A Photometric and $PM_{2.5}$ Study of Biomass Burning Aerosols Over Singapore During the 2015 Smoke Event

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ABSTRACT: Singapore is periodically affected by emissions of regional biomass burning fires during the southwest monsoon (June to September) such as in 2015, when burning in Sumatra was amplified by a strong El Nino event. In this study, we focus on the period of July to October 2015 to investigate the impact of the 2015 biomass burning smoke episode on Singapore's aerosol environment using ground level photometric and pollutant concentration measurements. During the study period, unhealthy to hazardous levels of $PM_{2.5}$ concentrations were measured and reported from August to October. The AERONET station in Singapore also showed elevated values of aerosol optical depth (AOD). We analysed time series of $PM_{2.5}$ and AERONET products including level 1.5 total and fine mode AOD, total and fine mode Ångström exponent (AE) at 500 nm and fine mode fraction (FMF) from July to October 2015 to examine the evolution of physical and optical characteristics of aerosols. We observed an increase in the mean total and fine mode AOD from 0.6 and 0.3 in July and August to 1.8 and 1.6 in September and October respectively which coincided with the increase in $PM_{2.5}$ concentrations. A bimodal size distribution of aerosols was initially observed during July and August from the time series of total and fine mode AE and FMF. Subsequently, a shift towards a unimodal size distribution was detected corresponding to the arrival of biomass burning emissions in mid September. A comparison between fine mode AOD and $PM_{2.5}$ yielded a good coefficient of determination ($R^2 = 0.750$).

1. INTRODUCTION

Singapore is located at the southern tip of the Malay Peninsula and its climate is characterised by two distinct seasons: the wetter northeast monsoon from December to March and the drier southwest monsoon from June to September, with transitional periods in between. (Reid et al., 2013) Singapore is periodically affected by emissions of regional biomass burning fires during the southwest monsoon such as in 1997, 2006, 2010 and more recently in 2015. During 2015, a strong El Niño event (Wolter and Timlin, 1993; Kousky and Higgins, 2007) led to drier and hotter conditions which amplified biomass burning activity. A high number of hotspots (forest fires) were detected by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra and Aqua satellites from July to October in Sumatra and Borneo (Figure 1). The seasonal south-westerly winds, prevailing during the southwest monsoon, transported the resulting smoke from its source at the Sumatra region (Indonesia) towards the neighbouring countries in the South-East Asia (SEA) region. This biomass burning smoke episode heavily affected the air quality in the region especially Singapore, Malaysia and Thailand. Singapore's National Environment Agency (NEA) measured and reported unhealthy to hazardous levels of particulate matter concentrations ($PM_{2.5}$) from August to October.

Given the vast geographical size of the SEA region, satellite based remote sensing is well suited to monitor the development of such events as it offers the advantage of large spatial coverage. However, the endemic cloud cover occurring across the SEA region (Reid et al., 2013) severely restricts the amount of cloud free days available for useful remote observations.

Moreover, the temporal availability of daily passes over the region is limited for satellites with sun-synchronous orbits. For example NASA's Terra and Aqua satellites each have two passes over the region daily. Under these circumstances, in-situ or ground measurements are a good and complementary alternative that can be used to characterise the local aerosol environment as they offer a much better temporal resolution. In this study we analysed the temporal evolution of several parameters derived from Sun photometer data, namely aerosol optical depth (AOD), Ångström exponent (AE) and fine mode fraction (FMF) as well as $PM_{2.5}$ data. From this we characterised the aerosol environment in Singapore before and during the biomass burning event from July to October 2015 with a focus on aerosol concentration and distribution.

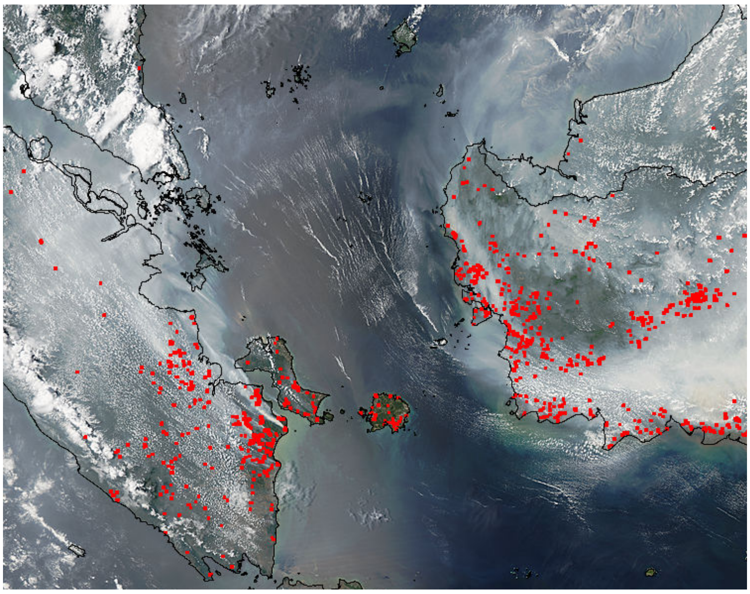


Figure 1: Aqua MODIS picture of 22 September 2015 showing smoke plumes and hotspots (red) in Sumatra and Borneo.

2. METHODOLOGY AND DATA PROCESSING

As part of the AErosol RObotic NETwork (AERONET) (Holben et al., 1998) network, a CIMEL (CE-318 Version T) sun photometer is operated by the Centre for Remote Imaging, Sensing and Processing at the National University of Singapore (1.298° N, 103.780° E). The photometer measures the aerosol optical depth (AOD) by averaging over three direct solar measurements taken within 90 seconds at different wavelengths. AOD products are computed at three different data quality levels: Level 1.0 products consists of raw data that are unscreened. Automatic cloud screening, based on the variability within the triplet measurement, is applied to the raw data to obtain the level 1.5 product. Lastly, level 2.0 products represent data that are cloud screened and quality assured by applying a list of quality control checks. The AOD products are then processed using the Spectral De-convolution Algorithm (SDA) by (O'Neill et al., 2003). The algorithm's key outputs include total, fine mode and coarse mode AOD (τ_a, τ_f and τ_c), fine mode fraction (FMF, $\eta = \frac{\tau_f}{\tau_a}$) and total and fine mode Ångström exponent (AE) which are all computed at a reference wavelength of 500 nm. Aerosol mass concentrations in Singapore are measured by the National Environment Agency (NEA). These mass concentrations are reported as $PM_{2.5}$ dry mass concentrations (particulate matter with an aerodynamic diameter of less than 2.5 µm) and are collected hourly at a number of stations around the island. The data is then collated into five regions: north, east, south, west and central.

Our study period is from 1st of July to 31st of October 2015, during which a biomass burning smoke episode affected Singapore and the SEA region. We chose this study period to highlight both the aerosol environment before and after the arrival of transboundary biomass burning smoke and to make a comparison between the two periods. In this study, we used AERONET version 2.0 level 1.5 cloud screened SDA products including total and fine mode AOD, fine mode fraction and total and fine mode AE data. There exists some possible problems with level 1.5 SDA products such as potential cloud contamination as the cloud screening is not as stringent as level 2.0 products. However, level 2.0 AERONET data was not yet available for our study period. Furthermore, level 1.5 products may exclude useful smoke data as cloud, especially under high particle concentration situations. For ground level particulate matter concentration ($PM_{2.5}$) we used the hourly $PM_{2.5}$ data published on the website of NEA[1]. We used only the $PM_{2.5}$ data from the west region as the AERONET site falls within this region. This was done to minimise the distance between the $PM_{2.5}$ measurement station and AERONET site so as to reduce uncertainty due to geographical differences. Daily averaged $PM_{2.5}$ data were obtained by averaging hourly data between the hours of 08:00 to 18:00 which coincides with the daily operation of the CIMEL sun photometer. These daily averages of $PM_{2.5}$, together with total and fine mode AOD, total and fine mode AE and FMF were used in time series analysis of the study period.

[1] http://www.nea.gov.sg/anti-pollution-radiation-protection/air-pollution-control/psi/1-hr-pm2-5-readings

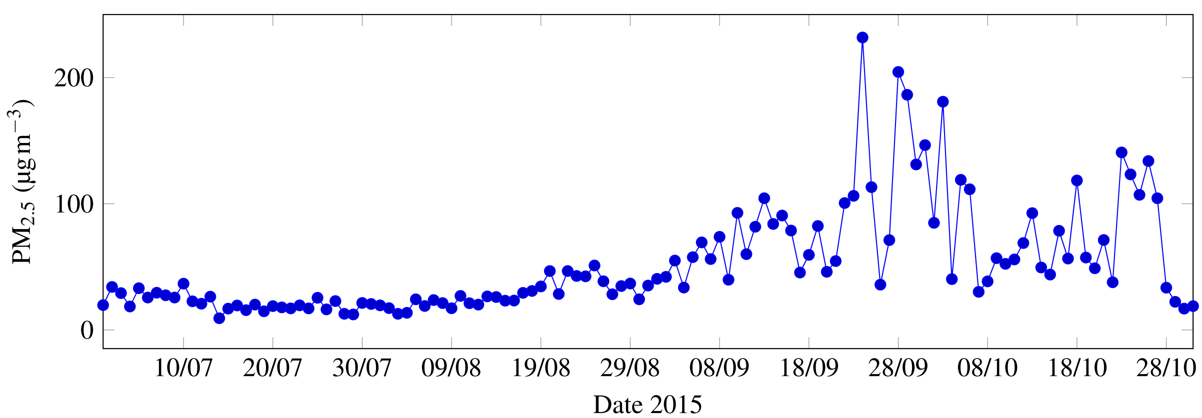
3. RESULTS AND DISCUSSION

We show the time series of $PM_{2.5}$ and AOD in figure 2. The first two months of our study period had a rather low aerosol load with $PM_{2.5}$ mostly below 50 $\mu g\,m^{-3}$ and a mean AOD of 0.61 which is slightly higher than the typical values for Singapore of $0.2 < \tau_a < 0.4$. (Salinas et al., 2009) There were several occasions where total AOD spiked during July and early August, notably on 1, 4, 10, 20 July, 3-4, 9, 24 and 26 August. Those events are reflected neither in the fine mode AOD nor in the $PM_{2.5}$ and all have low values of AE (Table 1). The slightly elevated mean AOD during these events thus appear to be due to cloud contaminations.

Table 1: Dates with cloud contamination.

Date	AOD	FMF	AE	Date	AOD	FMF	AE
04/07	2.84	0.16	0.17	24/08	2.90	0.34	0.47
10/07	3.51	0.09	0.05	26/08	2.64	0.39	0.53
20/07	1.15	0.15	0.21	17/09	3.22	0.36	0.41
03/08	4.93	0.05	-0.05	20/09	1.04	0.76	0.71
04/08	1.77	0.15	0.18	28/09	5.70	0.98	0.76
09/08	3.39	0.11	0.08				

$PM_{2.5}$ west Jul-Oct 2015



SDA AOD from level 1.5 AOD Jul-Oct 2015

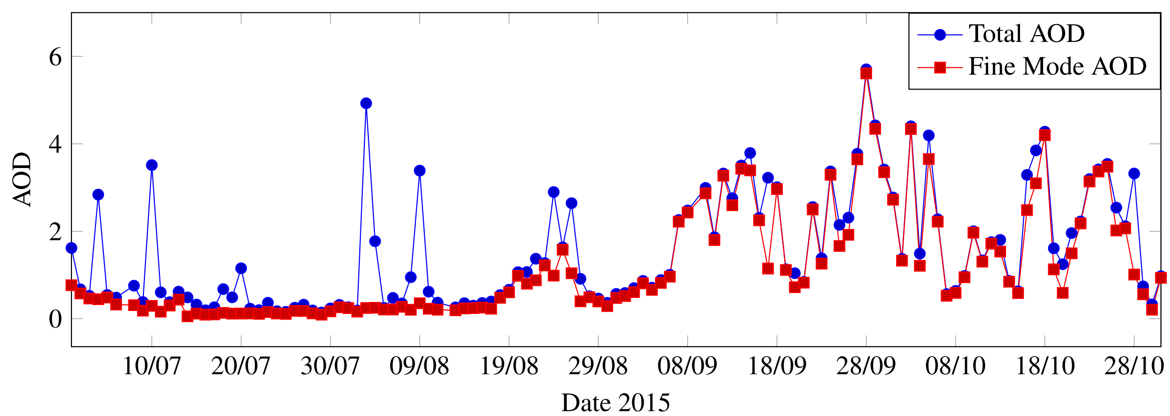


Figure 2: Time series of daily averages of $PM_{2.5}$ in Singapore from July to October 2015 (top). Time series of daily averages of total and fine mode aerosol optical depth in Singapore from July to October 2015 (bottom).

Both AOD and $PM_{2.5}$ concentration rose during the second half of August and remained high until the end of October. Three distinct phases of high aerosol concentrations were observed from 7 to 18 September, from 24 September to 6 October and from 16 to 25 October. Maximum values of 231 $\mu g\,m^{-3}$ and 5.7 respectively were reached for daily averages of $PM_{2.5}$ and total AOD on 28 September. The peaks occurring on 17 September, 20 and 28 October manifest a gap between the values of total and fine mode AOD, as well as a rather low fine mode fraction as shown on the fine mode fraction time series (Figure 3), indicating that these peaks are due to clouds rather than smoke.

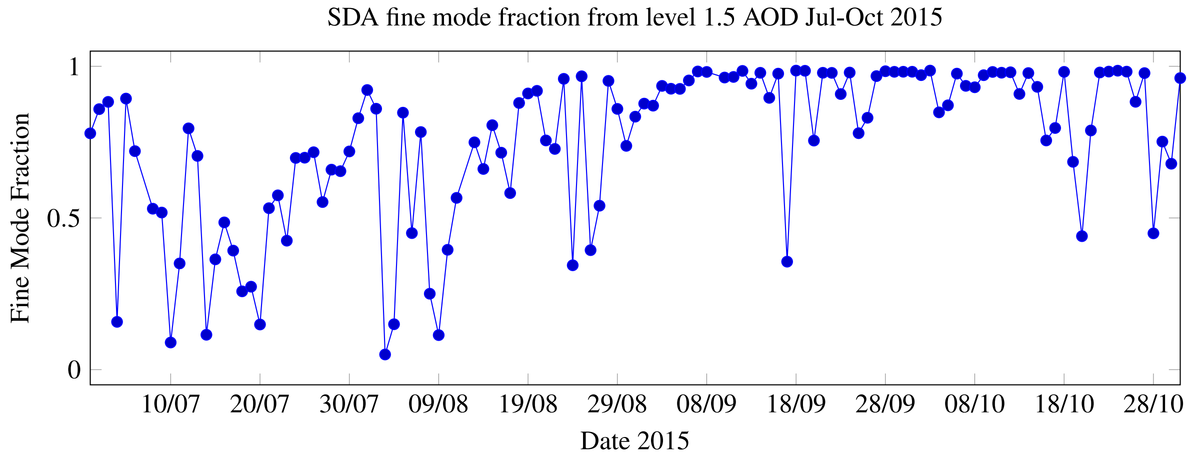


Figure 3: Time series of daily averages of the fine mode fraction in Singapore from July to October 2015.

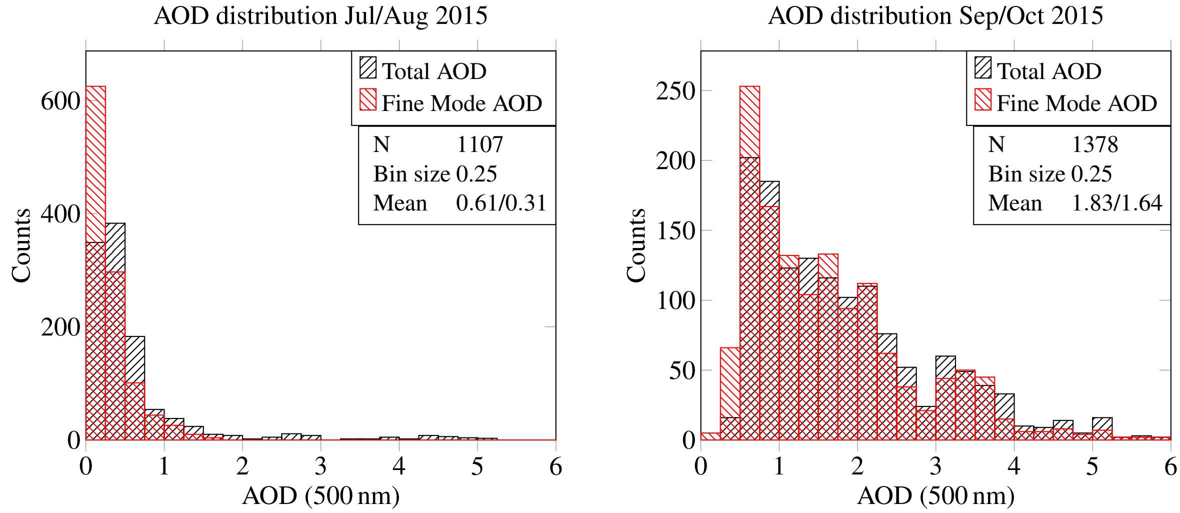


Figure 4: Distribution histogram of the aerosol optical depth during July and August 2015 (left) and during September and October 2015 (right).

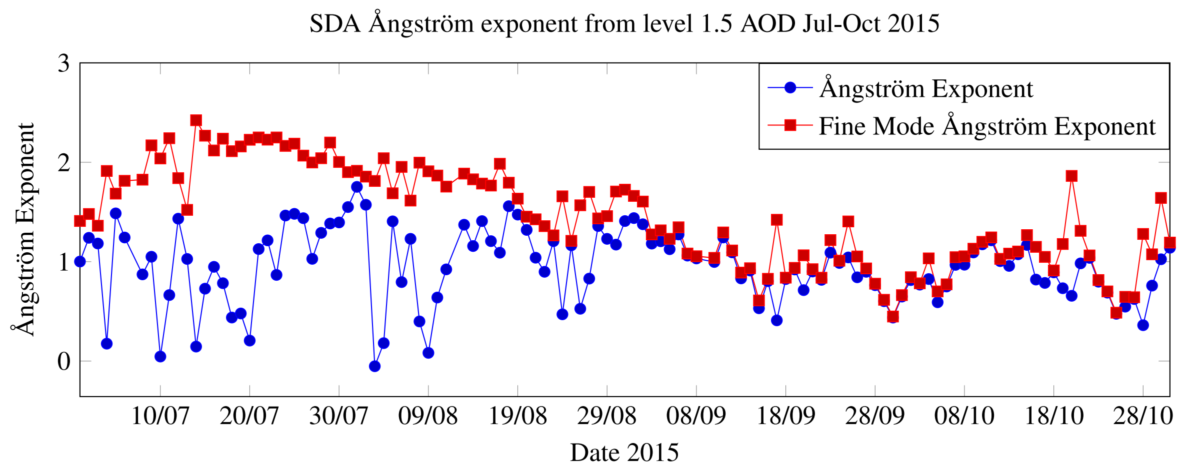


Figure 5: Time series of daily averages of total and fine mode Ångström exponent in Singapore from July to October 2015.

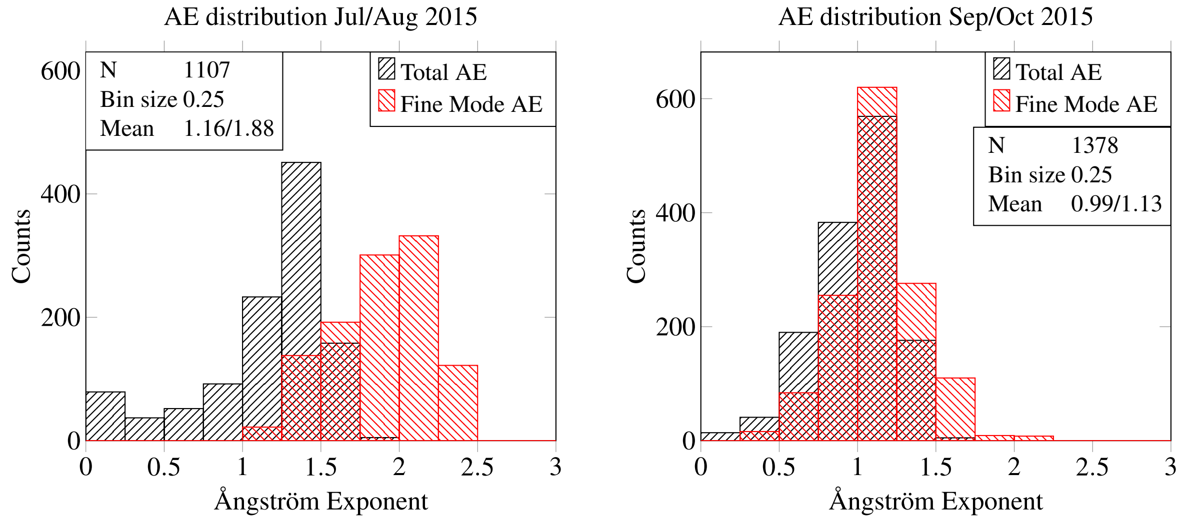


Figure 6: Distribution histogram of the Ångström exponent during July and August 2015 (left) and during September and October 2015 (right).

Figure 4 shows the distribution histograms for AOD. Overall there is a significant increase in the total aerosol concentration in Singapore from July/August to September/October. The mean total AOD and mean fine mode AOD increased from 0.61 and 0.31 to 1.82 and 1.64 respectively. The value of fine mode fraction in the months of September and October is consistently close to unity (Figure 3), showing that the aerosol present is mostly made up of fine mode particles.

We show the total and fine mode Ångström exponent time series from July to October 2015 in figure 5. The particle size of aerosols is commonly described using the Ångström exponent number, which is inversely proportional to the aerosols' size. The value of the total AE only slightly decreased from the first to the second half (from an average of 1.16 to 0.99), whereas the fine mode AE decreased more significantly (from 1.88 to 1.13). We speculate that this decrease in fine mode AE might be caused by aged long range transported aerosol that has gone trough particulate growth due to humidity and mixing with local sources.

Throughout the months of July and August, we observe a bimodal distribution of aerosol particle size as the peaks for total AE and fine mode AE are clearly distinct in the distribution histogram of AE (Figure 6, left), demonstrating the contribution from both coarse and fine mode aerosols to the total AE. For the months of September and October how-

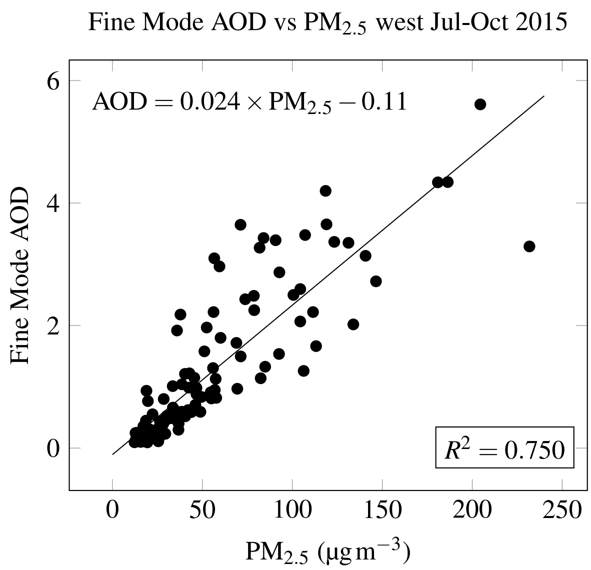


Figure 7: Scatter plot of fine mode aerosol optical depth versus $PM_{2.5}$ for the months of July to October 2015 in Singapore.

ever, after the arrival of the transboundary biomass burning aerosols, the total and fine mode AE peaks mostly overlap (Figure 6, right). This indicates that the aerosol environment transitions into a unimodal particle size distribution and in this case is largely dominated by fine mode particles. The fine mode fraction time series (Figure 3) shows a similar picture: It fluctuates a lot during July and August, but less so during the later months, when it is mostly stable around 1, confirming the dominance of fine mode particles.

As AOD was used as a proxy for $PM_{2.5}$ concentrations in this study, we assessed its validity by comparing the fine mode AOD and $PM_{2.5}$, shown as a scatter plot in figure 7. We obtained a coefficient of determination of $R^2 = 0.750$ as well as a p-value of $p = 5.32 \times 10^{-37}$ indicating a good linear correlation. Other factors could affect this correlation such as the planetary boundary layer height as AOD measures the aerosol concentration in an air column while the $PM_{2.5}$ concentration was measured at ground level. Another factor is hygroscopic growth of the aerosol particles which affects the AOD values but is usually not reflected in the $PM_{2.5}$ dry mass.

4. SUMMARY

In this study, we investigated the period of July to October 2015 in regard to an episode of transboundary biomass burning particles in Singapore. By using AERONET and $PM_{2.5}$ we found:

- Both the AOD and the $PM_{2.5}$ increased from rather low values in July and August to higher values in September and October, indicating an influx of aerosols.
- Over this time period, the Ångström exponent shifted from a bimodal distribution between coarse and fine mode aerosols to a unimodal distribution mostly consisting of fine mode aerosols. At the same time the fine mode fraction increased to mostly unity. These observations confirm that there was a change to an aerosol environment completely dominated by fine mode aerosols, most probably from biomass burning emissions, in the later months.
- The value of the fine mode Ångström exponent decreased during the smoke episode, indicating that the size of transported fine mode aerosols is somewhat larger than fine mode aerosols due to local emissions due possibly to aging, hygroscopic growth and mixing with local sources.
- There is a good correlation between fine mode AOD and $PM_{2.5}$, justifying the use of AOD as a proxy for particle concentration.
- Effects of boundary layer height and hygroscopic growth of particles on AOD should be examined further.

5. ACKNOWLEDGMENTS

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