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LETTER

Impact of the June 2013 Riau province Sumatera smoke haze event on regional air pollution

Sheila Dewi Ayu Kusumaningtyas and Edvin Aldrian

Indonesia Agency for Meteorology Climatology and Geophysics (BMKG) Jl. Angkasa I, No. 2, Kemayoran, Jakarta 10720, Indonesia

E-mail: sheila.dewi@bmkg.go.id

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Abstract

Forest and land fires in Riau province of Sumatera increase along with the rapid deforestation, land clearing, and are induced by dry climate. Forest and land fires, which occur routinely every year, cause trans-boundary air pollution up to Singapore. Economic losses were felt by Indonesia and Singapore as the affected country thus creates tensions among neighboring countries. A high concentration of aerosols are emitted from fire which degrade the local air quality and reduce visibility. This study aimed to analyze the impact of the June 2013 smoke haze event on the environment and air quality both in Riau and Singapore as well as to characterize the aerosol properties in Singapore during the fire period. Air quality parameters combine with aerosols from Aerosol Robotic Network (AERONET) data and some environmental parameters, i.e. rainfall, visibility, and hotspot numbers are investigated. There are significant relationships between aerosol and environmental parameters both in Riau and Singapore. From Hysplit modeling and a day lag correlation, smoke haze in Singapore is traced back to fire locations in Riau province after propagated one day. Aerosol characterization through aerosol optical depth (AOD), Ångstrom parameter and particle size distribution indicate the presence of fine aerosols in a great number in Singapore, which is characteristic of biomass burning aerosols. Fire and smoke haze even impaired economic activity both in Riau and Singapore, thus leaving some accounted economic losses as reported by some agencies.

1. Introduction

Over recent decades, forest fires have raised tremendous concerns from the national and international community since fires cause a serious impact on environment, socio-economic, and health (Taconi 2003). Vegetation fires are common in southeast Asia especially in Indonesia (Murdiyarso and Lebel 2007). Fires are used by people to clear and convert the land into other agricultural purposes mainly for palm oil plantation (Anderson and Bowen 2000, Heil and Goldammer 2001, Jones 2006, Miettinen and Liew 2009, Miettinen et al 2011, Gaveau et al 2014, Lestari et al 2014, Vadrevu et al 2014). This activity produces the sickening and deadly cloud of smoky pollution caused by widespread burning of land and forests in Indonesia, which not only threaten the nation but also neighboring countries. This smoky pollution, which is called smoke haze, contains significant amounts of greenhouse gasses and aerosols (Folkins et al 1997, Heil and Goldammer 2001, Chan et al 2006, Hyer et al 2013, Tsay et al 2013, Gaveau et al 2014, Hayasaka et al 2014). It is possible for aerosol pollutants to be transported thousands of kilometers and affect the environment for weeks or months at a time (Radojevic 2003), causing regional pollution. Haze pollution influences the atmospheric composition as well as regional-to-global climate (Andreae et al 2005). Since 1982, trans-boundary haze pollution has become a recurring phenomenon in southeast Asia with the worst episodes in 1997–1998 and 2006–2007. This phenomenon usually occurs during the dry season in July to October or during the southwest monsoon in February to March (Heil et al 2007, Vadrevu et al 2014).

The issue of vegetation fire in Indonesia began to bloom along with the increase of land conversion and triggered by the dry climate. According to Anderson and Bowen (2000), 60% of fires in Sumatra originate from the Riau province. Riau has the greatest
frequency of vegetation fires than any province in Indonesia in terms of the number of fires per square kilometer. The province continues to log the remaining forests quickly and rampantly causing the dry land forests to become nearly exhausted. Thus, swamp forest or peatland becomes a new target for land conversion. Conversion is a major and planned component of Riau’s development strategy (Anderson and Bowen 2000).

One of the worst trans-boundary haze pollution events occurred in June 2013. According to satellite Terra and Aqua MODIS (Giglio et al. 2003) monitoring, the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) recorded a number of hotspots in that month of more than 3400 (http://satelit.bmkg.go.id/satellite/image/HOTSPOT/2013/06/). Gaveau et al. (2014) concluded that Riau fires in that period occurred over an area of 163,336 ha, of which 137,044 ha or 84% of them are peat. These fires resulted in the emission of green house gases (GHGs) of approximately 172 ± 59 Tg CO2-eq (or 31 ± 12 Tg C) or about 5–10% of the average annual GHG emissions in 2000–2005 Indonesia.

In the case of June 2013, economic and environmental losses were felt by the country and this also impacted other neighboring countries. During that time, the Indonesian Government received sharp criticism from the public and foreign mass media related to smoke haze affecting the palm oil business. Today, plantation crop development opportunity is promising with the strong government support to the palm oil business.

2. Data and methods

2.1. Study location

The period of this study is in year of 2013 in Riau Province and focuses on June since this was the month with the highest number of hotspots throughout the year that caused regional air pollution to neighboring countries. Riau Province is located in Sumatera Island and quite near to Singapore and Malaysia. The eastern side of the province is covered by more than 3.08 million ha of peatland (Wahyunto et al. 2005). Economic development in Riau is strongly influenced by the presence of oil and gas companies as well as commodity products from agriculture and plantations such as oil palm. These two latter sectors provide a substantial contribution to the Gross Domestic Product (GDP) of Riau with percentages, respectively, of 51.49% and 17.01% (http://regionalinvestment.bkpm.go.id). Nowadays, plantation crop development opportunity is promising with the strong government support to the palm oil business.

2.2. Dataset

Monthly rainfall data in 2013 was collected from BMKG. This data was collected daily as measured from the 24 h accumulation from and to 7 o’clock local time. Hotspot parameters as an indication of fires were derived from the observation of the satellites Aqua and Terra MODIS (Giglio et al. 2003). PSI, a parameter describes the air quality, is an index to provide accurate and easily understandable information about daily levels of air quality. This index represents the highest sub-index of five common pollutants computed based on the concentration averaged over a 24 h period: particulate matter (PM10), sulphur dioxide (SO2), carbon monoxide (CO), ozone (O3) and nitrogen dioxide (NO2). PSI in Riau was obtained from Chevron Company in 5 locations, Dumai, Duri Camp, Duri Field, Rumbai and Minas. This data was collected and reported daily at 3 pm. According to the Indonesia Ministry of Environment regulation No. 107, PSI from 0 to 100 is considered ‘good’ to ‘moderate’ (corresponding to PM10 ≤ 150 μg m⁻³), an index value up to 199 is described as unhealthy (corresponding to PM10 ≤ 350 μg m⁻³), an index from 200 to 299 is categorized as ‘very unhealthy’ (PM10 ≤ 420 μg m⁻³), and an index more than 300 as ‘hazardous’ (PM10 ≤ 600 μg m⁻³) (Aldrian et al. 2014). Meanwhile, Singapore air quality data such as PM2.5 concentration and PSI were retrieved from the National Environmental Agency (NEA) of Singapore, while visibility was obtained from the Meteorological Service Singapore. Those pollutant concentrations are measured in five monitoring stations over Singapore. Prior to 24 August 2012, 24 h PSI was reported once a day at 4 pm. On 24 August 2012, NEA increased 24 h PSI reporting frequency to three times a day (i.e. 8am, 12 noon and 4 pm). Since 20 June 2013, 8 pm, hourly 24 h PSI reporting was implemented. From 1 April 2014, PM2.5 data was subsumed into PSI. Computational of PSI in Indonesia and Singapore are adopted from the computational of Air Quality Index established by the United State Environmental Protection Agency and
the World Health Organization (WHO). However, each country adopts different index systems based on their local needs and circumstances.

Characterization of aerosol properties has been done using the atmospheric radiation data taken from the AERONET Singapore site (Holben et al 2001). The AERONET Singapore site is located at the National University of Singapore (1.30° N, 103.77° E, 79 m above mean sea level). This site is situated off the southern part of the Malay Peninsula and north of the Indonesian Archipelago, where is an ideal place for monitoring regional pollution events such as trans-boundary biomass burning emissions, clouds, local anthropogenic emissions and climate variability (Salinas et al 2013).

Aerosol properties under the AERONET program are measured by a sun photometer instrument CIMEL Electronique CE-318A. This instrument measures the intensity of solar radiation at wavelengths 340, 380, 440, 500, 675, 870, 1020, and 1640 nm, whose results then are used to calculate the value of AOD or \( \tau_a \) as the main product. While other associated optical and physical parameters such as \( \alpha \) (Ångström 1929) and its derivative as well as its fine and coarse mode counterparts can be subsequently retrieved from these measurements. AOD is considered as an indicator of aerosol amounts in the atmospheric column. The AERONET data are available in three categories (Smirnov et al 2000): cloud-contaminated (level 1.0), cloud-screened (level 1.5), and cloud-screened and quality assured (level 2.0). There is a reduction about 60% of the amount data from level 1.5 to level 2.0 for Singapore site during June 2013. As a result, it is quite difficult to analyze the smoke event on a daily basis; therefore we use the AERONET level 1.5 dataset. The 1.5 level dataset ensures cloud screened data while maintaining the amount of data for analyzes during the smoke haze event. In this study we use the AOD at 500 nm since this wavelength represents the visible spectrum, which is the most relevant to the aerosol measurement during day time (Holben et al 2001). Beside AOD, Ångstrom exponent (AE) and aerosol particle size distribution (PSD) are also assessed. In order to complement the quantitative assessment, Hysplit trajectory model has been applied for Riau during the entire haze period.

2.3. Methodology
To study the impact of fire in Riau to the air quality condition both in Riau and Singapore we used a quantitative approach. We first identified the period of the month in which the hotspot reached its peak during 2013 and collected the rainfall data within the same period. According to the MODIS satellite, the hotspot peak occurred in June during 2013. Then, we established the relationship between the hotspot and PSI observed in 5 locations in Riau using correlation analysis. To support the correlation analysis, ArcGIS software has been used to map the distribution of hotspot and PSI sites. Correlation analysis was also established between the hotspot in Riau and both Singapore PSI and PM\(_{2.5}\) concentration. Visibility is influenced by the presence of particulate matter. Therefore, we also conducted correlation analysis between PM\(_{2.5}\) concentration and visibility in Singapore during June 2013 when the massive fire occurred in Riau.

Charaterization of aerosol pollutant founded in Singapore during the Riau fire event is conducted by analyzing AERONET data (AOD, \( \alpha \), and PSD). To justify whether the air quality in Singapore is affected by the fires in Riau, we used haze modeling with the Hysplit model. Unlike any other studies which performed back trajectory, in this paper we performed a real time Hysplit trajectory during fire events. Analyzes on the social and economic impact of fire have been done by collecting data and information through secondary data from in-depth interviews with several key persons such as the Director of Center for Data and Information of Indonesia National Agency for Disaster Management, Head of Riau Province Transportation Department and Head of Forest Fire Management section of Riau Province Forestry Department; literature studies and legal documents. In this paper, we only present the conclusion of interview result and keep the details of the interview unpublished.

3. Results and discussion

3.1. Rainfall and fire activity
Monthly rainfall and hotspots in 2013 are presented in figure 1, from which can be seen that the hotspot peak occurred in June when the lowest rainfall observed during the year that is equal to 56.08 mm. Such an amount of rainfall is far below the normal (average of 30 years) which is 145.06 mm. While April and May (the period before the fire) were also experiencing a deficit of rainfall, allowing the accumulation of the hotspot occurrence in June. Usually the lowest rainfall month is induced by an event in the Pacific basin (Aldrian et al 2003).

3.2. Impacts on ambient air quality in Riau and Singapore
3.2.1. Riau air quality condition
According to MODIS satellite observations in the period of June 2013, more than 3000 hotspots were found in Riau Province and distributed mostly in Rokan Hilir, Bengkalis (Duri), Dumai, Siak and Pelalawan region as shown in figure 2(a). Observations in May 2013 (period before the fire) showed that the PSI in five locations ranged from 20–175. As a result, from the observations in June when a massive fire event occurred, the PSI level from 12th to the end of June 2013 showed unhealthy to hazardous condition especially in Dumai and Duri. Even on June 20th, PSI...
Figure 1. Monthly rainfall at Pekanbaru Meteorological Station and provincial hotspot in 2013.

Figure 2. Distribution of 3000 hotspots detected in June 2013 and PSI monitoring sites (a); Riau PSI in 5 monitoring sites (Rumbai, Minas, Duri Camp, Duri Field, and Dumai) vs hotspots (b). The definition of thresholds is given in the section 3.2.1.
in Duri reached in 1084, as shown in figure 2(b). Positive correlations are shown between the number of hotspot and PSI in all monitoring locations. Strong and significant correlations are found in Dumai and Duri Field with $r = 0.704; p = 0.002$ and $r = 0.0596; p = 0.019$, respectively, which indicate that particulate matter was the major atmospheric pollutant contributing to the increasing value of PSI compared to any other species. A study by Anwar et al. (2010) found that a significant correlation between the number of hotspots and PM10 concentration indicates that particulate matter was the major atmospheric pollutant trigger from the biomass burning.

3.2.2. Singapore air quality condition

According to Kunii et al. (2002) and Heil and Goldammer (2001), when the dry season comes, circulation monsoon winds will normally blow from the south to north, causing emissions from fire in Indonesia to be transported across to the equator mainly to Singapore and Malaysia. Satellite imagery MODIS Terra and Aqua showed that haze emanating from Riau moved toward the east and northeast to the area of Singapore (figure 3(a)). This finding is justified by the result of the Hysplit trajectory model ran during the fire period in June 2013. The model showed that smoke haze from sources located in Riau is transported to east and northeast and headed to Singapore, building on results from Vadrevu et al. (2014) (figure 3(b)).

Figure 4(a) exhibits the relationship between hotspots in Riau province with a concentration of PM$_{2.5}$ (measuring 24 h) that were detected in Singapore. The increase in the number of hotspot is accompanied by the increase in the concentration of PM$_{2.5}$ with significance correlation $r = 0.483$ and $p = 0.023$. This result is also building on findings from Gaveau et al. (2014). The correlation value increases to $r = 0.813$ after we correlate hotspot in Riau with PM$_{2.5}$ concentration in Singapore one day later. This is in line with research of Anwar et al. (2010), who found relatively similar correlation between hotspot and PM$_{10}$ concentration in Riau during biomass burning event in 2006–2007. Artaxo et al. (1994) in his research also concluded that an increase of the concentration of small particulate matter (diameter $<2.00 \mu m$) in the dry season is the result of biomass burning.

The concurrent plot of PM$_{2.5}$ with hotspot count shows the time lag between the peaks of hotspot occurred on June 19th in Riau with the highest concentration peak of PM$_{2.5}$ on 20th that was observed in Singapore. The 24 h Hysplit model (figure 3(b)) also
confirms the propagation of smoke haze from Riau that reaches Singapore one day later. Aerosols have a life time in the atmosphere ranges from several days to several weeks and so it is possible to experience long-range transport due to the floating effect and influence of turbulence and other meteorological factors. In this case, the 20th June PM2.5 peak occurred as a result of aged smoke accumulated from 18th and 19th June peaks of hotspot number and fresh smoke contributed from 21st onwards. This result is similar to the case found in Singapore during the October 2010 haze event (Salinas et al 2013).

During the period of June 2013, the highest concentration of PM2.5 were recorded at 244.89 μg m⁻³ and far exceeded the ambient air quality standards in Singapore referring to the World Health Organization (2006) which is 25.89 μg m⁻³. Velasco and Rastan (2015), who modeled the 1 h PM2.5 concentration with statistical model during the haze crisis, revealed that PM2.5 concentration even reached over 600 μg m⁻³, which was twice from the maximum 24 h moving average reported by the NEA. Furthermore, PSI in Singapore began to rise from June 14th along with the increasing PM2.5 concentration and hotspot in Riau. PSI reached the value of 206 in the southern region of Singapore, and then gradually reduced on 24th due to a reduction of number of hotspot in Riau (figure 4(b)).

3.3. Impact on visibility in Singapore

Visibility degradation is an indicator of a polluted environment. Visibility declined due to scattering and absorption of solar radiation of particles and gaseous pollutants (Latha and Badarinath 2003, Seinfeld and Pandis 2006, Han et al 2012) primarily from aerosol particles. Figure 5 shows the variation of PM2.05 concentration and visibility at three locations in Singapore during June 2013. The visibility in Singapore was the lowest between 19 to 21 June as also illustrated by figure 1 in Velasco and Rastan (2015).

Declining visibility was coincided with the increase of PM2.5 concentration starting on 13 June as an impact of smoke haze in Riau. Lowest visibility observed was 1.01 km when the PM2.5 concentration reached the peak at 266.62 μg m⁻³. According to Han et al (2012), who studied the effects of aerosols on radiation in visibility and Tianjin-China, aerosol particles with a very small size (fine particles) such as PM2.5 have a greater effect in lowering visibility than coarser particles such as PM10. Additionally, visibility is also affected by the aerosol size distribution.
and chemical composition. The former feature is clarified by significance and anti-correlations between the PM$_{2.5}$ concentration and visibility with $r = -0.777; -0.782; -0.740$ ($p = 0.0001$) in Changi, Paya Lebar, and Seletar, respectively. Similar findings by Kusumaningtyas et al (2016) showed a considerable reduction of visibility below 500 m whenever the AOD reached above 3.00 during the biomass burning in Palangkaraya, Central Kalimantan.
3.4. Aerosol characterization in Singapore during the biomass burning period in Riau

3.4.1. Aerosol optical depth and Ångström exponent distribution

As discussed previously, one of the indicators of polluted environment is the amount of aerosol present in the atmosphere emitted from fire. AOD gives information on aerosol amount distributed in the atmospheric column through measurement of a sun-photometer instrument. In this study we try to characterize the aerosol properties from AOD, AE, and aerosol particle size distribution during biomass burning event that occurred in Riau.

Figure 6(a) presents the variation of AOD (500 nm) recorded in Singapore plotted together with hotspot numbers in Riau. Corresponding to the increase of PM$_{2.5}$ concentration in Singapore, as a result of fire occurrences in Riau, AOD will increase as well. This is consistent with numerous studies, which stated that biomass burning is expected to increase AOD. For example, Eck et al (2016) found that during the 2015 fire episode, three AERONET sites in Borneo (Palangkaraya, Pontianak, and Kuching) measured monthly mean fine modes AOD (500 nm) in September and October ranging from 1.6 to 3.7, with the daily average as high as 6.1, which is a similar finding to that of Kusumaningtyas et al (2016). Increase in AOD that coincides with an increase in fire events in Indonesia and southeast Asia was also reported earlier by several researchers (Kanniah and Yaso 2010, Rajab et al 2011, Feng and Christopher 2013). Meanwhile, Vadrevu et al (2014) conducted a research on the increase of AOD value in Riau through satellite observations in the event of fire in June 2013.

A more detailed investigation reveals that hotspot numbers started to decrease from 20 June while the AOD remained high. That feature could be explained, firstly, unlike common flaming combustion, fires in peatland have typical smoldering combustion and underground fires (Elvidge et al 2015). As concluded by Gaveau et al (2014) that 84% of peat area in Riau was burned during that time. Although no hotspots were detected, the emission continued to be released into the atmosphere. Secondly, it is likely due to the accumulation of emissions resulting from the fire on the earlier days. Thirdly, it could be the result of failed detection of a hotspot due to persistent cloud cover or timing of MODIS satellite orbit. Another parameter that can provide information on the source of aerosol pollutant is the Ångström exponent ($\alpha$). The Ångström parameter is the first derivative (negative slope) of AOD at specific wavelengths. Figure 6(b) presents the scatter plot of AOD and $\alpha$, which is quite useful to describe their respective aerosol amount and size in atmospheric column. Therefore, the combined analyzes of these two parameters would provide a better interpretation.

The study found that there were several types of aerosols present in Singapore. The value of $\alpha < 1$ indicates that the size of the aerosol is dominated by coarse particles (radius $> 2.5 \mu m$) from dust and seasalt, whereas $\alpha > 1$ indicates the presence of fine aerosol (radius $< 2.5 \mu m$) associated with urban pollution and biomass burning emissions (Holben et al 2001, Salinas et al 2009, Salinas et al 2013). Aerosol from urban areas has a higher $\alpha$ with AOD variation depending on the level of pollution (concentration of aerosols) in the atmosphere as a result of urban activity. On the other hand, AOD from biomass burning can reach up to 6 in heavy smoke coming from peatland fire (Kusumaningtyas et al 2016).

Higher AOD in the range of 0.8 to 1.3 and $\alpha$ varies from 1.3 to 1.7 (showed by the dashed line circle) indicates the domination of fine particles during a biomass burning event. Furthermore, this phenomenon occurred mainly on 22 to 30 June when Singapore experienced air quality degradation as a result of haze transported from Riau. The solid line circle on figure 6(b) indicated the existence of coarse aerosol particles with lower AOD variations from 0.25–0.75 and $\alpha$ lower than 1.0. This type of aerosol may originate from dust and sea-salt considering this region near Malaka Strait. Salinas et al (2009) and Asmat et al (2012) showed similar result which found dust contamination and sea-salt in Singapore and Kuching (Malaysia) under normal condition.

3.4.2. Particle size distribution

Particle size distribution is another parameter, which can help to identify the aerosol particle type. This parameter is helpful in identifying the particle concentration numbers for a bimodal aerosol size distribution. In addition, the parameter delivers information on particle size composition, which is beneficial to identify the pollutant source; its impact on visibility; its behavior related to transport and deposition mechanisms; and its effect to climate system. These distributions were derived from the algorithm by Dubovik et al (2000), which utilized measurements of spectral $\tau_a$ and almucantar sky radiance distributions from a CIMELS sun-sky radiometer (Eck et al 2001).

The retrieved aerosol size distributions during burning season (June 2013) are shown in figure 7. The distribution was a bimodal type of distribution representing fine and coarse mode. The distribution of fine particles with radius $< 0.33 \mu m$ (dashed line circle) for Singapore shows a large increase on 24th to 28th (dashed line rectangular) due to transportation of smoke aerosol from biomass burning in Riau to Singapore. This situation corresponds with previous sections (sections 3.2.2 and 3.4.1), in which PM$_{2.5}$ concentration and AOD ($\alpha > 1$) increase during same period. The smoke event reaches its highest fine mode concentration at 0.176 $\mu m^3 \mu m^{-2}$ with radius $\approx 0.25 \mu m$. The coarse mode contribution is relatively low with volumetric distribution $\approx 0.126 \mu m^3 \mu m^{-2}$. In detail, domination of coarse mode (solid line circle) occurs in the period of early June or pre-burning (solid
This could be an indication of dust and sea-salt existence.

3.5. Social and economic impacts

Clearing of peatland for plantations using fire, which carried out by small farmers to large corporations, is considered cheap and effective. However, the consequences and collateral impacts caused by the fire are much more expensive. Haze crisis in June 2013 has paralyzed the economy not only in Riau but also in Singapore as an affected country. According to the Regional Economic Assessment Report of Bank of Indonesia (2014), the economic performance of Riau on the third and fourth quarter of 2013 slowed down. Without taking into account of oil and gas businesses, Riau economic growth in the third and fourth quarters of 2013 recorded, respectively, 3.93% and 6.01% lower than the second quarter, which reached 6.74%. The Bank of Indonesia reported that the increase in inflation in the third and fourth quarters of 2013 caused by disruption of goods distribution and infrastructure due to natural disasters. In this case the haze crisis that occurred in June 2013 contributed to the Riau economic slow down. Riau is one of the top five regions with highest GDP in Indonesia, therefore the decreasing of Riau GDP would affect national economic.

Smoke haze in June 2013 and February–March 2014 led to the disruption of transportation facilities such as slowing business productivity and delays of distribution of goods and services which at the end may result in rising prices of basic commodities. According to Head of Riau Transportation Department, the smoke haze in June 2013 caused delays on fuel distribution. As a result, the traveling time was doubled. Angkasa Pura or the Pekanbaru (Riau Province capital) Airport administrator suffered a total estimated loss of Rp 147 273 1147.71 ($108 thousand USD) due to delays and cancellations of domestic and international flights. The World Bank (2014) also noted that the devastating fire in February–March 2014 resulted in huge environmental damage and economic losses estimated at 935 million US dollars, or 2.8% of GDP Riau Province in 2014 (projected GDP). That numbers is not including the government’s costs for health care and fire fighting operations.

Based on separate interviews with several key persons such as the Director of Center for Data and Information of Indonesia National Agency for Disaster Management, Head of Riau Province Transportation Department and Head of Forest Fire Management section of Riau Province Forestry Department, there are several factors that hinder the implementation of forest and land fire prevention and smoke haze management policies, which among others are weak leadership and law enforcement, lack of coordination among institutions in local level and low utilization of early warning information. These interview results are similar with previous findings from Quah and Varkkey (2013), and Herawati and Santoso (2011).

4. Conclusions

This study highlights the impact of the Sumatra smoke haze event during June 2013 on regional air pollution based on several in situ observations. The study provides a comprehensive approach using physical relationship, remote sensing, air quality modeling and socio-economic impact studies. Several combinations of environment parameters such as hotspots, rainfall and visibility with aerosol parameters such as PSI, hysplit modeling and PM$_{2.5}$ concentration establish clear and supporting evidences of the pollution source and pollution impacted areas relationship. Hotspots in Riau in June 2013 were found to reach more than 3000 in just a week. Trajectory modeling with Hysplit showed that smoke fire moves towards the east and northeast towards Singapore. A decline in air quality
in Riau and Singapore were marked by the increase in the value of PSI in Riau that reached up to 1084 (hazardous category), the increase in the concentration of PM$_{2.5}$ and decrease visibility in Singapore. Positive correlation was shown by PSI and hotspots in Riau. Positive correlation of 0.483 was also shown between the concentration of PM$_{2.5}$ in Singapore and hotspots in Riau. Conversely, visibility and hotspot have a strong and opposite relationship of $-0.766$. Characterization of aerosols through AOD parameters, Ångstrom, and particle size distribution showed a small aerosol with a greater distribution on the date of 19 June 2013 coinciding with a period of fires in Riau. In summary, the existence of trans-boundary pollution has also been identified by characterizing aerosols in Singapore, which indicates the dominance of small-sized aerosol that are identical to the source of the fire biomass in Riau. The Riau fire in June 2013 proved to slow down the economic both in Riau and Singapore by disruption of transportation facilities such as slowing business productivity and delaying the of distribution of goods and services, which at the end result in a price hike of basic commodities.

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