Why was the sky red in Jambi during the forest fire?

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Abstract. Extreme biomass burning occurred in Jambi, Indonesia, in 2019 and coincided exacerbated with El Nino. Peak burning season was in September, with a total hotspot of 7034. Red sky has been reported on September 21 during the day. Sun photometer measurements in Jambi as one of the Aerosol Robotic Network (AERONET) stations in Indonesia from 1 to September 26, 2019, were used to investigate the red sky phenomenon. Assessment of aerosol optical properties and spectral variation analysis is conducted. The study reveals that the red sky occurred due to, firstly, very high aerosol loading with fine size particles were present. The aerosol optical depth (AOD) was 0.34 at 500 nm on a non-hazy day (early September) and increased sharply to 5.74 during a hazy day. A high level of fine-mode particle was indicated with Angstrom Exponent>1. Secondly, during September 23, only longer wavelengths of AOD were measured at 675, 870, 1020, and 1640 nm, while AOD in shorter wavelengths cannot be retrieved. Highest AOD on September 23 was 6.19 at 675 nm, which is associated with the red sky in the previous day. Thirdly, SSA was near 1, indicating purely aerosol scattering due to coagulated fine-mode particles due to high humidity.

1. Introduction

Electromagnetic radiation passing through the atmosphere may either be scattered or absorbed. This phenomenon is called light extinction. There are several causes of light extinction by the atmosphere, such as extinction by air molecules (nitrogen and oxygen), ozone absorption, and aerosols [1], [2]. The question of why the sky is blue has been asked by scientists more than centuries ago. During the daytime, we see the sky as blue. The question of why the sky is blue has been asked by scientists more than centuries ago. The incoming solar radiation hits small objects such as nitrogen and oxygen molecules and bounces off in all directions. The short wavelengths of blue light are scattered more efficiently by small objects than those of other colors. This form of light scattering is known as Rayleigh scattering. Rayleigh scattering causes the photon to change direction, while the scattering molecule is unaffected [1].

Scattering and absorbing of incoming solar radiation by aerosols influence the Earth's radiation budget. Aerosol scattering reduces the amount of incoming radiation reaching the Earth's surface and hence constitutes cooling. On the other hand, aerosol warming the atmosphere by absorbing the incoming solar radiation [1], [3], [4]. Aerosol scattering is known as Mie Scattering. Mie scattering depends on the wavelength and the particle properties. The particle properties' ability to absorb and scatter light depends on the type of particle and its size.
on particle size, shape, chemical composition, and mixing state [1]. As described elsewhere, smoke particles from biomass burning are much larger than gas molecules. They are effectively removing blue light from view and causing red light to appear more prominent.

Recurrent forest and land fires in Jambi and its surrounding areas released smoke containing large amounts of aerosols. The fires in the dry season of 2019 coincided with extreme El Nino, bring enormous consequences to the environment and societies. The reddish sky appeared pronouncedly during the day on September 21st due to very thick smoke emission. This paper attempts to understand the reddish sky phenomenon by investigating the spectral variation of aerosol optical depth (AOD) during fires in Jambi using the Sun Photometer as part of the Aerosol Robotic Network (AERONET) [5]. AOD in each wavelength, Angstrom Exponent (AE/α), and Single Scattering Albedo, among others retrieved from the Sun Photometer, were examined. Determination of microphysical properties and study on aerosol spectral dependence is essential to understand aerosols' radiative effect on the atmosphere and surface, apart from their health impact.

2. Data and methods

AERONET is a federated instrument network and data archive for aerosol characterization. This network provides real-time aerosol remote sensing measurement using a ground-based Sun Photometer instrument [5], [6]. This network is globally distributed worldwide, with more than 550 sun radiometers deployed, including in Jambi, Sumatera, Indonesia (figure 1). Sun Photometer of the AERONET provides retrievals from direct sun measurements of aerosol and water abundance in the total column atmosphere [5]. The Sun scanning measurements take ~8 seconds to scan eight spectral bands (340, 380, 440, 500, 675, 870, 1020, and 1640 nm). The instrument makes triplet measurements in each wavelength [7], [8].

![Figure 1. Sun Photometer installed on the roof of the Sultan Thaha Meteorological Station which is located inside Jambi airport with latitude 1.633 and longitude 103.65.](image)

The AOD is the primary product of the measurement and obtained from direct-beam irradiance, which reaches the instrument at the surface [9], [10]. AOD represents the vertically integrated extinction of radiation by aerosol from the instrument on the ground to the top of the atmospheric column [11]. To study the red sky phenomenon, we analyzed all eight spectral bands of AOD. The second important parameter retrieved from the instrument is Angstrom Exponent (α), representing the slope of AOD wavelength dependence. Angstrom exponent is helpful to determine dominant aerosol particle size and is calculated in the wavelength range from 440 to 870 nm. Another parameter that is useful to understand aerosol light extinction in association with the red sky phenomenon is Single Scattering Albedo (SSA). SSA is one of the AERONET inversion products and is derived using spectral deconvolution algorithm (SDA) following the methodology of [12]. SSA is the ratio of scattering to extinction (\(\tau_{\text{ext}} = \tau_{\text{scat}} + \tau_{\text{abs}}\)). It indicates the probability that an aerosol particle will scatter a photon, so that SSA = \(\tau_{\text{scat}}/\tau_{\text{ext}}\), where
retrieved scattering aerosol optical depth is defined as $\tau_{\text{scat}}$, and $\tau_{\text{ext}}$ is the measured aerosol optical depth [7].

AERONET has three different levels of data. Level 1.0 is raw data and cloud contaminated; level 1.5 is cloud-screened near-real-time data product, and automatic instrument anomaly quality controls; level 2.0 is a quality assured data product, which pre and post-deployment calibration applied [8], [13]. In this study, we use version 3 of Level 2 AERONET data. However, only level 1.5 data is available for SSA. This study also employed hotspot data derived from Terra and Aqua aboard the MODIS satellite. We analyzed the aerosol properties during September 2019, which was concurrent with the reddish sky in Jambi, and compared them with the same reddish sky event in California in September 2020.

3. Results and Discussion

3.1 Fires in Jambi

Forest and land fires in Sumatera are recurrent every year during the dry season. These fires become severe whenever they coincided with El Nino events such as in 2015 and 2019. El Nino will induce an extremely dry climate, thus quickly igniting a fire in drained peatland and escalate to more significant areas. According to the Indonesia Ministry of Environment and Forestry, some parts of Sumatera, such as Jambi, Riau, South, and North Sumatera own more than 6 million ha peatland areas and are subject to burn every year. Figure 2 depicts the satellite image with hotspots observed around Sumatera. During 2019, the burning season in Jambi started in August, indicated by the hotspots number observed through satellite and peaked in September with 7034 hotspots recorded from MODIS Aqua-Terra. Red sky appearance was reported to be seen in Jambi on 21 September 2019 within the period of severe smoke fires (figure 3a), while California also experiences a similar phenomenon reported on 9 to 10 September 2020 (figure 3b).

![Figure 2. Hotspots satellite image observed from MODIS Aqua and Terra around Sumatera on September 21, 2019. AERONET site location is in the middle of forest fire spots.](image-url)
Figure 3. Red sky was seen in Jambi, Indonesia in 21 September 2019 during daylight (a) and California, western United States of America in 9 September 2020 (b). Photo credit: www.kompas.com and https://www.theweek.in

3.2 AOD wavelength dependence

To investigate the reddish sky, we analysed AOD in eight wavelengths as demonstrated in figure 4. The total number of measurements during September 2019 were 281 within 25 days. As presented in figure 4(a), daily averages of AOD (500 nm) ranged from 0.34 in early September to 5.74 on September 22nd, 2019. This number is very high, indicating aerosol pollution in the atmosphere, though slightly lower than the fire period in October 2015 which was 6.46 [8], [14]. An interesting feature to explain the red sky phenomenon is captured from the missing AOD in shorter wavelengths, particularly during the peak days of fires that started from 20 to September 26. During September 23, only longer wavelengths of AOD were measured and retained at 675, 870, 1020, and 1640 nm; while AOD in shorter wavelengths cannot be retrieved. The shorter wavelength is completely attenuated, and only the longer wavelength passed through the atmosphere (λ>675 nm, red electromagnetic light) with the highest AOD (675 nm) was 6.19. This explained the red sky occurrence in the previous day.

Similar characteristics were also shown during California's extensive fires in September 2020. The red sky was reported on 9 September when the AOD peaked from 8 to 11 September. During extremely hazy days, AOD in shorter wavelength cannot be retrieved from the Sun Photometer AERONET installed in Monterey airport, California. AERONET site in Monterey has the most recent and complete data than other sites in California; however, only level 1.5 data is available for our study period. Remarkable distinct aerosol characteristic is shown by figure 4 between Jambi (a) and California (b). Large spectral variability of AOD is reflected at Jambi, with shorter wavelengths having larger AOD, indicating a characteristic of fine mode aerosol. Meanwhile, little spectral variability of AOD at Monterey as the characteristic of dust and mixed state of aerosol resulting from semi-arid burning regions in the western US [13], [15].

Figure 5 depicts the comparison of AOD (500 nm) and α (440 and 870 nm) in two different places, and different timeframe coincided with the red sky phenomenon. AE or α is a useful parameter to inform aerosol particle size responsible for reducing the radiation [11]. AE value >1 indicates fine-mode (submicron) aerosols are dominant, while AE<1 is for coarse-mode particles (diameter < 2.5 micron) [11], [16]. As clearly seen from the figure, α>1 with very high AOD were identified as a result of smoke fires emission in Jambi during the entire month of the burning season. The mass scattering efficiency is greatly dependent on wavelength and particle size. Particles with a diameter near the light's wavelength will be scattered effectively, and the most efficient size range for scattering is 0.1 to 1.0 µm [17]. It is also clear from the figure that AOD in shorter wavelength (500 nm) cannot be retrieved on 23 to 25 September 2019, two days from the red sky occurrence on 21 September 2019. At the Monterey site, mixed aerosols with smaller sizes indicated from α>1 were present several days before and after the red
sky was acknowledged on 9 to 10 September 2020. Unlike in Jambi, AOD in a larger size (coarse-mode particle) indicated with $\alpha<1$ was dominant after the red sky-event following AOD values' decreasing.

![Figure 4. AOD level 2 measured in different wavelengths during September 2019 in Jambi, Sumatera, Indonesia (a) and AOD level 1.5 during September 2020 in Monterey, California, The United States of America (USA) (b). The black circle indicates the period of red sky.](image)

![Figure 5. Comparison of level 2 AOD (500 nm) and Angstrom Exponent (440 and 870 nm) during smoke fires period at Jambi site September 2019 and Monterey site September 2020.](image)

3.3 Single Scattering Albedo
Single Scattering Albedo (SSA) is a powerful parameter to explain the red sky phenomenon and study radiative effects of aerosol. A single scattering albedo of 1 indicates purely aerosol scattering of the incident light, and a value near zero indicates purely aerosol absorption [7]. SSA is also associated with chemical composition and morphology [18]. In this study, unfortunately, there were no available SSA retrievals on the exact date that coincided with red sky day. The closest retrieval date to red sky day was on 4 September 2019, with only one retrieval of level 1.5 SSA. We then compared Jambi with aerosols SSA in California on 4 September 2020, as depicted in figure 6. Both periods were within smoke fires though it was not the peak of fires event; however, only a few days before the red sky was seen.

![Figure 6](image)

**Figure 6.** The spectral variation of aerosol single scattering albedo computed from Level 1.5 for Jambi (4 September 2019) and California (4 September 2020). SSA nearly 1 is an indication of homogenous aerosols scattering.

Figure 6 shows the wavelength dependence of the SSA from 440 nm to 1020 nm as measured at Jambi and Monterey sites during smoke fires period in different years. The SSA value at Jambi shows very little or no wavelength dependence in this spectral range. This may be due to the coagulation of fine-mode particles in high relative humidity (RH), causing larger particle sizes of aged smoke, which enhances scattering over absorption [18]. This finding is similar to an aerosol characteristics found during peatland fire in Palangkaraya, Kalimantan [8] [19], and Singapore [18]. Also, aerosols are hygroscopic thus easily take up water depending on the ambient RH and changing size as well as chemical composition [20]. Higher RH will increase the scattering enhancement factor of aerosol. The daily average of RH from the observation at two locations in Jambi (Climatological and Meteorological Stations) shows an increased and high RH of 80.1% and 88.5% consecutively on 23 and 24 September 2019. This likely contributed to the increase scattering properties of aerosol and caused red sky.

SSA in Jambi exhibits very high, nearly 1 indicating the dominant of aerosol scattering. According to Eck et al. (2019) [8] and Lewis et al. (2008) [21], peat fuel burns underground and in a smoldering phase combustion. This type of burning produces very little black carbon, which is the solid absorbing component of biomass burning smoke in the visible and near-infrared wavelengths. Further study by Chand et al. (2005) [22], aerosols SSA from burning of Indonesia peat in the laboratory was 0.99 at 540 nm. Very high SSA nearly one at Jambi likely due to high sulfur content or sulfate aerosol and carbonaceous aerosol, which is scattering aerosols. SSA > 0.95 will contribute to negative climate forcing, thus cooling the atmosphere [11]. Further by Ikekami et al. (2000) [23], sulfur dioxide and sulfate levels were very high found in the smoke from biomass burning in Kalimantan during prominent peat burning 1997. Therefore, aerosol scattering was more dominant during the September fire period at Jambi, thus contributing to the occurrence of the red sky on the following days. Unlike at Jambi, SSA shows a variation of wavelengths dependence at Monterey. SSA also shows high value though it was
not as high as Jambi. This could be due to the mixing state of aerosol and influence by combustion phase and vegetation type.

4. Conclusions

This study investigates the cause of reddish sky during severe smoke fires event in Jambi September 2019 by analyzing the AOD wavelength dependence and other associated parameters such as α and SSA. We also compared aerosol characteristics in Jambi with Monterey, California, during the same red sky event. The study found that the red sky occurrence in Jambi is explained from the following:

1. Very high AOD (500 nm) with the domination of fine-mode particle (indicated from α>1) ranged from 0.34 to 5.74 during the peak of fires and a day before the red sky.
2. Only longer wavelengths of AOD were recorded and retained at 675, 870, 1020, and 1640 nm, while AOD in shorter wavelengths cannot be retrieved due to complete attenuation.
3. Very high SSA near one which indicates purely or dominant of aerosol scattering with characteristics coagulated fine-mode particles or aged smoke due to high relative humidity.

5. References

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