Visibility deterioration and hygroscopic growth of biomass burning aerosols over a tropical coastal city: a case study over Singapore’s airport

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Abstract
Biomass burning in the Maritime Continent frequently results in region-wide haze pollution, causing concerns for aviation and maritime navigation. Indonesian peat smoke is high in sulfates and water soluble organic carbon, and we show that in Singapore, particle hygroscopic growth results in a strongly non-linear relationship between visibility and aerosol concentration under humid conditions. Thus, even for a tropical coastal city, the consideration of ambient relative humidity is desirable when forecasting for visibility deterioration caused by haze aerosols.

Keywords: Indonesia biomass burning; aerosol hygroscopic growth; visibility forecast; Singapore aviation

1. Introduction
Over the past decades, seasonal biomass burning in Indonesia has resulted in recurrent episodes of haze pollution. Emissions from biomass burning in the Indonesian islands of Sumatra and Kalimantan have been frequently transported to Singapore and Malaysia (Koe et al., 2001; Atwood et al., 2013). In severe episodes, often occurring during strong El Niños such as in 1997 and 2015, the haze aerosols have been transported much further afield (Duncan et al., 2003; Murphy, 2006; van der Werf et al., 2006; Field et al., 2009; Wooster et al., 2012; Cohen, 2014). The biomass burning is of global concern due to its large-scale release of carbon stores into the global atmosphere (Page et al., 2002; van der Werf et al., 2008), but in haze-affected regions, local concerns primarily involve health (Kunii et al., 2002; Frankenberg et al., 2005) and reduction in visibility. This reduction is of particular concern to aviation and maritime navigation (e.g. Dancel, 2015; Today Online, 2015).

During severe episodes of biomass burning, particulate concentrations increase more than tenfold, e.g. PM$_{2.5}$ of 489 $\mu$g m$^{-3}$ from a typical background value of about 10 $\mu$g m$^{-3}$ during the peak of the 2013 episode. Pollutant concentration values fluctuate within a haze episode itself, and members of the lay public have anecdotally noted that the visibility they observed and the officially released figures of aerosol concentration do not match. The confusion arises from a misconception that visibility is solely a function of aerosol concentration, but this is not the case if aerosol particles experience strong hygroscopic growth. In such cases, visibility is also a function of humidity, since scattering extinction increases with the growth of particle size, to the extent determined by the composition of the aerosol.

Much of the seasonal haze is produced by the combustion of Indonesian peat, and about 60% of the PM$_{2.5}$ constituent mass consists of water soluble organic carbon, sulfates and nitrates (Nakajima et al., 1999; Narukawa et al., 1999; See et al., 2007). The relatively high concentration of ionic species is due to conversion from gaseous emissions as peat smoke ages, and the unusually high amount of sulfates from Indonesia peat combustion is believed to have volcanic origins (Christian et al., 2003; Dusek et al., 2005; Reid et al., 2013). Considering the high amount of sulfates and water soluble organic carbon in Indonesian peat smoke, relative humidity and resultant hygroscopic growth may play a role in the relationship between visibility and aerosol concentration (Reid et al., 2013; Chew et al., 2016). However, this is far from certain since the smoke has already been transported over a considerable distance through a maritime environment before it reaches coastal Singapore. Furthermore, being a tropical island located only one degree from the equator, Singapore generally experiences high humidity. For these two reasons, local variability in relative humidity may not have any relationship with aerosol size, aerosol scattering and the visibility.

Therefore, an objective study is needed to quantify the visibility deterioration brought about by hygroscopic growth of aerosols. This case study compares local visibility and PM$_{2.5}$ aerosol concentration during the haze episodes of 2013, 2014 and 2015. The study focuses on PM$_{2.5}$ because light-scattering in the visible spectrum is primarily due to particulate matter of this size.

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2. Data and methodology

Visibility or visual range have been used interchangeably as the distance at which it is just possible to distinguish a black object from the horizon (Seinfeld and Pandis, 2006), or simply the contrast of the object relative to the horizon. Koschmieder (1924) had shown that contrast \( C \) is decreased exponentially with distance \( x \) from the object due to atmospheric particle extinction \( b \) as follow:

\[
C(x) = \exp(-bx)
\]

Typical observers can detect objects on the horizon with the minimum visual contrast of 0.02 to 0.05 (Waggoner and Charlson, 1977), and thus the corresponding distance is termed ‘visibility’ \( V \).

For this study, visibility was measured at the Changi meteorological station using a Vaisala FD12P visibility meter, up to a meteorological optical range of 50km. The unit consists of an infrared light transmitter, receiver and controller. The intensity of forward scattered infrared light at 33° was measured by the receiver, and assumed to be proportional to particle extinction. By using the instrument contrast threshold of
0.05, the particle extinction \( (b) \) can be determined from Equation (1) following the Koschmeder’s equation:

\[
b = \ln (0.05) / V
\]  

PM2.5 was measured by a (Thermo Scientific FH, Franklin, MA, USA) 62 C14 series continuous ambient particulate monitor. The monitor samples ambient air through an inlet with a cutoff diameter of 2.5 μm and heats it above ambient temperature to remove condensation. Sampled aerosol particles were collected on a filter tape positioned between a Carbon-14 source and detector, and particle concentration measured with the beta attenuation method (Hinds, 1999). For quality control, the monitor was calibrated every month using calibration test kits. In addition, flow and filter loading checks of the monitor were carried out every day. The measurements were collected to hourly means, if at least 75% of the data were available, with values having unphysical drift rejected.

Hourly mean visibility and PM2.5 were analyzed for the haze episodes of 2013, 2014 and 2015. These episodes are the months of May to July in 2013, September to November in 2014, and August to October in 2015, when multiple hotspots and haze plumes were observed through satellite over the islands of Borneo and Sumatra. The haze episodes of 2013 and 2015 were severe, while that of 2014 was relatively mild. Data hours are grouped into bands of relative humidity. The details of data selection are described in Appendix A.

### 3. Results

Local relative humidity affects the deterioration of visibility with increasing PM2.5 concentration in all three haze episodes (Figure 1(a)–(c)). Despite the common perception that Singapore experiences uniformly high humidity as a coastal tropical city, in reality, the local relative humidity ranges from 40 to 100% (Figure 1(d)).

Assuming minimal change of composition and number density throughout the haze episodes, \( (b) \) was linearly fitted to the PM2.5 concentration \( P \) for different bands of relative humidity \( (b = a_1 P + a_0) \). The fitted coefficient \( a_1 \) increases from \( (3.78 \pm 0.07) \) m² kg⁻¹ for relative humidity of 40–60% (Figure 2(a)), to \( (5.67 \pm 0.06) \) m² kg⁻¹ for relative humidity of 80–85% (Figure 2(d)), to \( (9.7 \pm 0.2) \) m² kg⁻¹ for relative humidity of 90–95% (Figure 2(f)). This is an increase of 1.5-fold and 2.6-fold scattering at 80–85% and 90–95% relative humidity, respectively. Such values are quite consistent with the 1.65-fold increase at relative humidity 80% as measured at Kalimantan during the 1997 haze episode (Gras et al., 1999), indicating that errors brought about by the assumption of minimal composition and number density changes throughout haze episodes is still acceptable for the purpose of this analysis.

Assuming that PM2.5 is the dominant light-scattering aerosol in the atmosphere, the extinction coefficient \( b \) can be expressed as an adjustment.

\[
b = f (H) \ b_d
\]  

where \( b_d \) is the extinction coefficient of the dry aerosol (in m⁻¹), and \( f (H) \) is the aerosol hygroscopic growth function at relative humidity \( H \). The hygroscopic growth function is frequently written as

\[
f (H) = \left[ \frac{(100 - H)}{(100 - H_0)} \right]^{-g}
\]  

with \( H \) expressed as a percentage and \( H_0 \) the reference relative humidity of 30%. The empirical parameter \( g \) describes the increase of the extinction coefficient with relative humidity (Kasten, 1969), and range from zero for insoluble particles to almost unity for highly soluble particles. The above-described ratios of \( a_1 \), i.e. \( a_1 \) \((90\% < H \leq 95\%)\) to \( a_1 \) \((40\% < H \leq 60\%)\) were fitted to

\[
b (H) = b / b_d = A \left[ \frac{(100 - H)}{(100 - H_0)} \right]^{-B}
\]

This required the estimation of \( b \) at \( H = 30\% \) to that at \( 40\% < H \leq 60\% \), because relative humidity values below 40% were not measured during the time period. Due to this, and that the growth ratios were constructed from relative humidity bands, the least-squares fit included both uncertainties in \( x \) and \( y \), i.e. both humidity and growth function. The values of \( A = 0.75 \) and \( B = 0.51 \)
Figure 3. Triangles mark the locations of air quality monitoring stations in the vicinity of and including the Temasek Polytechnic air quality monitoring station. Small circles mark the locations of meteorological stations in the vicinity of Temasek Polytechnic where relative humidity measurements are available. Black and gray denote data quality of good and unusable, respectively. The large shaded circle has a radius of about 6 km, the distance between Temasek Polytechnic and Changi meteorological station.

were obtained. Note that an alternative method of performing the fit would be to let \( H_0 = 40\% \). However, we reject this method since the fitted \( f(H) \) would no longer have the physical meaning of being the growth from dry aerosol.

4. Conclusions

Seasonal biomass burning in Southeast Asia frequently results in region-wide haze pollution. Visibility reduction by haze aerosols is of particular concern to aviation and maritime navigation. As such, the forecast of visibility during haze episodes is desirable. However, there has been an anecdotal mismatch between observed visibility and the PM\(_{2.5}\) concentration in Singapore. This case study quantifies the reported mismatch for the first time, by comparing local visibility and aerosol concentration during the haze episodes of 2013, 2014 and 2015.

We show even for a coastal tropical city (Singapore), the consideration of particle hygroscopic growth is desirable for visibility forecast. Assuming minimal change of composition and number density throughout the haze episodes, there is a 2.6-fold increase in the coefficient of extinction at relative humidity levels of 90–95\%, while the ambient relative humidity varies between 40 and 100\%. The hygroscopic growth function was estimated as \( f(H) = 0.75 (100 – H) / (100 – H_0)^{-0.51} \), where \( H \) is the relative humidity and \( H_0 \) the baseline relative humidity of 30\%. The exponent of 0.51 is comparable to literature values for a sulfate environment (e.g. 0.63 in Hänel, 1976). The results of this analysis will be used to convert the concentration output of the Met Office’s Numerical Atmosphere-dispersion Modelling Environment (NAME) for Southeast Asia haze forecasts and for hindcast verification with aerosol optical depth products. The inclusion of the empirical hygroscopic growth function would also be useful for other researchers for converting between aerosol concentration measurements and remote sensing measurements, e.g. by lidar.

Finally, we note that the difference between observed and predicted extinction coefficient using simple linear regression is frequently large for high values of PM\(_{2.5}\). Unfortunately, such times are precisely when precision in forecast is needed, so further consideration of composition and number density would facilitate an increase in forecast precision.

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Appendix: Data Selection Details

Due to the air quality monitoring and meteorological stations not being co-located, the PM\(_{2.5}\) measurements recorded at Temasek Polytechnic air quality monitoring station (marked with triangles in Figure 3) are about 6 km away from the relative humidity and visibility measurements recorded at the Changi meteorological station (marked with a pentagon in Figure 3). Therefore, two robustness checks were performed.

Firstly, a comparison of the 2013 PM\(_{2.5}\) measurements at Temasek Polytechnic air quality monitoring station was made with measurements from the close-by Environment Building and Bishan air quality monitoring stations about 10 km away.

The PM\(_{2.5}\) at the Environment Building (\( P_{\text{EnvB}} \)) and Bishan (\( P_{\text{Bishan}} \)) air quality monitoring stations are strongly correlated with that at Temasek Polytechnic (\( P \)), with a Pearson’s correlation of 0.96 for both locations. Linear fits produce relationships of:

\[
P_{\text{EnvB}} = (1.083 \pm 0.003)P - (0.9 \pm 0.1) \text{ mg m}^{-3} \quad ((A.1))
\]
\[ P_{\text{Bishan}} = (0.875 \pm 0.002) P + (0.9 \pm 0.1) \mu g \text{ m}^{-3} \quad (A.2) \]

Therefore, hourly mean PM$_{2.5}$ at Temasek Polytechnic is representative of PM$_{2.5}$ at locations within the vicinity. Since the Changi meteorological station is located within this vicinity, the measurements at Temasek Polytechnic are very likely a good representative of the hourly mean PM$_{2.5}$ at Changi. In general, hourly PM$_{2.5}$ at most air quality monitoring stations over the island are quite coherent with one another and the summary values are available in the public domain.

Secondly, relative humidity at Changi was compared with that at four meteorological stations closest to Temasek Polytechnic air quality monitoring station, during the haze periods. Their locations are shown in Figure 3 as the stations within the shaded circle and the eastern-most station.

Relative humidity at the other two meteorological stations within the 6 km vicinity of Temasek polytechnic, $H_{\text{UAO}}$ and $H_{06}$, were well-correlated with that at Changi ($H$), with Pearson’s correlation of 0.92 and 0.83, respectively. Data quality at S06 was poor for the 2015 period with many unphysical values, but for 2013 and 2014 the Pearson’s correlation was 0.92. Due to data quality deterioration in 2015, Station 06 could not be used. The relative humidity at the remaining two stations, $H_{96}$ and $H_{107}$, had Pearson’s correlation of 0.84 and 0.78, respectively. Linear fits between relative humidity at the other stations and at Changi are as follows, with the Pearson’s correlation:

\[ H_{\text{UAO}} = (0.997 \pm 0.006) H - (3.6 \pm 0.5)\% \quad r = 0.92 \quad (A.3) \]

\[ H_{06} = (1.00 \pm 0.01) H - (3.0 \pm 0.7)\% \quad r = 0.83 \quad (r = 0.92 \text{ before 2015}) \quad (A.4) \]

\[ H_{96} = (0.550 \pm 0.004) H + (33.8 \pm 0.4)\% \quad r = 0.84 \quad (A.5) \]

\[ H_{107} = (0.635 \pm 0.006) H + (26.2 \pm 0.5)\% \quad r = 0.78 \quad (A.6) \]

Hourly mean relative humidity values at the Upper Air Observatory and S06 have a close to one–one relationship with relative humidity at Changi. These three stations likely differ from S96 and S107 stations due to the latter being located right at the coast whereas the former are at more internal locations of the island. Temasek polytechnic is more internal than coastal. Therefore, hourly mean relative humidity at Changi is very likely representative of that at Temasek Polytechnic.

Visibility is only measured at the Changi meteorological station. As water droplets in the air affect visibility, hours where rainfall was detected at Changi were differentiated from hours without rain. While it is also possible that there may be suspended water droplets in the form of mist after rain, only the distribution of visibility during the raining hours themselves was found to be strongly different from distributions of visibility at different lag times after rain. Thus, hours after rainfall were not differentiated from the rest of the data.

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