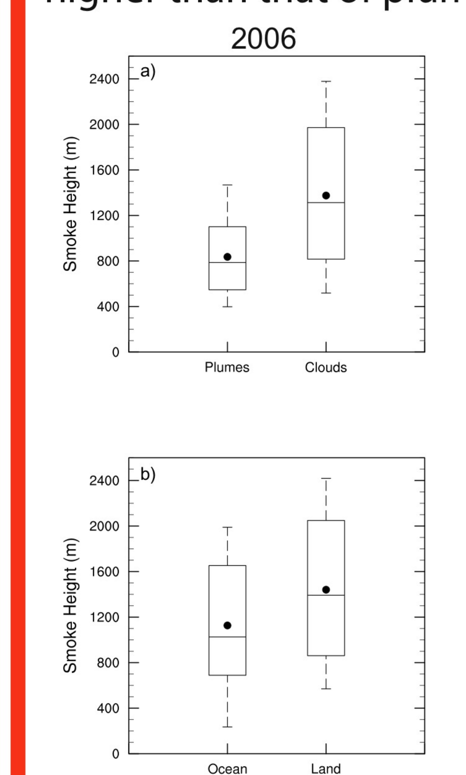


Figure 8. (a) Comparison of smoke plume altitudes and smoke cloud altitudes on Borneo. (b) Comparison of ocean smoke clouds and land smoke clouds . The central line indicates the median; the dot represents the mean.

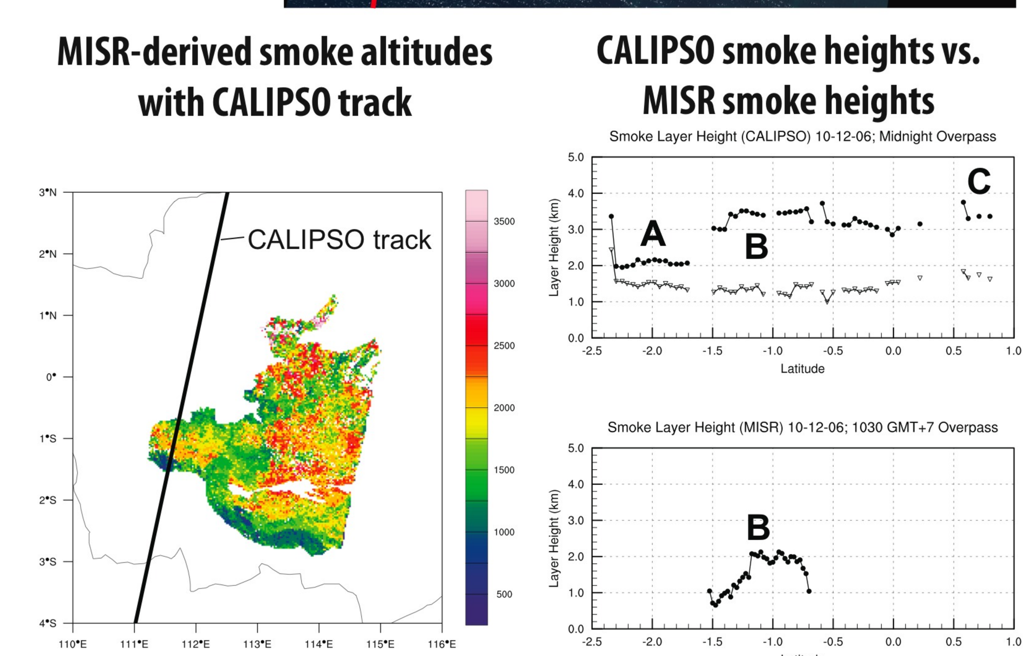


Figure 9. CALIPSO case-study from 12 October 2006. Top panel is the MISR radiance image showing regions of plumes (A), smoke clouds (B) and water clouds (C). The bottom left panel displays pixel heights for just the smoke cloud portion of the image. The black line is the CALIPSO satellite product track. The bottom right two panels display smoke heights for both the CALIPSO path, and the MISR smoke cloud, along the CALIPSO track.

Summary

BORNEO
- Total mean plume height was 757.3 ± 16.8m
- Mean plume height during dry years was higher than during wet years
- No correlation between seasonal timing and plume height
- Plume heights and El Niño strength were positively correlated

SUMATRA
- Total mean plume height was 887.4 ± 29.2m
- Mean plume height during Jan-Apr plumes was higher than May-Nov
- Plume heights, fire counts and fire power were higher in north Sumatra

CLOUDS
- Mean smoke cloud altitudes were higher than plume altitudes
- Heights consistent with daytime BL expansion and accumulation over time
- Cloud altitudes exhibited greater variability than plumes altitudes

Acknowledgements/References

This project was funded by a NASA Earth System Science Fellowship (ESSF), NASA grants to Randerson, Zender and Diner (including NNX08AF646), an EPA grant to Logan, and an NSF Carbon and Water in the Earth System Grant (ATM-0628637)

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Val Martin, M., J. A. Logan, R. A. Kahn, F-Y Leung, D. L. Nelson, and D. J. Diner. Smoke injection heights from fires in North America: Analysis of 5 years of satellite observations. Submitted to Atmos. Chem. Phys. Disc., August 2009.