1 **El Niño driven haze over the Southern Malaysian Peninsula and Borneo**

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32 **Abstract**

33 The Southeast Asian (SEA) region, however, is no stranger to forest fires - the region has been
34 suffering from severe air pollution (known locally as 'haze') as a result of these fires, for decades. The
35 fires in SEA are caused by a combination of natural (the El Niño weather pattern) and manmade
36 (slash-and-burn and land clearing for plantations) factors. These fires cause the emissions of toxic
37 aerosols and pollutants that can affect millions of people in the region. Thus, this study aims to
38 identify the impact of the South East Asia haze on the Southern region of the Malaysian Peninsula and
39 Borneo region of East Malaysia using the entire air quality observation data at surface level in 2015.
40 Overall, the concentration of PM₁₀ was about two-fold higher during the haze period compared to non-
41 haze period. The concentrations of CO, flux of CO and flux of BC were aligned with PM₁₀ during the
42 entire observation period. The wind field and cluster of trajectory indicated that the southern
43 Malaysian Peninsula and Borneo were influenced mainly from the wildfires and the combustion of
44 peat soil in the Indonesian Borneo. This study finds that wildfires from Borneo impacted the Southern
45 Malaysian Borneo more seriously than that from Sumatra region.

46 **Keywords:** Aerosol; Trace gases; Haze; Wild Forest fires; Biomass burning; Peatland fires

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48 **Highlights**

- 49 • The yearly average of PM₁₀ exceeds all health guidelines during haze in 2015
- 50 • CO has been established well to reflect the intensity of the haze
- 51 • A covariation of BC flux with CO and PM₁₀ concentrations was observed during haze Southern
- 52 Malaysian Peninsula and Borneo were impacted from fires in Kalimantan

61 **1. Introduction**

62 Urban air pollution is a serious health issue globally due to excess or premature death burden (Brauer
63 *et al.*, 2016; Cohen *et al.*, 2017; WHO, 2016). According to the World Health Organisation (WHO),
64 nine out of ten people breathe polluted air throughout the world (WHO, 2018). About 7 million deaths
65 a year was potentially due to the exposure of ambient and household air pollution (WHO, 2018). It has
66 been established now that air pollution is a critical risk factor for non-communicable diseases (NCDs)
67 which leads to 24% of all adult deaths from heart-related diseases, 25% from stroke, 43% from chronic
68 obstructive pulmonary disease and 29% from lung cancer (WHO, 2018). A recent study also showed
69 that the exposure of air particles could cause dementia and other brain-related diseases to the people
70 staying near urban roadways and power plants (Underwood, 2017).

71 In South-East Asia, air pollution has been dangerously impacted on human health, visibility,
72 ecosystem and agricultural production (Kumar *et al.*, 2020; Kumar *et al.*, 2015). Haze is defined as the
73 increased load of atmospheric aerosol which causes visibility to reduce significantly. Visibility is
74 reduced by the absorption and scattering of light by both gases and particles in ambient air (Seinfeld
75 and Pandis, 2016). Haze is a regional air pollution issue. In Southeast Asia (SEA), haze occurs due to
76 the “slash and burn” activities to clear land for new plantations and to manage agricultural waste and
77 wild forest fires which form high amounts of aerosol or black smoke (Keywood *et al.*, 2003; Khan *et*
78 *al.*, 2016). This haze spreads over the entire SEA region and the visibility decreases due to the
79 absorption of sunlight in the black smoke. Haze also occurs due to the formation of photochemical
80 smog such as ozone, peroxyacetyl nitrate (PAN), etc. During conditions of high humidity with larger
81 relative humidity (RH%), the hygroscopic ionic composition in aerosols increase, for example sulfate,
82 nitrate, and water vapor which are potential light scattering species which lead to reduced visibility as
83 reported by Friedlander (2000). Haze or smoke is the potential cause of air pollution in South East

84 Asia. During the haze episodes, the concentration of aerosol particles sharply increases and the
85 ambient visibility reduces proportionally in Malaysia (Khan *et al.*, 2016; Koe *et al.*, 2001). The main
86 causes of haze pollution in Malaysia are “slash and burn” activities to clear land for new plantations
87 and to manage agricultural waste, mainly in Indonesia’s Sumatra and Kalimantan regions. These
88 activities are closely related to economically important sectors like palm oil and pulp and paper there.
89 During previous haze episodes, it has been understood that Singapore has been impacted by the
90 emission of air pollutants from Borneo while the Kuala Lumpur City in Malaysian Peninsula was more
91 influenced by fire smoke of the Sumatra region (Koe *et al.*, 2001). Thus, the wildfires in the Sumatra
92 and Kalimantan (Indonesian Borneo) region are the potential hotspots causing the recurrence of the
93 annual haze in this area. Peat burning has been initially ignited by the above ground biomass of forest
94 materials above the peat soil and worsened by El Nino phenomena. In pristine condition, fire rarely
95 occurs in peat soil due to its high moisture content as it occurs at coastal wet areas (Hope *et al.*, 2005).
96 However, in recent years peatlands have become more unstable and degraded due to largescale
97 extraction to make way for agricultural developments, forestry and urban development contributing to
98 the main cause of lowland peat soil loss (Kumar *et al.*, 2020). Peat fires may last for days, week and
99 even months as the fire can penetrate underneath the peat layer, making it difficult to put out and
100 persist to smoulder, producing huge amounts of CO₂ and smoke (haze) in short time (Field *et al.*,
101 2016). Fires from peat soils emit a substantial amount of air particles and reactive gases in the Sumatra
102 and Indonesian Borneo region (Jayarathne *et al.*, 2017; Roulston *et al.*, 2018; Stockwell *et al.*, 2016;
103 Wooster *et al.*, 2018). So, a large quantity of reactive gases, aerosol and its compositions, greenhouse
104 gases are emitted during the biomass and peatland fires.

105 El Niño is an inter-annual phenomenon and can intensify the wildfires in this region. The El Niño
106 phenomenon that occurred in 2015 was another precursor for the escalated wildfire event in Southeast
107 Asia. An El Niño condition is a non-regular occurrence in the tropical Pacific region that occurs when
108 surface water in the equatorial Pacific becomes warmer than average and east winds blow weaker than

109 normal (NOAA, 2015). An El Niño event as Nino Z index anomaly ≥ 0.5 °C in five consecutive
110 months, and a strong El Niño event as Nino Z index anomaly ≥ 1 °C in five consecutive months (Zhai
111 *et al.*, 2016). The year 2015 was the warmest on record and a super-strong El Niño also formed that
112 year (Zhai *et al.*, 2016). In South-East Asia, this brings drier weather and cause drought in lots of
113 places across the region. During dry weather, peat soil is more susceptible to fire. Thus such
114 conditions further degrade peat soil, causing it to lose its stability and moisture. The slash and burn
115 during this dry weather escalate fire which can spread in an uncontrollable manner. The fire will burn
116 and smoulder in peat soil, as peat acts as fuel for the fires.

117 Acknowledging the role of peat fires in the haze, the Indonesian government has established various
118 laws that prevent the unsustainable development of peatlands. These include the Indonesian
119 Government Regulation 26/2008 and Presidential Decree 32/1990 which dictate that peat more than
120 three metres deep should be automatically designated as protected areas, Ministry of Agriculture
121 Regulation 14/2009 which prohibits the clearing of an entire concession if more than 30% of the
122 concession is located on deep peat (Varkkey, 2016) and a moratorium on issuing new concession
123 licenses to use land designated and peatland, which has been in force since 2011 and has recently been
124 made permanent in 2019 (Jong, 2019). Despite these regulations, large areas of peatlands are regularly
125 opened up for plantations, enabled by close, mutually reinforcing patron-client relations cultivated by
126 elite business interests (clients) and administrative officials and politicians (patrons). These patrons
127 often arrange for these restricted lands to be released to their clients in exchange for personal and
128 professional kickbacks, including much needed local administrative revenue. Furthermore, with slash
129 and burn being the cheapest technique to clear this land, some of these concessionaires do resort to this
130 method despite it being prohibited under the Environmental Management Act No. 23/1997. The close
131 relationship with the administrative elites often allows these concessionaires to escape prosecution for
132 illegal land clearing and fire use, further encouraging the practice (Varkkey, 2016). In light of the
133 studies in the literature, there is a lack of scientific link how do the natural and semi-natural wildfires

134 alter the air quality over the Southern Malay Peninsula and Malaysian Borneo. Therefore, the present
135 study attempts comprehensively focus on the covariation of aerosol and reactive gases with respect to
136 the intensity of wildfires during the strong haze in 2015 in the Southern Malaysian Peninsula and
137 Borneo region. This study also explores the potential factors that impact on the elevated load of the
138 pollutants in these sites.

139 **2. Material and Methods**

140 **2.1 Description of the sampling site**

141 **Figure S1** shows the two studied sites. These two sites will literally represent an emission level of
142 aerosols and reactive trace gases for the region. As reported in the literature, both areas are
143 significantly impacted as a result of the frequent forest fires in Indonesia (Gaveau *et al.*, 2016; Monks
144 *et al.*, 2015). The Pasir Gudang site in the state of Johor is located nearby Singapore and is greatly
145 influenced by industrial emissions. The main industrial settings in this city are transportation, logistics,
146 shipping industries, petrochemical activities, palm oil storage, heavy industries and refineries. The site
147 is located near the highway's transection of Pasir Gudang and Johor Bahru. Kuching in the state of
148 Sarawak in Malaysia is the capital city and the densest city in that state. The main industrial areas in
149 Kuching are Pending Industrial Estate (Mixed and Light Industries), Demak Laut Industrial Park
150 (Mixed, Light, and Medium Industries), and Sama Jaya Free Industrial Zone (Hi-Tech and Electronics
151 Industry). These industrial areas were designated by the Sarawak government to boost the city's
152 commercial and industrial activity in making it a major growth centre in East Malaysia. Apart from the
153 local emissions from industrial and anthropogenic sources, Kuching is closer to the peat-fire hotspots
154 and thus, the relative contribution of fire smoke may literally also impact the site of Pasir Gudang in
155 Peninsular Malaysia. The above considerations were carefully accounted to select the study sites.
156 With regards to land-use change detection, surface reflectance product of Landsat provided by United
157 States Geological Survey (USGS) was used, and ArcGIS and ENVI software were used to process

satellite imageries and spatial analysis. Different land cover objects have different spectral patterns due to spectral characteristics of the materials hence, a variety of supervised classification methods has been applied and tested extensively. Maximum likelihood is one of the most popular supervised classification methods used in this study. This method is based on the probability that a pixel belongs to a particular class. It was found that much of the area of Johor and Sarawak has undergone various land-use change within about 15 years (2000–2014). The change in land use has been shown in **Figure S2** and Table S1. In this study, **Figure S3** shows the change in elevation over Sarawak and Johor state. Figure S4 showed the distribution of peat soil covered in this region. The gradient of the intensity in the peat soil distribution is evidently larger over the Sarawak region compared to the Southern Peninsular region. Figure 1. Shows the monthly change for the distribution of AOD at 550 nm over SEA in 2015. A thick of aerosol layer was evidently observed from August to September as haze episode compared to the non-haze episode plotted using the data obtained from May-June 2015.

2.2 Observation of the data

Observation data were secondary in nature and obtained from the Department of Environment (DOE) Malaysia. The duration and resolution of the data were from January to December 2015 and were measured on an hourly basis. The main parameters of aerosol and trace gases were PM₁₀, carbon monoxide (CO), ozone (O₃), sulphur dioxide (SO₂), nitric oxide (NO), nitrogen dioxide (NO₂) and oxides of nitrogen (NO_x). Wind speed (WS), wind direction (WDir), relative humidity (RH) and ambient temperature (T) were also measured to determine the local weather pattern. PM₁₀ and gas variables were continuously measured at the Malaysian DOE operated sites. As reported earlier by (Khan *et al.* (2015); Samsuddin *et al.* (2018)), a beta ray attenuation method used to measure PM₁₀ (BAM 1020, Teledyne, USA). The nondispersive infrared absorption (NDIR) method was applied to monitor CO (API M300, Teledyne, USA). A florescence-based sensor was used to measure SO₂ (API M100A, Teledyne, USA). Chemiluminescence is a commonly used method to measure oxides of nitrogen (NO_x) and O₃ (API 200A and Analyzer 400A, Teledyne, USA). As reported by Khan *et al.*

183 (2015), an autocalibration was scheduled for each instrument on a daily basis. Zero air calibration as
184 well as standard cylinder gas were injected during the calibration process. A private company named
185 Alam Sekitar Sdn. Bhd. (ASMA) formerly managed the monitoring sites in Malaysia. Currently, a new
186 private company named TransWater API Sdn Bhd took over this operation and manages the sites and
187 data on behalf of the Malaysian DOE.

188 ***2.3 Local weather variation during the measurement***

189 In this study, the transport of air mass on a monthly basis was examined using Hybrid Single-Particle
190 Lagrangian Integrated Trajectory version 4.9 (HYSPLIT 4.9) (Stein *et al.*, 2015). The duration of the
191 backward trajectories was chosen as 120 h and 6 h intervals and initial trajectory height was
192 considered as 500 m and the individual backward trajectory was calculated at 0.00, 0.06, 12.00, 18.00
193 UTC. To see the transboundary origin of the air mass from the mainland of China and also Indonesian
194 region, 120 h is suitable to cover the backward origin of the air mass. Several other studies also used
195 120 h for the trajectory in this region (Khan *et al.*, 2018; Samsuddin *et al.*, 2018). Then, the cluster of
196 the backward trajectories was obtained on monthly basis using the Window-based HYSPLIT 4.9
197 compiler as shown in Figures 2 and 3. The input data for HYSPLIT were obtained
198 from <ftp://arlftp.arlhq.noaa.gov/pub/archives/reanalysis>. To determine the change in the wind vector in
199 the SEA region, a vector field was generated using the Grid Analysis and Display System (GrADS).
200 Wind vector and planetary boundary layer height (PBL) data were downloaded from the European
201 Centre for Medium-Range Weather Forecasts (ECMWF) website. The data resolution was $0.25^{\circ} \times$
202 0.25° for the period of January to December 2015 in the domain of SEA region as shown in Figure S5.
203 The Global Fire Assimilation System (GFAS) emissions data as netCDF format was downloaded from
204 the ECMWF website using python script (<https://apps.ecmwf.int/datasets/data/cams-gfas/>). The
205 domain of latitude +0.87 to -2.06 and longitude 110.31 to 114.01 and -3.5 to 0.77 of latitude and 100.8
206 to 104.9 of longitude were chosen to represent the predominant fires in West Kalimantan and Sumatra,
207 respectively. A similar of gridbox data for PBL was also resampled Then, the gridded data with a 0.5°

208 $\times 0.5^\circ$ resolution from 01 January to 31 December 2015 as daily data at 00.00 UTC was analysed,
209 using averaging functions in the climate data operator (CDO). The data summary statistics, backward
210 trajectories and time-series figures were performed by using R software version 3.4.2 (R Development
211 Core Team, 2008). The monthly magnitude of the wind vector is shown in Figure S5. The radiative
212 fire forcing was demonstrated in Figure S6. The black carbon (BC) flux and CO flux received from
213 GFAS of ECMWF represent the intensity of the forest fire in 2015 in West Kalimantan region.

214 **3. Results and Discussion**

215 **3.1 Geographical Background**

216 Table S1 shows the land-use change for Johor from the year 2000 to 2014 and for Sarawak, in the year
217 2000. For Johor, built-up and cropland shows an increasing percentage from 1% to 6.6% and 55.8% to
218 70.9%, respectively. Forest, wetland and water shows decreasing percentage from 32.7% to 19.2%,
219 8.9% to 2.7% and 1.6% to 0.6%, respectively. Percentage of land use in Johor for development has
220 increased from 56.8% to 77.5% and the natural resources have decreased from 43.3% to 22.5% over
221 15 years. The distribution of land use in Johor shows an increase in built-up at the developing cities
222 especially near to the port. The elevation of the land at Johor in Figure S3a shows that Johor is mostly
223 made up of lowland. This has made the development for build-up areas and croplands much easier to
224 be expanded. Blessed with the fertile soil of peat at low land as seen in Figure S4, Johor now a days is
225 the largest contributor to the agricultural gross domestic product in Peninsular Malaysia (Pakiam,
226 2018) where the crops produced are mainly palm oil followed by rubber, vegetables and fruits. For
227 Sarawak, the year 2000 shows the land use for development account about 33% which consist of built-
228 up 0.1% and cropland 32.9% (Table S1). Sarawak's natural resources accounted at 67% which are
229 consist of forest 57.9%, wetland 9% and water 0.1%. Data for land-use change in Sarawak was not
230 available for the year 2014. The elevation of the land at Sarawak in Figure S3b shows that Sarawak
231 has high elevation land near its border with Kalimantan. The low land area near to the sea is enriched
232 with peat soil as shown in Figure 4b and most of the development and cropland took at that place.

Based on the development at Sarawak and Johor especially at the chosen site which is Pasir Gudang and Kuching, local emission was already in existence and the deteriorated air quality was observed at the study sites. The rain forest coverage in the Malaysian region has changed in the last decades (Gaveau *et al.*, 2016; Keywood *et al.*, 2003; Seinfeld and Pandis, 2016). Relatively the rain forest coverage in Sarawak is higher than that in Johor which is significant to the emission of biogenic organic compounds at the study sites. Studies in the literature showed that the biogenic organic compounds particularly isoprene and monoterpene impacts potentially as the precursor gases to the ozone build up at the surface level in the presence of sunlight (Friedlander, 2000; Kumar *et al.*, 2019; Monks *et al.*, 2015). Such factor alone could not cause severe haze and a load of pollutants are observed to be carried from other transboundary sources as discussed below.

3.2 *Time series of aerosol and trace gases*

Table 1 shows the overall yearly average of PM₁₀, trace gases and meteorological factors. Some of the key variables were PM₁₀, CO and NO representing mainly the biomass burning and combustion of fossil fuel from the transportation sector. For the Pasir Gudang site, the yearly average concentration of PM₁₀ was 64.90 µg/m³ ranging from 11.00 to 446.0 µg/m³ while the concentration of CO was 0.78 mg/m³ with a range of 0.023 to 4.66 mg/m³. NO as a proxy for the fuel combustion by the traffic source was 10.31 µg/m³ ranging from 1.25 to 188.8 µg/m³. The SO₂ concentration was 11.17 µg/m³ with a range of 2.62 to 133.6 µg/m³. The concentration of PM₁₀ exceeded the Malaysian air quality standard (IT2-2020). From **Figure 4**, the time-series of the pollutants was shown during the entire year of 2015. The concentration of PM₁₀ and CO abruptly increased during September and October in 2015 compared to the other months. However, O₃ has shown no significant change during the haze period. We noticed that there were small spikes for SO₂ and NO₂ during September and October. The RH level was relatively lower in this span of time fully representing that it was a dry monsoon. During this dry haze period, the small surge of SO₂ and NO_x is possibly due to the emissions originating from

257 local industry and traffic, and a relatively reduced mixing depth turns the local air quality worse in this
258 regard.

259 From Table 1 for the Kuching site, the PM₁₀ yearly average was 50.50 µg/m³ with a range from 5.00
260 µg/m³ to 612.0 µg/m³ and CO was 0.57 mg/m³ with a range from 0.03 mg/m³ to 3.74 mg/m³. The
261 yearly average of gaseous pollutants NO, SO₂ and O₃ were 4.41 µg/m³ with range from 1.25 µg/m³ to
262 77.50 µg/m³, 3.81 µg/m³ with range from 2.62 µg/m³ to 23.58 µg/m³ and 24.30 µg/m³ with range from
263 2.00 µg/m³ to 146.0 µg/m³, respectively. The concentration of PM₁₀ for Kuching site at 50.50 µg/m³
264 exceeded the Malaysian air quality standard (IT2-2020) of 40.00 µg/m³. From Figure 5, the time-series
265 of the pollutants at the Kuching site in the year 2015 was presented. PM₁₀ and CO show a distinct
266 trend from August to October with significant increases in the number of the pollutant's concentration.
267 O₃ shows a slight concentration was added during August and October while a slight drop of the
268 concentration was observed in September. SO₂ and NO do not show significant changes in the trend.
269 NO, NO_x and SO₂ are significantly important proxy variables for government's intervention to
270 manage local air quality. NO and NO_x demonstrated relatively higher concentrations during April-
271 May 2015 which play key roles in titration of O₃ as seen in Figure 4. At the same time, surface ozone
272 build up was also seen during August – September which might potentially link to the higher
273 emissions of CO, NO_x, biogenic volatile organics and strong warming conditions as described in the
274 literature (Geng et al., 2011; Kumar et al., 2019; Monks et al., 2015; Wennberg et al., 2018). SO₂
275 showed higher value during August -September 2015 which possibly originates from local industrial
276 emissions under a reduced mixing depth during haze in Malaysia. However, the variability of the
277 above parameters was not potentially significant in the Borneo site..

278 **3.3 Variation of concentrations during haze and non-haze**

279 Tables 2 and 3 showed the descriptive statistics of the observation data during the haze episodes in
280 2015 and non-haze period, respectively for Pasir Gudang and Kuching. Observation at the Pasir
281 Gudang site, the level of PM₁₀ was 61.94 µg/m³ during the non-haze which was increased two-fold

282 during the strong haze episode in 2015. The median value of PM_{10} as $110.5 \mu\text{g}/\text{m}^3$ was higher
 283 compared to the non-haze period. This abrupt change was also noticed during the haze episode in
 284 September-October 2015 as demonstrated in Figure 4. The NO and NO_2 were less influenced due to
 285 the haze strike. The NO and NO_2 are of short-residence time and play as potential in O_3 chemistry. As
 286 explained in the earlier section, NO_x , CO, and biogenic VOCs are precursors to enhance O_3 under
 287 tropical warming atmospheric condition as suggestion in the literature (Geng et al., 2011; Kumar et al.,
 288 2019; Wennberg et al., 2018). However, the CO level was two times higher during haze compared to
 289 non-haze. Thus, it was clearly shown that PM_{10} and CO were emitted sporadically due to the biomass
 290 and peat soil burning in 2015. According to the EDGAR emissions inventory, the major emission
 291 sources of SO_2 are electricity and power generation (59%), industry and construction (25%), road
 292 transportation (8%) and residential and other sectors (6%) (EDGAR, 2016). Thus, SO_2 did not
 293 demonstrate any significant change during the haze and non-haze period although there was a small
 294 spike of SO_2 during the haze period. As reported in the previous section, this dry monsoon increases
 295 the fires spreading into soil particularly peatland which helps to accumulate more air particles and
 296 reactive gases to accumulate in the ambient air over this region.
 297 From Figure 8, it shows that the PBL height at both the fire hotspots in West Kalimantan and Sumatra
 298 were relatively higher during the haze period starting from September to October compared to other
 299 months. Thus, PBL does not influence the limit of transport of the pollutants from the fire region to the
 300 study sites.. The concentration of PM_{10} started decreasing from December until April as this is the wet
 301 season in Malaysia and experiences the largest frequency of rainfall or precipitation. Aldrian and Dwi
 302 Susanto (2003) described that the moist air transported from the South China Sea can help to reduce
 303 the impact of haze during the northeast monsoon. However, these do not happen due to El Nino
 304 phenomenon takes place which pushes drier air to the Southeast Asia region.
 305 Observation at the Kuching site for PM_{10} during haze shows the concentration was at $97.68 \mu\text{g}/\text{m}^3$ that
 306 is three times higher than the concentration during the non-haze episode. The gaseous pollutant CO

also shows an abrupt increase of three-fold concentration at 1.06 mg/m^3 compared to the non-haze period at 0.36 mg/m^3 . Among the pollutants generated from peat soil burning, CO_2 and CO were found to be the dominant elements released into the air due to high organic compound (Langmann *et al.*, 2009; Stockwell *et al.*, 2015; Yokelson *et al.*, 1997) and particulate matter was the next highest element after CO_2 and CO from peat soil burning (Blake *et al.*, 2009). Peat undergoes smoldering combustion in the tropical region. As suggested by Hu *et al.* (2018) smoldering combustion is the slow, low temperature, flameless burning of porous fuels and is the most persistent type of combustion phenomena which enables peat to burn or char. Smoldering is the dominant combustion phenomena in megafires in natural deposits of peat and coal which are the largest and longest burning fires on earth. This phenomenon has great potential to emit a substantial quantity of aerosols, CO and CO_2 as reported in the literature (Malaysia-DOE, 2019b; Stockwell *et al.*, 2015; Yokelson *et al.*, 1997). O_3 during the haze period was $31.12 \text{ } \mu\text{g/m}^3$ and shows a slight increase than during non-haze averaged concentration of $20.11 \text{ } \mu\text{g/m}^3$. SO_2 and NO do not show an apparent change in the concentration value during haze and non-haze period.

3.4 Factors influencing the concentrations

3.4.1 A monthly change in wildfire radiative power, BC and CO over SEA in 2015

Figure S6 shows a monthly change in wildfire radiative power over SEA in 2015 where forest fire radiation force (FRP) measures the radiant energy released per time unit by burning vegetation (Wooster *et al.*, 2005). The FRP over SEA was observed to have obvious small spark starting July where small yellow dots were seen at Sumatra region representing 1 to 2 (W/m^2). In August, FRP was observed at both Sumatra and Kalimantan region with darker yellow colour plotted and be regarded as 2 to 3 W/m^2 . The FRP was at its peak during September where red dots presenting high FRP between 5 to 9 W/m^2 was detected at Sumatra and Kalimantan, and then reduced in October and no significant FRP was observed in November. Figures 6 and 7 show the monthly distribution of black carbon (BC) and carbon monoxide (CO) fluxes over the SEA in 2015. They have an almost similar pattern, where

both BC and CO starts in June at Sumatra and expanding to Kalimantan in July. BC keep increased in August and at its peak in September while the month of October and November shows a gradual drop. CO was at its peak in August and have a steady reduction starting from September to November. Additionally, from Figure 6 and Figure 7 for BC flux and CO flux during the 2015 haze, it shows that the strength of the emission flux of these two variables was potentially visible in the west of Borneo and Sumatra region. As seen from Figure 8 of CO flux in West Kalimantan vs Sumatra, the emission of CO flux in Kalimantan was about 6-7 times higher in strength that at Sumatra during the fire 2015. Thus, the study sites are more impacted from the fire events in Kalimantan areas compared to Sumatra in the 2015 haze in Malaysia. This is further to the surge of FRP in the month of September and October 2015 (Figure S6) which clearly links to the O₃ build-up in the study sites. As discussed in the previous section, the prevalence of O₃ occurs under a warming condition in the presence of biogenic organic precursors (Monks et al., 2015). As such, O₃ concentrations showed higher at both study sites during haze which is possibly due to the elevated FRP in the hotspots regions..

3.4.2 Wind vector over the entire SEA in 2015 and air mass movement

Figure S5 shows the monthly change in the monsoonal wind velocity over Southeast Asia in 2015. From January to March, the wind velocity strongly blows from South China Sea direction for both locations at Southern site, Pasir Gudang and Borneo site, Kuching. The month of April show a slight change in the direction of wind velocity for Kuching site, the wind was blown from the Kalimantan region. Starting May to October, the wind was shown blowing from Kalimantan region and the Java Sea for both Pasir Gudang and Kuching with a strong wind in July to September.

Figure 2 shows the transport of air mass during 2015 at Pasir Gudang site. It was transported from the mainland of China and the South China Sea during December, January and February. Then, the air mass moved slightly to the Philippine region before arriving at the current Pasir Gudang location during March and April. During May and June, we observed that air mass was from South Sumatra, Indonesian Borneo and the Java Sea. The dominant air mass was from the Jakarta and Indonesian

357 Borneo region during July while it was travelling over the Java Sea in August and September. The
 358 backward trajectory was shifted and split significantly in October. The dominant air mass was from the
 359 Philippine region while about 30% frequency of the backward trajectories were from the Borneo
 360 region. About 52% frequency of the trajectories were influenced by localized sources while 48% of
 361 them was from the maritime region in the South China Sea. The vector of the wind field was
 362 visualized in Figure S5. The flow pattern of the wind in this region is consistent with the transport of
 363 air mass from January to December 2015. Thus, the Indonesian Borneo is likely to have more
 364 influence over the concentration of PM_{10} and CO at this site in Southern Peninsula Malaysia compared
 365 to the biomass burning in the Sumatra region. After comparing the level of impact using PM_{10} as a
 366 proxy in this case, the impact of haze from Borneo was more severe than that from the Sumatra region
 367 of Indonesia. This finding is informative for policy development and assistance strategies for
 368 Malaysia. Previously, it was understood that the haze affecting Peninsula Malaysia was generally
 369 originating from the Sumatra region of Indonesia, specifically the Riau province. This understanding
 370 was, for example, central in the decision of the Malaysian government to ‘adopt’ Riau under the
 371 ASEAN Adopt-A-District Program, a five-year memorandum of understanding which involved
 372 Malaysia providing community training and capacity-building projects, peatland rehabilitation
 373 assistance, and haze early warning system in the province, in the hope that such improvement of
 374 conditions on the ground in Riau would translate to reduced haze in Peninsula Malaysia (Varkkey,
 375 2016). With this new finding, the Malaysian government may need to re-target assistance to Malaysia
 376 to be more aligned towards provinces in Kalimantan in Indonesian Borneo.

377 Figure 3 shows the backward trajectory of air mass plotted for Kuching Sarawak in the year 2015. In
 378 January and February, the air mass cluster came from the East China Sea near Taiwan and Luzon
 379 Island, Philippines. March and April showed the air mass blowing from Palawan Island, Philippines
 380 and the Philippine Sea. The air mass cluster split into three significant directions coming from Central
 381 Kalimantan, Karimata Straits and the South China Sea near the Kuching site. It was observed in June

382 and July, Kuching received most of the air mass flowing from Central Kalimantan, West Kalimantan
383 and the Java Sea. The haze occurred starting from August 2015 to September 2015 as reported in the
384 Chronology of Haze Episodes in Malaysia by the Official Portal of Department of Environment
385 Malaysia (Malaysia-DOE, 2019a). In August, the largest percentage of air mass flow was from West
386 Kalimantan at 46% frequency, followed by 37% frequency of air mass coming from Central
387 Kalimantan and the least air mass came from the Java Sea at a rate of 17% frequency. In September
388 the dominant air mass was from Java Sea 46% frequency, West Kalimantan 41% frequency and a
389 small portion of 6% frequency from the region of Brunei. During October, the airflow received the
390 large contribution from West Kalimantan, a medium portion from the sea in the direction of the North
391 from Kuching and the least air mass from the sea near Sabah region. The air mass was observed to
392 move from the South China Sea near East Malaysia during November. In December, the dominant air
393 mass flowed from the South China Sea near Sarawak state, the Philippines Sea and China mainland.
394 From the backward trajectory plot during the haze episode of August 2015 to September 2015, Central
395 Kalimantan, West Kalimantan and the Java Sea contributed a significant portion of air mass flowing to
396 Kuching state.

397 Overall, the knowledge perceived from the synoptic velocity of wind vector for the entire study period
398 in 2015 is that moist water vapor is transported from the marine region during December to March and
399 dry air is transported around the study sites from June to October 2015. This pattern coincides broadly
400 with each month of the transport of air back from the backward trajectories to the study sites. When air
401 mass is transported from the maritime region, air quality parameters particularly PM_{10} started
402 decreasing. Interestingly, dry air mass is dominantly transported from the Borneo mainland and partly
403 from the Sumatra region, which are potential causes of the spike of PM_{10} concentration at both study
404 sites.

405

406 4. Conclusion

407 The observation data presented in this representing Johor region, a southern Malaysian Peninsula and
408 nearby to Singapore and another site in Kuching, Malaysian Borneo. The yearly average concentration
409 of PM₁₀ was 64.85 µg/m³ ranging from 11.00 to 446.0 µg/m³ while the concentration of CO was 0.77
410 mg/m³ with a range of 0.023 to 4.66 mg/m³. The concentration of PM₁₀ exceeded the Malaysian air
411 quality standard (IT2-2020) while CO and other trace gases are at a safe level. A comparison of the
412 observation data was made during haze and non-haze period in 2015 and the results showed that the
413 level of PM₁₀ was 61.94 µg/m³ during the non-haze period which was increased by two-fold during the
414 strong haze episode in 2015. The median value of PM₁₀ as 110.5 µg/m³ was higher compared to the
415 non-haze period. For Kuching site, the PM₁₀ yearly average was 50.50 µg/m³ with a range from 5.00
416 µg/m³ to 612.0 µg/m³ and CO was 0.57 mg/m³ with a range from 0.03 mg/m³ to 3.74 mg/m³. The
417 concentration of PM₁₀ for Kuching exceeded the Malaysian air quality standard (IT2-2020) of 40.00
418 µg/m³. It was observed that the pollutants at these locations were more impacted by fire events in
419 Indonesia's Sumatra and Borneo. However, the southern part of the Malaysian peninsula was impacted
420 mainly from the biomass burning and the combustion of peat soil from the Indonesian Borneo region.
421 Further, BC flux and CO flux during the haze in 2015 showed that the strength of the emission flux of
422 these two variables was potentially visible in the west of the Borneo and Sumatra regions which
423 impacted at the study sites. Particularly, CO flux was observed about 6-7 times higher in West
424 Kalimantan compared to that in Sumatra in the 2015 haze which is a clear evidence that the study sites
425 are more impacted from the emission received from Kalimantan.. This finding is important in
426 informing future local and foreign policy and diplomatic assistance decisions of the Malaysian
427 government in response to external haze. A better understanding of the directional source of haze
428 affecting Malaysia will allow the Malaysian government to offer more targeted assistance to the
429 Indonesian government at both the bilateral and regional (ASEAN level) so that assistance targeted to
430 specific source provinces in Indonesia can be translated to a maximum reduction of haze severity in

431 Malaysia during future episodes. It will also inform a more targeted and improved local fire prevention
432 strategy. A well-planned management of the land use in Sarawak and peninsular Malaysia can help
433 build national resilience against wild forest fires..

434

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440 Observing System Fire Information for Resource Management System fire archive (link:
441 [https://firms.modaps.eosdis.nasa.gov/ download/](https://firms.modaps.eosdis.nasa.gov/download/)). The data of the HYSPLIT model were available at
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449

450 **Conflict of Interest**

451 The authors declare no financial competing interests.

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576

577

TABLES

Table 1. A summary statistic of the observation data during the entire year of 2015

Pasir Gudang										
Variable	Valid N	Mean	Geometric	Median	Min	Max	10%	90%	SD	MAQS*
CO (mg/m ³)	8437	0.78	0.65	0.60	0.02	4.66	0.33	1.48	0.53	10 (8 h) 30 (1 h)
O ₃ (µg/m ³)	8232	36.11	25.78	32.00	2.00	198.0	6.00	70.00	26.35	100 (8 h) 180 (1 h) 40 (y)
PM ₁₀ (µg/m ³)	8634	64.90	56.92	54.00	11.00	446.0	33.00	104.0	40.81	100 (24 h) h)
SO ₂ (µg/m ³)	8360	11.17	8.54	7.86	2.62	133.6	2.62	20.96	9.30	80 (24 h) 250 (1 h)
NOx (µg/m ³)	7117	36.37	27.12	28.82	3.13	222.6	8.77	75.13	28.43	-
NO (µg/m ³)	7120	10.31	4.42	3.75	1.25	188.8	1.25	28.75	17.86	-
NO ₂ (µg/m ³)	8143	25.50	20.37	24.44	1.88	103.4	7.52	47.00	15.67	70 (24 h) 280 (1 h)
Temperature (°C)	5519	28.82	28.71	28.60	23.60	35.60	25.70	32.60	2.55	-
Humidity (%)	8722	72.61	71.58	75.00	34.00	94.00	55.00	87.00	11.80	-
Wind Speed (km/hr)	8721	5.89	4.50	5.50	0.80	18.40	1.10	11.30	3.73	-
Kuching										
CO (mg/m ³)	8313	0.57	0.45	0.40	0.03	3.74	0.22	1.17	0.45	10 (8 h) 30 (1 h)
O ₃ (µg/m ³)	8136	24.30	18.38	22.00	2.00	146.0	6.00	46.00	16.43	100 (8 h) 180 (1 h) 40 (y)
PM ₁₀ (µg/m ³)	8554	50.50	38.51	36.00	5.00	612.0	18.00	97.00	49.65	100 (24 h) h)
SO ₂ (µg/m ³)	7914	3.81	3.49	2.62	2.62	23.58	2.62	5.24	1.89	80 (24 h) 250 (1 h)
NOx (µg/m ³)	7158	16.75	13.87	14.40	3.13	105.7	6.89	31.29	10.84	-
NO (µg/m ³)	7172	4.41	2.85	2.50	1.25	77.50	1.25	10.00	5.38	-
NO ₂ (µg/m ³)	8162	11.95	10.03	11.28	1.88	54.52	3.76	20.68	7.09	70 (24 h)

Temperature (°C)	2184	27.49	27.31	26.70	20.70	36.20	23.80	32.40	3.24	-
Humidity (%)	2184	86.37	85.44	91.00	48.00	100.0	67.00	99.00	12.07	-
Wind Speed (km/hr)	8685	4.97	3.81	4.30	0.90	20.10	1.10	9.90	3.39	-

MAQS* : Malaysian Air Quality Standard (2020)

Table 2. A comparison of the variables during the haze and non-haze 2015 in Pasir Gudang

Pasir Gudang Haze								
Parameters	N	mean	stdev	min	10th	median	90th	max
CO (mg/m³)	61	1.22	0.45	0.57	0.71	1.13	1.91	2.51
O ₃ (µg/m³)	61	40.30	9.98	19.06	26.45	40.17	53.91	61.48
PM ₁₀ (µg/m³)	61	125.7	46.80	47.21	78.58	115.96	188.0	271.1
SO ₂ (µg/m³)	61	15.37	6.84	2.96	7.75	15.26	22.16	38.10
NOx (µg/m³)	61	40.49	15.02	21.64	24.81	35.76	63.83	76.96
NO (µg/m³)	61	9.06	6.55	1.46	2.50	6.99	19.02	29.06
NO ₂ (µg/m³)	61	30.65	8.76	13.40	20.21	28.12	44.58	49.78
Temperature (°C)	-	-	-	-	-	-	-	-
Humidity (%)	61	69.87	4.50	61.75	65.08	69.42	76.83	80.13
Wind Speed (km/hr)	61	5.32	1.43	2.78	3.64	5.01	7.15	10.18
Pasir Gudang Non-Haze								
Parameters	N	mean	stdev	min	10th	median	90th	max
CO (mg/m³)	61	0.64	0.23	0.37	0.42	0.55	1.05	1.20
O ₃ (µg/m³)	61	33.55	11.50	6.52	18.61	33.22	50.55	57.22
PM ₁₀ (µg/m³)	61	61.66	9.58	40.83	52.00	59.60	77.46	84.83
SO ₂ (µg/m³)	61	15.19	4.81	3.93	9.11	14.47	21.20	30.30
NOx (µg/m³)	61	43.59	15.18	23.52	26.51	37.90	62.66	85.66
NO (µg/m³)	61	12.02	10.31	1.88	2.50	7.87	27.20	39.35
NO ₂ (µg/m³)	61	31.06	6.46	20.43	23.89	29.70	39.97	46.67
Temperature (°C)	61	29.80	1.06	26.96	28.17	29.93	31.03	31.40

Humidity (%)	61	70.79	4.83	63.38	65.54	70.00	78.38	85.29
Wind Speed (km/hr)	61	6.03	1.54	2.29	3.96	6.14	8.02	8.58

Table 3. A comparison of the variables during the haze and non-haze 2015 in Kuching

Kuching Haze								
Parameters	N	mean	stdev	min	10th	median	90th	max
CO (mg/m ³)	92	1.06	0.52	0.26	0.50	0.95	1.84	2.31
O ₃ (µg/m ³)	90	31.12	11.87	8.08	15.82	30.19	44.41	65.75
PM ₁₀ (µg/m ³)	92	97.68	64.97	26.13	36.51	73.46	184.4	297.1
SO ₂ (µg/m ³)	92	4.60	1.53	2.62	2.85	4.27	6.75	8.73
NOx (µg/m ³)	91	17.72	5.66	6.48	10.43	17.20	25.65	33.06
NO (µg/m ³)	91	3.77	2.12	1.25	1.79	3.26	6.32	13.37
NO ₂ (µg/m ³)	91	13.13	3.72	5.97	8.15	12.67	18.06	22.48
Temperature (°C)	31	28.13	1.09	25.38	26.68	28.39	29.22	29.60
Humidity (%)	31	84.09	3.83	78.50	80.13	83.54	89.46	93.67
Wind Speed (km/hr)	92	4.75	0.80	2.92	3.69	4.71	5.89	6.50

Kuching Non-Haze								
Parameters	N	mean	stdev	min	10th	median	90th	max
CO (mg/m ³)	61	0.36	0.09	0.15	0.25	0.35	0.48	0.60
O ₃ (µg/m ³)	61	20.11	5.91	10.96	13.33	19.45	26.64	36.55
PM ₁₀ (µg/m ³)	60	33.65	7.36	19.17	25.48	32.08	43.43	49.08
SO ₂ (µg/m ³)	61	3.45	0.75	2.62	2.62	3.33	4.67	5.70
NOx (µg/m ³)	61	14.06	4.57	4.59	8.38	14.51	19.80	24.11
NO (µg/m ³)	61	3.66	1.40	1.25	1.78	3.59	5.30	7.56
NO ₂ (µg/m ³)	61	10.30	3.37	3.17	6.54	10.87	15.29	18.67
Temperature (°C)	-	-	-	-	-	-	-	-
Humidity (%)	-	-	-	-	-	-	-	-
Wind Speed (km/hr)	61	4.67	0.98	1.76	3.73	4.60	5.72	7.14

Figures' captions

Figure 1. Total aerosol optical depth (AOD) during non-haze and haze period over Southeast Asia in 2015 ([assimilated Tera/Aqua MODIS AOD received from CAMS in the ECMWF website](#))

Figure 2. Transport of air mass over a Southern Peninsular site in Malaysia in 2015. [Percentage frequency of each cluster. January \(c1\(30%\), c2\(70%\)\), February \(c1\(69%\), c2\(31%\)\), March \(c1\(61%\), c2\(39%\)\), April\(c1\(40%\), c2\(60%\)\), May \(c1\(85%\), c2\(15%\), June \(c3\(36%\), c2\(64%\)\), July \(c1\(55%\), c2\(45%\)\), August \(c1\(75%\), c2\(25%\)\), September \(c1\(10%\), c2\(90%\)\), October \(c1\(37%\), c2\(63%\)\), November \(c1\(58%\), c2\(42%\)\) and December \(c1\(19%\), c2\(71%\), c3\(10%\)\)](#)

Figure 3. Transport of air mass over a Borneo site in Malaysia in 2015. [Percentage frequency of each cluster. January \(c1\(12%\), c2\(88%\)\), February \(c1\(59%\), c2\(41%\)\), March \(c1\(67%\), c2\(33%\)\), April\(c1\(56%\), c2\(44%\)\), May \(c1\(26%\), c2\(27%\), c3\(47%\)\), June \(c1\(33%\), c2\(23%\), c3\(44%\)\), July \(c1\(39%\), c2\(61%\)\), August \(c1\(46%\), c2\(37%\), c3\(17%\)\), September \(c1\(41%\), c2\(6%\), c3\(46%\)\), October \(c1\(32%\), c2\(62%\), c3\(6%\)\), November \(c1\(35%\), c2\(58%\), c3\(7%\)\) and December \(c1\(22%\), c2\(65%\), c3\(12%\)\)](#)

Figure 4. Daily variation of aerosols and reactive gases in a Southern Peninsular site in Malaysia in 2015 ([annotated Malaysian air quality standard values](#))

Figure 5 Daily variation of aerosols and reactive gases in a Borneo site in Malaysia in 2015 ([annotated Malaysian air quality standard values](#))

Figure 6. Assimilated Flux of BC during the wild forest fires in 2015 over the Southeast Asia

Figure 7. Assimilated Flux of CO during the wild forest fires in 2015 over the Southeast Asia

[Figure 8. Emission flux of CO and planetary boundary layer \(m\) received from GFAS in West Kalimantan and Sumatra in 2015](#)

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