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Vertical distribution of aerosols over the Maritime Continent during El Nino

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Abstract. The vertical distribution of aerosols over Southeast Asia, a critical factor of aerosol lifetime, and impact on radiative forcing and precipitation, is examined for the 2006 post El-Nino fire burning season. Additionally, through analysis of measurements and modeling, we have reconfirmed the hypothesis that fire radiative power is underestimated. Our results are significantly different from what others are using. The horizontally constrained Maritime Continent's fire plume median height, using the maximum variance of satellite observed Aerosol Optical Depth as the spatial and temporal constraint, is found to be 2.17 ± 1.53km during the 2006 El Nino season. This is 0.96km higher than random sampling and all other past studies, with 62% of particles in the free troposphere. The impact is that the aerosol lifetime will be significantly longer, and that the aerosols will disperse in a direction different from if they were in the boundary layer. Application of a simple plume rise model using measurements of fire properties underestimates the median plume height by 0.34km and more in the bottom-half of the plume. The center of the plume can be reproduced when fire radiative power is increased by 20% (range from 0% to 100%). However, to reduce the biases found, improvements are required in terms of measurements of fire properties when cloud covered, representation of small scale convection, and inclusion of aerosol direct and semi-direct effects. The results provide the unique aerosol signature of fire under El-Nino conditions.

1. Introduction

Properly quantifying the vertical distribution of aerosols is essential to constrain their atmospheric distribution, and in turn, the atmospheric energy budget [*Ming et al.*, 2010; *Kim et al.*, 2008], and understand their impact on circulation, clouds and precipitation [*Tao et al.*, 2012; *Wang* 2013], and human health [*Burnett et al*, 2014]. However, there are complicating factors including spatial and temporal heterogeneity in emissions [*Cohen and Wang*, 2014; *Cohen*, 2014; *Giglio et al.*, 2006; *Petrenko et al.*, 2012; *Wooster et al.*, 2012], and uncertainties and non-linearities associated with aerosol processing and removal from the atmosphere [Tao et al., 2012; *Cohen* and *Prinn*, 2011; *Cohen et al.*, 2011]. Furthermore, a lack of sufficiently dense measurements leads to difficulty constraining the measured distribution of aerosols over scales from hundreds to thousands of kilometers or over time frames on the decadal to longer time scales [Cohen and Wang, 2014; *Delene* and *Ogren*, 2002; *Dubovik et al.*, 2000; *Cohen* et al., 2016].

Models do a poor job of reproducing the vertical distribution of aerosols [*Cheng et al.*, 2012; *Schuster et al.*, 2005; *Tsigaridis et al.*, 2014] as well as the related value of total column loading [*Colarco et al.*, 2004; *Leung et al.*, 2007]. Furthermore, vertical measurements are sparse, often not providing adequate statistics to make informed comparisons with real world conditions. This is no more apparent than over Southeast Asia, where studies [*Tosca et al.*, 2011; *Martin et al.*, 2012] have concluded that the aerosol height is narrowly confined in the planetary boundary layer, although measurements throughout the region demonstrate otherwise [*Lin et al.*, 2014]. Presently, there are no known modeling efforts that have been able to reproduce this significant loading.

Additionally, aerosol emissions databases in Southeast Asia are quantified using a bottom-up approach, where small samples and statistics of the activity, land-use, economics, population, and hotspots are aggregated [*van der Werf*, 2010; *Lamarque*, 2010; *Bond et al.*, 2004]. This generally leads to significant bias, since there are few measurements and rapidly changing land-surface features over Southeast Asia. A recent couple of papers, using measurements and models in tandem, has quantified a significant underestimation in aerosol emissions over Southeast Asia in terms of magnitude [*Cohen and Wang*, 2014], spatial, and temporal distribution [*Cohen*, 2014], including interannual and intraannual variation from fires.

Furthermore, the vertical distribution is uncertain due to incomplete understanding of in-situ production and removal mechanisms, which are dependent on washout, which is also poorly modeled [*Tao et al.*, 2012; *Wang* 2013], especially in the tropics during the dry season [*Petersen and Rutledge*, 2001; *Ekman et al.*, 2012], due to the random nature of convective precipitation. Heterogeneous aerosol processing may also change the hydroscopicity and hence vertical distribution of the aerosols [*Kim et al.*, 2008; *Cohen et al.*, 2011]. These factors have been show to combine such that small changes in the initial vertical distribution can lead to ultimate transport thousands of kilometers apart [*Wang,* 2013].

The Maritime Continent of Southeast Asia has faced widespread and ubiquitous fires the past few decades, due to expanding agriculture, urban development, economic growth, and changes in the base climatology that induce drought [*Center*, 2005; *Dennis et al.*, 2005; *van der Werf et al.*, 2008; *Taylor*, 2010]. These fires contribute the major fraction of the atmospheric aerosol burden during the dry season

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[*Cohen*, 2014]. However, these fires are unique: they are relatively low in radiative power and temperature, yet cover a massive net surface area, making their statistics and extent hard to characterize from remote sensing. Yet, their total emissions are very high and they dominate the aerosol optical depth (AOD) and $PM_{2.5}$ levels over thousands of kilometers [*Field et al.*, 2009; *Nakajima et al.*, 1999]. Due to their widespread nature, fires in this region are geospatially coherent in their timing and geography, although individually they burn for different lengths of time, as a function of localized precipitation and soil moisture, and global circulation patterns such as El-Nino [*Cohen*, 2014; *Wooster et al.*, 2012; *Hansen*, 2008].

This work describes a new approach to comprehensively sample the vertical distribution of smoke aerosols, by first using decadal scale measurements of AOD from the MISR satellite [*Cohen*, 2014], and then separating the smoke impacted regions by the magnitude of the measured variability. During the 2006 El-Nino enhanced burning, one of the 2 largest such events over the past 15-year measurement record, this approach yields a much higher vertical aerosol height than the traditional random sampling approach. A simple plume-rise model [*Achtemeier et al.*, 2011; *Briggs*, 1965] using reanalysis meteorology [*Kalnay et al.*, 1996] and measured fire properties was found to underestimate the measured heights. However, the model could be improved to match the median heights by increasing the measured fire radiative power [*Sessions et al.*, 2011; *Sofiev et al.*, 2012], implying that the measured fires may be underestimated in terms of their strength, or that there are missing fires. However, the top and bottom heights of the measured plume still cannot be reproduced. The data shows that an improved representation of both localized convective transport and the aerosol direct and semi-direct effects [*Ekman et al.*, 2007; *Wang*, 2007] are required to make further improvements. It is hoped that these results will provide insight to those working on understanding the strong 2015-2016 El-Nino conditions.

2. Methods

2.1 Geography

This work is focused on the Maritime Continent, a sub region of Southeast Asia (8°S to 8°N, 95°E to 125°E) (**Figure 1**) that experiences wide-spread and highly emitting fires on a yearly basis during the local dry season (August to October/November). The combined magnitude of the fires produces a single massive smoke plume, that covers much of the region, extending thousands of kilometers [*Cohen*, 2014]. These wide spread fires are due to anthropogenic clearing of rainforest and agriculture [*Cohen* et al., 2016; *Dennis et al.*, 2005; *van der Werf et al.*, 2008; *Taylor*, 2010; *Miettinen et al.*, 2013; *Langmann et al.*, 2009]. Over this region, during the dry season, the removal of aerosols is quite slow, leading to the overall properties of the plume being relatively consistent over space and time [*Cohen*, 2014]. Therefore, the overall properties of the smoke plume, when correctly bounded in space and time, can be robustly statistically related to the overall properties of individual fires, and daily measurements of AOD from the MISR satellite (**Figure 1**) [*Cohen*, 2014].

In 2006, the El-Nino conditions led to an enhanced drought, with subsequent fires lasting from September through November. To ensure that the data analyzed is definitely from this event, only data from

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October is used. The region in (**Figure 1**) with the EOF (Bjornsson and Venegas, 1997; Cohen et al., 2016) of the measured MISR AOD larger than 2.2 is the net of the source regions (over land) and downwind regions (over both land and sea), thereby providing a holistic representation of the impact of fires on the large-scale structure, and allows for a comprehensive sampling of the vertical distribution of the smoke, including observed fires, fires obscured by clouds (very common in this region), and aged aerosols directly downwind from their initial sources.

2.2 Measurements

CALIPSO is an active lidar that quantifies both the vertically resolved atmospheric backscatter strength (a reasonable approximation of the vertical profile of aerosols), and an indication of particle size (large or small) [*Winker et al.*, 2003]. Specifically, we use the backscatter at 532nm and the vertical feature mask (vertical resolution 30m, horizontal resolution 1/3km) [*Hostetler et al.*, 2006]. Since the width of each pass is narrow, they are not spatially representative in general. However, given the relative consistency of the plume as a whole, samples constrained within the plume's spatial extent, taken on the same day, are statistically representative of the smoke plume as a whole [*Cohen*, 2014].

The extinction-weighted top (10% vertically integrated height), middle-upper (30% vertically integrated height), median (50% vertically integrated height), middle-lower (70% vertically integrated height), and bottom (90% vertically integrated height) are computed for each individual measurement, with the values retained if the aerosol is not in the stratosphere (assumed to be 15km). The data is then aggregated first by day, and secondly by geography, either into the fire-impacted region, or non fire-impacted region, based on (**Figure 1**) [*Cohen*, 2014]. The aggregated set of measurements is used to compute probability densities and statistics, demonstrating the vast difference over the fire-impacted and non-fire impacted regions (**Figures 2a,2b)**. with the vertical heights both significantly higher and less variable ($p<0.01$) over the fire region than the non-fire region.

Measurements of aerosol optical depth (AOD) [*Kaufman et al.*, 2003], fire radiative power (FRP) and fire temperature (T_F) [*Freeborn et al.*, 2014; *Ichoku et al.*, 2008] are obtained from the MODIS instrument aboard both the TERRA and AQUA satellites. Version 5, level 2, swath-by-swath measurements, at daily resolution are use for AOD (best solution 0.55 micron), with a spatial resolution of 10kmx10km, and FRP/T_F, with a spatial resolution of 1kmx1km. Given the prevalence of clouds in this region, the cloud-cleared products are used, leading to a possible low bias in the FRP/T_F measurements, as well as some fires not measured at all [*Cohen* et al., 2016; *Freeborn et al.*, 2014; *Ichoku et al.*, 2008; *Kahn et al.*, 2008; *Kahn et al.*, 2007]. On the other hand, while some grids are contaminated, the sheer spatial distance of the plume and the fact that the overwhelming majority of atmospheric aerosols during this time of the year are due to fires, means that there is no significant bias in the overall statistics of the measured AOD [*Cohen*, 2014], as observed by looking at the spatially averaged MODIS AOD and statistics over the fire-constrained and non fire-constrained regions (**Figure 3**). The AOD is significantly higher ($p<0.01$) over the fire-constrained region, making the findings consistent with the approach employing the 12 years worth of MISR measurements.

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2.3 Plume Rise Model

A simple model is employed to simulate the height to which a parcel of air initially at the surface over the fire will rise, based on buoyancy, vertical, and horizontal advection (**Supplement**). The formulation requires information about the temperature and radiative power of the fire as well as local meteorology [*Achtemeier et al.*, 2011; *Briggs*, 1965], and yields an idealized height to which aerosols emitted will rise. The buoyant plume rise is a thermodynamic approximation in nature and thus not as physically realistic as a large eddy approach, which solves the atmospheric fluid dynamical equations by parameterizing turbulence at the scale of tens of meters. However, it is less computationally expensive and more generalizable in the context of approximating the thousands of fires spread geographically over hundreds of thousands of square kilometers. On the other hand, it is more physically realistic than empirical relationships from multi-angle measurements [*Sofiev et al.*, 2012], which have also been attempted, but show poor performance in Southeast Asia.

These relationships are efficiently solved using measurements of meteorological and fire properties, allowing them to be used as rapid parameterizations within regional or global models. However, there are errors associated with reconciling the different temporal and spatial scales of reanalysis meteorology, especially convection and associated transport. Secondly, cloud-cover in this region leads to both missing fires and low-bias in measurements of fire properties [Sofiev et al., 2012; *Kaufman et al.*, 2003]. Third, the cloud-cover also leads to a heavier contribution of model results in the reanalysis meteorology. Finally, the effects of the optically thick aerosol plume's feedback on the radiative profile is likely significant, but not taken into consideration [*Ekman et al.*, 2007; *Wang*, 2007].

3. Results and Discussion

3.1 Measured Aerosol Vertical Distribution

The fire-constrained monthly aggregated daily statistics of the measured vertical aerosol height from CALIPSO [*Winker et al.*, 2003] is given in (**Figure 2a**), with the monthly aggregated statistics over the fire-constrained region of the bottom, middle-lower, median, middle-upper, and top heights respectively: 1.68 ± 1.59km, 1.92 ± 1.55km, 2.17 ± 1.53km, 2.50 ± 1.54km, and 2.98 ± 1.55km (**Table 1**). On the other hand, the non fire-constrained region's monthly aggregated statistics of the measured vertical aerosol height is quite different (**Figure 2b**), with the respective bottom, middle-lower, median, middle-upper, and top heights: 0.65 ± 0.98km, 0.93 ± 0.98km, 1.21 ± 1.00km, 1.53 ± 1.02km, and 1.98 ± 1.08km (**Table 1**). The average aerosol height over the fire-constrained region is both much higher and more variable at every vertical level as compared to the non fire-constrained domain, with 62% of the aerosol loading in the free troposphere over the fire-constrained domain, while only 17% is located in the free troposphere over the non fire-constrained domain. However, the variability is roughly constant at all levels over the fire-constrained region, while the variability increases with vertical level, over the non fire-constrained region.

All three findings, higher average aerosol height, larger variance of height, and a consistent variance of height at all levels, are consistent with areas where most of the aerosol loading is due to surface

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fires. Firstly, the buoyancy from fires increases the expected height, with differences in buoyancy from different strength fires producing random variability in the measured heights. So long as the distribution of fire strength and meteorology do not differ too much from day-to-day, the variance in aerosol heights should also not vary much. On the other hand, over non fire-constrained regions, the major contribution to the vertical aerosol variability is convection, which is expected to increase in variability the higher one moves upwards from the surface.

Furthermore, the relatively constant variability across the heights in the fire-constrained region is consistent with a proposed radiative-stabilization effect. The extremely high measured AOD values found by MODIS [*Kaufman et al.*, 2003] over the fire-constrained domain (from 0.5 to 2.0, with most days over 1.0), leads to significant surface cooling (**Figure 3**). Additionally, BC emitted from the fire, absorbs incoming solar radiation near the upper portion of the plume, providing a significant warming. This combination leads to additional stabilization of the atmosphere, and therefore the vertical aerosol distribution.

These results are thus consistent with the observed reduction in in-situ vertical processing over the regions downwind from the fire sources, but still within the fire-constrained plume region, where buoyancy from the fires and the self-stabilization effect seem to contribute more than random deep convection. However, over the non fire-constrained region, given the low AOD and lack of fires, both of these effects are not observed, and convection dominates, which is consistent with the less uniform vertical distribution. Given these clear and observed differences, only results from the fire-constrained region will be considered further.

A significant amount of aerosol mass exists in the free troposphere over this region. By assuming that the measured boundary layer height of 1000m as observed in Singapore [*Chew et al.*, 2013] is applied to the domain, then 62%, 73%, 83%, 93%, and 98% of the total monthly respective measurements of the bottom, lower-middle, median, upper-middle and top extinction heights are located in the free troposphere. This is much higher than previous studies, which indicated most of the smoke remained within the boundary layer [*Tosca et al.*, 2011].

Analysis of the daily measured heights demonstrates 3 statistically unique days: October 11th, 15th and 22nd (**Table 2**). On the 11th, the top and upper-middle measurements fall within the top 15%, while the median measurements fall within the top 20% of the month's measurements, implying that the result is consistent with a deep, single layer, extending throughout the lower and middle free-troposphere. The 15th and 22nd, while not being as high in the middle-troposphere, also have little to no aerosol in the planetary boundary layer due to being significantly more confined in the vertical, implying a narrow layer in the middle free-troposphere. These results are consistent with the measured aerosol layer being mostly in the free troposphere, a result that is not consistent with the measured FRP or meteorology, leading to two important implications. Firstly, the aerosol lifetime on these days will be considerably longer than models typically reproduce and the radiative forcing will be considerably more warming. Secondly, that typical modeling approach that fresh aerosols are mixed from the surface to the given top of the plume height is

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likely not true here, which has implications for the ability of most models to be able to correctly capture the aerosol loading.

On the remaining days, the measured heights are consistent on a daily average basis with relatively uniform emissions, meteorology, and vertical buoyant rise. Although present, intense but heterogeneous forcing impacting the vertical distribution, such as localized convection and aerosol cloud interactions are generally not observed to bias the overall plume's properties. Only on October 11th, 15th, and 22nd, are there significantly higher heights or a narrower vertical structure, combined with no readily available explanation to be found in the fire, AOD, or meteorological properties on these days, indicating a likely significant change in the convection on those days, or some other phenomena not considered or captured by the reanalysis meteorology. The robustness of this approach assures the validity over the region and time period considered herein.

3.2 Measured Fire and Meteorological Properties

The daily aggregated measurements of fire radiative power (FRP) [*Freeborn et al.*, 2014; *Ichoku et al.*, 2008] indicate there are 109395 actively burning 1kmx1km pixels in October 2006. However, filtering for high confidence [Level 9] active fires, reduces this number to 6941 1kmx1km pixels. The respective measurements have 10%, median, and 90% values of FRP of [115,300,975] W/m^2 for all fires and [185,540,1495] W/m^2 for high confidence fires (**Table 3**). Overall, these values are significantly lower than FRP measured over other intensely burning regions [*Giglio et al.*, 2006]. However, the results are consistent with the fact that fires in the Maritime Continent occur under relatively wet surface conditions, due to high levels of mineral-soil moisture, extensive peat, and intermittent localized precipitation [*Couwenberg et al.*, 2010].

There is only one day, October 2nd, with a significantly high FRP (daily mean more than monthly 90% value), for high confidence fires. Similarly, there are two days, October 28th and 30th, with an abnormally low FRP (daily mean less than monthly 15% value), for high confidence fires. None of these days have a significantly abnormal fire vertical height distribution. However, October 28th and 30th both show a significant increase in AOD over the fire constrained region, with the AOD more than 2 standard deviations greater than the mean over the non fire constrained region, as compared to the period of time from the 25th through the 27th.One consistent rationale is that there was large-scale precipitation increasing aerosol removal and subsequently wetting the surface. This in turn led to lower temperature and FRP and correspondingly higher aerosol emissions factor on these days. Overall, there is no apparent impact of day-to-day variability of measured FRP driving observed variation in measured aerosol heights, and hence only high confidence fire data is subsequently used.

MERRA [Rienecker et al., 2011] reanalysis meteorology is used for the horizontal and vertical wind, and vertical temperature profile at each location where a fire is measured (**Table 3**). MERRA was chosen because it is based on NASA satellite measurements, and thus should be more consistent with the measurements used here. With the exceptions of October 5th and 20th, the horizontal wind is relatively calm 6.0 $\pm$ 1.3m/s. Also, throughout the entire month, the vertical temperature gradient is relatively stable

-5.45 ± 0.16K/km, with only 7 individual fires occurring under unstable atmospheric conditions. Therefore, dynamical instability is not expected to contribute significantly to the vertical distribution [*Stone and Carlson*, 1979]. Also, the role played by the large-scale vertical wind is small 2.1 ± 1.6mm/s. Given the atmospheric stability and fire-controlled buoyancy conditions, the plume rise model approach should offer a reasonable approximation of the aerosol vertical distribution.

The approach used here relies upon the atmosphere being either stable or only minority non-stable. However, in general in this part of the world, there are two reasons that would contribute to most fires occurring under such conditions: firstly, that major instability would frequently lead to rain, fire suppression, and aerosol wash-out; and secondly that the induced surface cooling and atmospheric heating by the extensive aerosol layer itself would tend to increase the atmospheric stability. Such points are made clear in terms of the major unaccounted for processes in the MERRA data at this resolution, being: localized convection (due to the resolution), and the aerosol cooling and in-situ heating effects (not incorporated into MERRA's underlying model). In theory the direct and semi-direct effect may be able to be parameterized, but this would require a higher order model. Hence, since these conditions and effects are not considered by the plume rise model, they therefore cannot be explanations for discrepancies in the modeled vertical distribution.

3.3 Modeled Aerosol Vertical Distribution

Applying the plume rise model, the aggregated daily statistics of the vertical aerosol height at the bottom, lower-middle, median, upper-middle, and top are 0.60km, 1.14km, 1.85km, 2.87km, and 4.99km respectively (**Figure 4, Table 4**). The mean daily median, lower-middle, and bottom modeled heights are lower than the respective mean measured heights by 0.48km, 0.78km, and 1.07km respectively, with a wide underestimate day-to-day ranging from 1.91km to 1.11km. The upper-middle modeled height is about equal to measurements, with a mean difference of 0.03km, and wide day-to-day variations, from an overestimate of 1.97km to an underestimate of 1.36km. Finally, the top modeled heights are significantly higher than measurements, with an average overestimate of 1.02km, and a day-to-day range from an overestimate of 3.96km to an underestimate of 0.44km.

The model underestimates the height of the median through bottom of the plume, while simultaneously overestimating the top. First, this means that the model is not accounting for enough energy to obtain the average rise of the plume. At the same time, the modeled vertical spread is too large, implying other factors limit the height gain near the top of the plume while simultaneously enhance the height near the bottom. The results are consistent with one or both of the two hypothesized effects; first, that a low bias exists in the measured values of FRP [*Kahn et al.*, 2007; *Kahn et al.*, 2008, leading to insufficient buoyancy; and second, that in-situ stabilization occurs due to aerosol radiative cooling in the lower parts of the plume and aerosol radiative heating within the upper parts of the plume. This combination of factors is also consistent with the observed underestimate in measured FRP to match the median height, as well as the hypothesized complete non-detection of small fires [*Kaufman et al.*, 2003]. There are also uncertainties in the MERRA reanalysis products, but given the large sample size and the narrowness of the MERRA

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distribution, the impact of these uncertainties is considerably smaller than changes in the FRP on the order of 10%.

A sensitivity analysis is used to quantify the effects of a low bias in FRP, by applying a constant multiplicative factor to the measured FRP for each fire, from 1.0 to 2.0 in steps of 0.1 (although only the results in steps of 0.2 are given in **Table 4**). Although there are also uncertainties associated with measured vertical wind and temperature structure, this is not considered (**Table 3**), since there is no way to couple meteorological effects at sub-grid scale, or otherwise not included in the reanalysis meteorology. The results are obtained by minimizing the root-mean square (RMS) difference between the daily measured and modeled heights, for each FRP scaling factor, at each of the middle-upper, median, and middle-lower levels. The respective best-fit enhancement factors are **1.0** for middle-upper measurements (RMS=0.94km), **1.2** for median measurements (RMS=0.81km), and **2.0** for middle-lower measurements (RMS=0.74km) (**Table 4**). Although there is no single best-fit FRP scaling factor, the results produce a better fit to measured values from the middle-lower to the middle-upper than using the model without any FRP enhancement.

The results establish that current plume rise models can reproduce the median vertical plume height over Southeast Asia by increasing the FRP by 20%, a finding consistent with FRP generally underestimated over this region. By changing the FRP enhancement from 0% to 100%, the central height of the plume can be modeled, although the top and bottom heights of the plume cannot be reproduced. Additionally, the modeled plume is widely spread as compared to the narrowness of the measured plume. Unfortunately, rectifying these limitations will likely require the use of a more complex modeling approach and improvement of measured fire data.

4. Conclusions

This work comprehensively quantifies the significant present-day underestimation of the vertical distribution of aerosols over the Maritime Continent during an El-Nino influenced fire season, by introducing a new method to appropriately constrain the measurements over the geographical region of the aerosol plume. The measured heights over the constrained region are found to be higher than previously thought, with about 62% of aerosols found in the free troposphere, where they can be advected thousands of kilometers and have more impact on the atmospheric and climatic systems. Additionally, over the fire-constrained region, the vertical variability of the plume is found to be uniform throughout its height, implying that it is controlled mostly by local forcing, such as the buoyancy released by fires, localized convection, and aerosol/radiative feedbacks, such as the direct and semi-direct effects.

Application of a plume-rise model showed that there was an overall low bias against measured heights, which is consistent with the FRP being underestimated in this region of the world due to large-scale cloud cover. It was also determined that measured vertical heights are more narrowly confined than model simulations. Applying a robust sensitivity analysis found that the middle-lower through middle-upper extent of the plume can be reproduced if an appropriate (although changing) enhancement is applied to the FRP ranging from 1.0*FRP to 2.0*FRP (with 1.2*FRP the best fit-value). Hence, the variable FRP enhancement factor approach can allow for improved modeling of the height statistics for the middle-upper to middle-lower extent of the plume.

However, it is not possible to reproduce either the top or bottom of the measured heights, the knowledge of which is important to constrain the impacts of long-range transport and aerosol-climate interactions. Nor is it possible to reproduce the narrow spread of the measured heights. The results are consistent with the general understanding of current model shortcomings, which in addition to the underestimated FRP values, will also need to be addressed. Hence, the current community-wide dependence on FRP measurements for vertical aerosol modeling may lead to flaws in our being able to successfully model the distribution.

The results have been found to be robust over a region that behaves roughly uniformly over thousands of kilometers and includes regions both near and far from the source of the fires. Since there are only a few days that have relatively unique aerosol and meteorological properties over the period studied, the results support the most important aspect of improving the aerosol heights will be newer modelling approaches and improvements that will be able to resolve local-scale forcing, such as deep convection, aerosol/radiation interactions, and aerosol-cloud interactions. Secondly, the biased underestimation of FRP is also an important point to improve the aerosol height modeling, especially under conditions where cloudiness occurs or the measured AOD levels are very high. These errors are exacerbated over regions where large-scale precipitation is very low or where there is significant aerosol/cloud intermixing. In all cases, until these model and measurement improvements are made, there is expected to be a significant underestimation of the aerosol loadings and radiative forcing distribution regionally, and to some extent globally. It is hoped that in the interim, the community will adapt a variable enhancement of FRP in tandem with measurement-constrained boundaries of smoke plumes, as a way to more precisely reproduce the statistics of the vertical aerosol distribution.

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Table 1: Statistical summary of measured (CALIPSO) smoke plume heights in October 2006, at different percentiles of extinction height (top/Z=10%, middle-upper/ Z=30%, median/Z=50%, middle-lower/Z=70%, and bottom/Z=90%), over the subset of the Maritime Continent **impacted by smoke** (**FIRE**), and **not impacted by smoke** (**NO-FIRE**), based on MISR observations (**Figure 1).** "MEAN" is average, "STD" is standard deviation, and percentages XX% are the corresponding distribution's percentiles. Days which are statistical outliers (mean >**85%** or <**15%** of at least one variable) are listed as **1st**, **3rd**, etc.

	bottom [km]	middle-lower [km]	median [km]	middle-upper [km]	top [km]
FIRE 5%	0.18	0.36	0.56	0.89	1.31
FIRE 10%	0.25	0.49	0.76	1.09	1.53
FIRE 15%	0.31	0.59	0.92	1.29	1.67
FIRE 50%	1.38	1.59	1.83	2.22	2.82
FIRE 85%	2.75	2.92	3.13	3.37	3.70
FIRE 90%	3.14	3.30	3.45	3.72	4.07
FIRE 95%	4.18	4.38	4.70	5.56	5.65
FIRE MEAN	1.68	1.92	2.17	2.50	2.98
FIRE STD	1.59	1.55	1.53	1.54	1.55
NO-FIRE 5%	0.16	0.33	0.48	0.60	0.70
NO-FIRE 10%	0.19	0.38	0.55	0.68	0.87
NO-FIRE 15%	0.21	0.42	0.59	0.77	1.12
NO-FIRE 50%	0.31	0.57	0.83	1.25	1.76
NO-FIRE 85%	1.16	1.64	2.01	2.36	2.85
NO-FIRE 90%	1.65	1.98	2.27	2.60	3.05
NO-FIRE 95%	2.22	2.45	2.73	2.99	3.41
NO-FIRE MEAN	0.97	0.98	1.00	1.02	1.08
NO-FIRE STD	0.65	0.93	1.21	1.53	1.98

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Table 2: Summary of measured (CALIPSO) smoke plume heights in October 2006, for days that are statistical outliers **mean (>85% or <15%) of all data in bold**, mean (>80% or <20%) of all data in regular text. The levels are given as a percentile of extinction height over the subset of the Maritime Continent **impacted by smoke** (fire-constrained), based on MISR observations (**Figure 1).**

	bottom (90% Extinction) [km]	middle-lower (70% Extinction) [km]	median (50% Extinction) [km]	middle-upper (30% Extinction) [km]	top (10% Extinction) [km]
FIRE 11th	2.29	2.54	**3.26**	**4.11**	**4.93**
FIRE 15th	1.85	2.20			
FIRE 22nd	**2.55**	**2.85**	2.95		

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517 **Table 3**: Monthly statistics of measured fire properties (FRP and T_F), for all measured fires (**ALL**) and
518 level 9 confidence fires (**L9**) and MERRA meteorological properties (T_A, v, U, dT/dz) corresponding to the
519 geographic locations of **L9**. All data is constrained by the boundaries of the fire extent in October 2006
520 (**Figure 1**). The distribution's percentile is given as "**XX%**", the mean and standard deviation are given as
521 "**MEAN**" and "**STD**". Note that there were no observed fires of L9 on the following dates: 17^{th}, 22^{nd}, 23^{rd},
522 24^{th}, 25^{th}, 26^{th}, 27^{th}, 29^{th}, 31^{st}.

	FRP **ALL** [W/m^2]	FRP **L9** [W/m^2]	T_F **ALL** [K]	T_F **L9** [K]	T_A **L9** [K]	V **L9** [mm/s]	U **L9** [m/s]	dT/dz **L9** [K/km]
5%	95.	140.	370.	410.	296.0	0.2	4.1	-5.25
10%	115.	185.	390.	445.	296.4	0.4	4.4	-5.27
15%	130.	230.	400.	480.	296.6	0.6	4.5	-5.28
50%	300.	540.	535.	725.	298.4	1.5	6.0	-5.43
85%	775.	1240.	910.	1275.	301.1	4.1	7.4	-5.65
90%	975.	1495.	1070.	1525.	301.5	4.6	7.7	-5.69
95%	1290.	1855.	1335.	1850.	302.1	5.6	8.1	-5.75
Mean	510.	920.	702.	1029.	298.7	2.1	6.0	-5.44
StD	720.	1340.	573.	1057.	2.0	1.6	1.3	0.16

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Table 4: Monthly statistics of modeled aerosol heights, based upon level 9 confidence fires (**L9**) and MERRA meteorological properties (T_A, v, U, dT/dz) at the corresponding geographic locations. Sensitivity tests are shown with their respective weighting factor (**1.2, 1.4, 1.6, 1.8, or 2.0**) applied to the measured FRP. The modeled heights are given by percentile from the bottom (5%) to the top (95%), while the mean and standard deviation are given as "**MEAN**" and "**STD**". Note that the model was not run on the following days, during which there were no observed **L9** fires: 17^{th}, 22^{nd}, 23^{rd}, 24^{th}, 25^{th}, 26^{th}, 27^{th}, 29^{th}, and 31^{st}.

	FRP(x1.0) [km]	**FRP(x1.2) [km]**	**FRP(x1.4) [km]**	**FRP(x1.6) [km]**	**FRP(x1.8) [km]**	**FRP(x2)[km]**
5%	**0.41**	0.44	0.48	0.53	0.56	0.60
10%	**0.60**	0.67	0.73	0.80	0.85	0.91
15%	**0.75**	0.83	0.91	0.98	1.05	1.12
30%	**1.14**	1.28	1.40	1.52	1.63	1.74
50%	**1.85**	2.07	2.27	2.47	2.65	2.82
70%	**2.87**	3.23	3.54	3.84	4.12	4.38
85%	**4.21**	4.66	5.11	5.53	5.87	6.22
90%	**4.99**	5.54	6.08	6.58	6.97	7.41
95%	**6.10**	6.79	7.43	7.76	8.16	8.61
Mean	**2.41**	2.69	2.96	3.21	3.44	3.67
StD	**1.98**	2.21	2.42	2.62	2.81	2.99

Figure 1: Map of Maritime Continent. The smoke plume impacts the sub-region contained within the dashed lines, or the so-called **fire-constrained** region. On the other hand, the region outside of the dashed lines is the so-called **non fire-constrained** region. The plot is based on a variance maximization technique applied to the measurements from all MISR overpasses from 2000 through 2014 (*Cohen*, 2014). Note that in this part of the world 1 degree of latitude or longitude is approximately 100km, leading to a fire-impacted region over 2500km across.

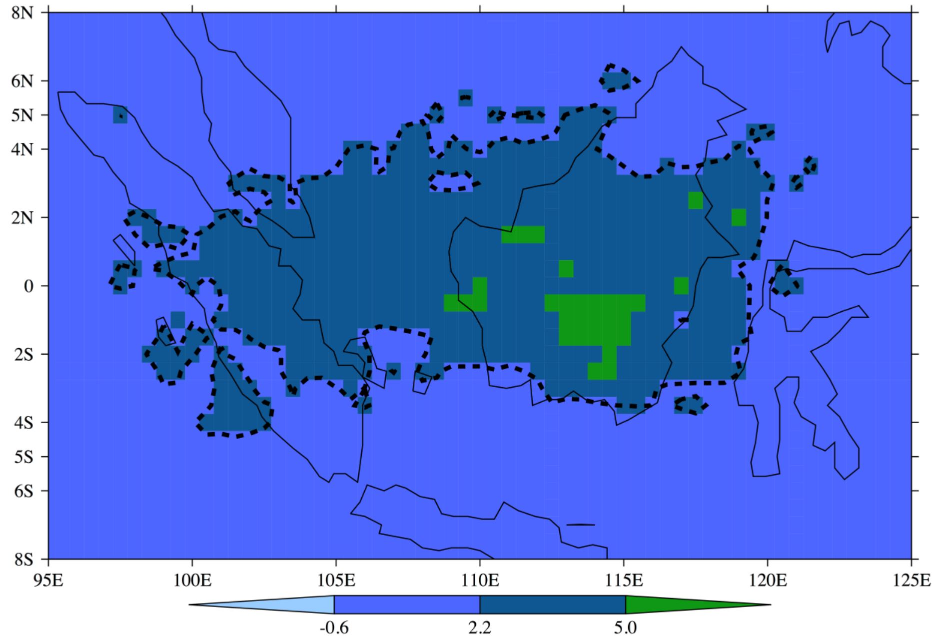

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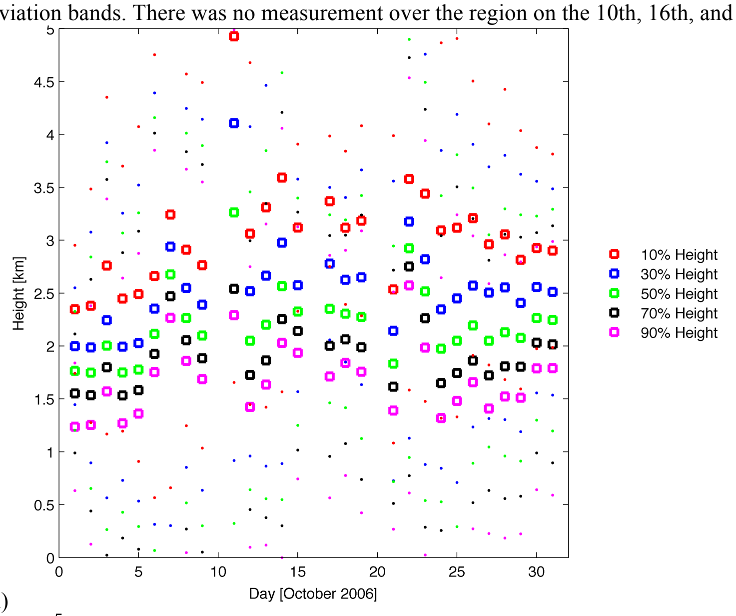
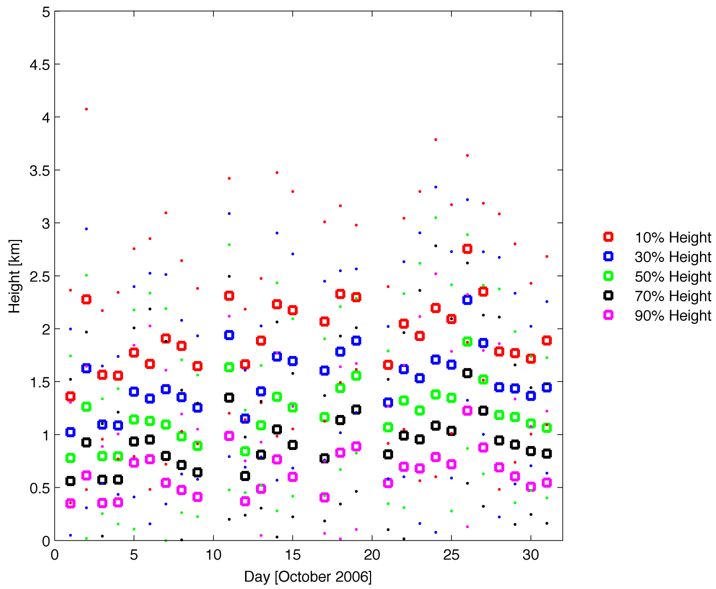
Figure 2a,2b: Time series of measured CALIPSO extinction heights over the fire constrained (A) and non fire-constrained (B) regions as given **Figure 1**. For both plots, the dots correspond to the height of the column integrated backscatter at: 10% [red] (top), 30% [dark blue], 50% [yellow], 70% [black], and 90% [light blue] (bottom). The circles are computed daily means, while dots are the computed daily standard deviation bands. There was no measurement over the region on the 10th, 16th, and 20th.



(A)



(B)

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Figure 3: Time series of daily averaged measured AOD over the fire-constrained regions of the Maritime Continent [blue], and the non fire-constrained regions of the Maritime Continent [red], as given in **Figure 1**. Circles are computed daily mean values, while dots are computed daily standard deviation bands.

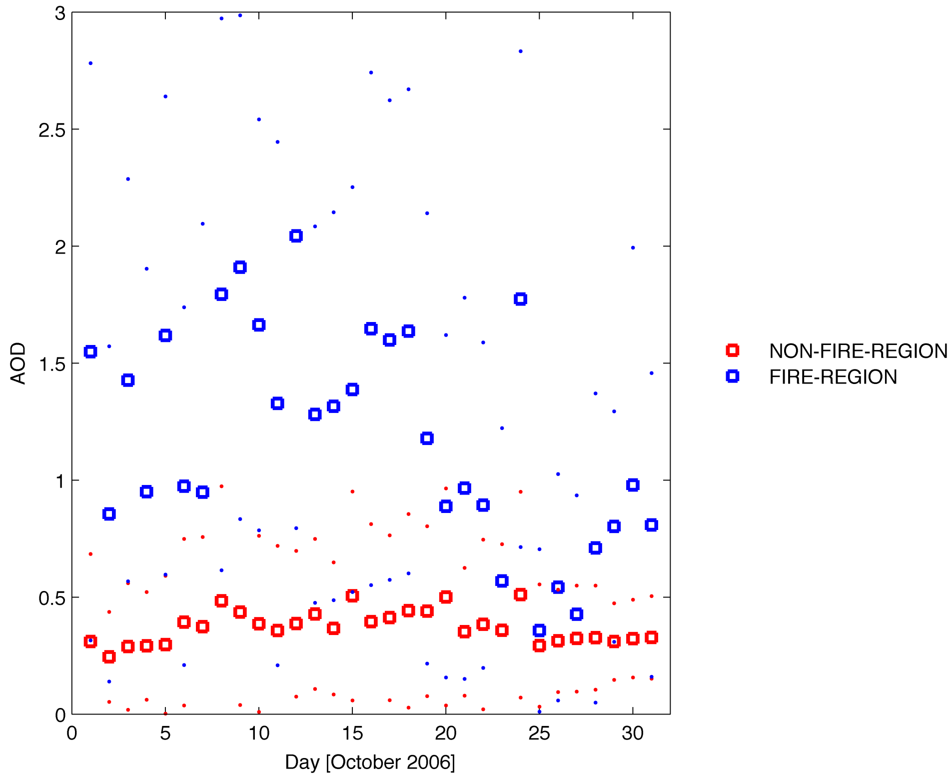

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Figure 4: Time series of PDFs (20% and 80% values are stars and mean values are given by lines) of the measured extinction heights for middle-upper (blue), median (red), and middle-lower (green) levels. The best fitting modeled heights are given as 0% FRP enhancement (solid black line) (best fit for middle-upper measurements), 20% FRP enhancement (dashed black line) (best fit for median measurements), and 100% FRP enhancement (dotted black line) (best fit for the middle-lower measurements).