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A study of the effect of open biomass burning aerosol on rainfall event over Malaysia by using EOF analysis

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Abstract. Significant biomass burning aerosols resulted from biomass burning activities from Sumatra and Kalimantan Island transported to Malaysia every year from August to October by the southeast monsoon. These transboundary haze changes the precipitation pattern by aerosol interaction with radiation and cloud which affects the solar radiation budget and cloud condensation nuclei properties. In this work, empirical orthogonal function (EOF) was used to assess the effect of biomass burning aerosol on rainfall pattern over Malaysia from both a spatial and a temporal perspective. Over Peninsular Malaysia, regional rainfall activities tend to be suppressed by concentrated biomass burning aerosols and produce another heavy rain over the downwind areas after 30-60 days (60 days) under highly (less) populated condition. Similar precipitation pattern has been indicated over Sarawak and Sabah where biomass burning aerosols suppress rainfall in the southwestern area while leads to a more intensified rainfall event in the northeast area with 30-60 days (60 days) interval under highly (less) populated condition.

Keywords: Biomass Burning Haze; EOF; Precipitation

1. Introduction

Haze has been investigated all over the world by scholars because dispersed aerosol particles are one of the greatest threats to human life [1]. Forest fires (natural sources) and biomass burning (anthropogenic sources) in Indonesia are the major emissions in the Maritime Continent. They release a huge amount of gas and aerosol particles into the atmosphere and contributing 0.9-1.1% to global biomass emissions in 2007 [2;3;4]. The scale of the open biomass burning activity affects by both primary (human actions) and secondary factors (climate phenomena) [5]. Due to its simplicity and affordable costs, cultivators use 'slash-and-burn' to clean the soil by fire. In China, a similar cleaning procedure is used, with roughly

20-30% of the residue being burned following the harvesting season [6]. Other than agricultural burning activity, climate phenomena is another factor that affects fire scale. In the El Niño year, the Maritime Continent is usually under dry condition with reduces atmospheric humidity and suppresses rainfall events over the region from June and November. Therefore, fire events become harder to control and fire duration is extended. The number of hotspots observed in El Niño year is three to four times that of non- El Niño years [5]. Several server haze episodes have been documented in Malaysia by the Department of Environment Malaysia, with the haze event in 2015 being the most severe since 1997 [7]. The haze episodes from end of August to October in 2015 was defined as transboundary haze from Indonesia due to the high correlation between biomass burning tracer (cationic surfactants) and agricultural practice in Sumatra and Kalimantan. Haze particles are mainly transported by the southwest monsoon and takes 2-3 days travel from Indonesia to Malaysia [1].

The biomass burning aerosols able to affect precipitation through altering the solar energy budget and could properties [8]. Concentrated anthropogenic aerosols tend to heat atmosphere (absorb radiation) and cause surface cooling (reflect radiation) at same time, which suppress the convection and reduce rainfall event. When the anthropogenic aerosol acts as cloud condensation nuclei (CCN), it could affect precipitation frequency and intensity if it is highly concentrated in the atmosphere [9]. Under the clean condition, clouds with more CCNs forms from natural sources (such as dust) are easily rain off in the shallow atmosphere when it becomes heavy enough. While under the polluted condition, clouds contain tinnier CCNs which formed from anthropogenic sources. Precipitation is unlikely to form at shallow atmosphere but raise to the higher amplitude. In contrast to the rainfall pattern under clean conditions (rainfall occurs in the shallow atmosphere), a significant number of cloud droplets rise to the high atmosphere and create rainfall with greater intensity under polluted conditions.

According to the studies, large aerosol concentrations is able to delay the rainfall and also increase intense for the later raining event. However, no previous research has been conducted on the focus of how long the rainfall will be delayed and how far the raining region will be affected from the high aerosol concentrated area. Therefore, the aim of this paper is to understand the relationship between haze and precipitation from both temporal and spatial aspects on the hazes occurs from 2014 to 2016 in Malaysia.

2. Methodology

The NASA Worldview server was used to display the map of thermal anomalies from August to October in 2014, 2015 and 2016 for representing the biomass burning (BB) activities during the period. The Global Precipitation Measurement (GPM) with resolution of 0.1 º x 0.1º was selected for dataset of precipitation event as it is more accurate result on the light rain over the tropical and subtropical oceans. In addition, Aerosol Optical Density (AOD) from Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) with 0.5 º x 0.625 º resolutions used to represent the BB hazes that released to the atmosphere through burning activities. AOD of less than 0.1 (bigger than 1) indicates a clear sky with maximum visibility (very polluted atmospheric environment). The region covers the Malaysia (steady area) and Indonesia (main emission sources) with coordinate of 7.3ºN, 94.8ºE to 8.6ºS, 121.8ºE.

Empirical orthogonal function analysis (EOF) was used for demonstrating the spatial and temporal association between aerosol and rainfall. It uses to maximise the variance of the dataset and extract the most prominent variation mode from it. Each mode reflects a single physical mode and is independent of the others.

3. Results and discussions

3.1 Biomass burning aerosol background environment

Overall, the majority of fires occurred in Indonesia from September to October, with little hotspots observed in Malaysia. Figure 1 shows that 2015 had the largest number of burning activities, followed by 2014 and 2016. Fires spread over the island of Kalimantan (Indonesia) in August 2014 and concentrated in southeast Sumatra and southern Kalimantan between September and October. There were also some burnings detected along the southwest Peninsular Malaysia (PM) from September to October. In 2015, fires in Sumatra and Kalimantan started form August and spread to the central part of the island in October. In 2016, only little burning was recorded in northwest Sumatra and PM.

The average monthly AOD also shows a consistent spatial and temporal pattern with fire spot map, as shown in Figure 2, where 2015 was the severest. Higher AOD was found in central-south Sumatra and southwest Kalimantan during September to October 2014, which correlates rather well with the burning site, as shown in Figure 1. When compared to the same period in 2014 and 2016, the monthly AOD in 2015 is the greatest. Aerosols originate in Southeast Sumatra and Southwest Kalimantan, then travel north-westly (Central-north Sumatra & Southeast PM, South China Sea (SCS) & Southeast Sarawak), indicating that the haze event in Malaysia during the southwest monsoon season was largely contributed by fire activities in Indonesia. The year 2016 is a non-haze year with average AOD values falling below 0.4 throughout the western Java Island.

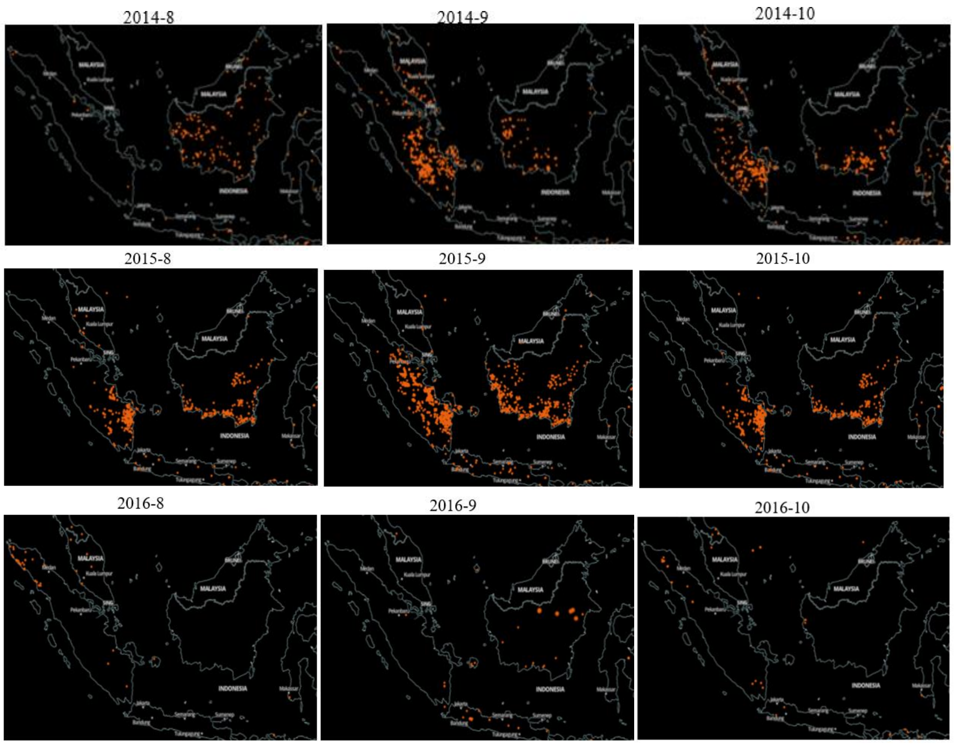

Figure 1. Fire spots from Aug.-Oct. 2014, 2015 and 2016

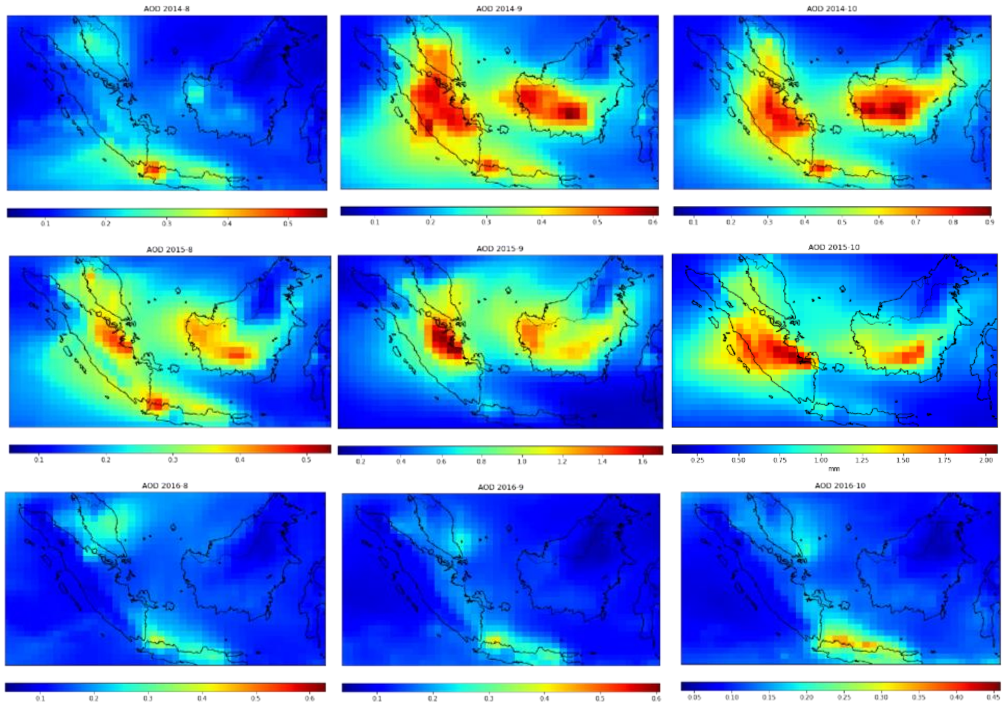

Figure 2. Monthly AOD from Aug.-Oct 2014, 2015 and 2016

3.2 EOF analysis of AOD and Precipitation

As the aim is to investigate the spatial-temporal relationships between biomass burning haze and precipitation for helping the government on giving precaution to the public, analysis will focus on the mainland Malaysia, and minimise the coverage of ocean as it has different atmospheric condition (humidity, surface temperature) from the continent. The mainland Malaysia divides into West Malaysia (PM) and East Malaysia (Sarawak and Sabah) in the following sections. Table 1 and Table 2 present the eigencoefficient for each EOF mode from 2014 to 2016 on the AOD and precipitation respectively. The region of major variation was determined from column a in Figure 3 and Figure 4, and the corresponding period (|PC|>1) was obtained from column b and c.

Table 1. 1st and 2nd principal mode of EOF analysis on AOD from Aug. to Dec. from 2014 to 2016 in East and West Malaysia

EOF (Eigencoefficient)			Major variation	
			Region ;(+ or - PC)	Period
East Malaysia AOD	2014	EOF1 (61%)	South Sarawak ;(+)	15th Sept. – 20th Oct.
		EOF2 (8%)	Northwest Sabah(Sarawak) ;(+), Southeast Sabah(Sarawak) ;(-)	-
	2015	EOF1 (70%)	Northwest Sarawak ;(+)	15th Sept. – 31st Oct.
		EOF2 (8%)	Northwest Sabah(Sarawak) ;(+), Southeast Sabah(Sarawak) ;(-)	-
	2016	EOF1 (41%)	Northwest Sarawak	1st Aug. – 1st Sept.
		EOF2 (12%)	Northwest Sabah(Sarawak)	-
	2014	EOF1 (51%)	Southwest PM ;(+)	10th Sept. – 10th Nov.

West Malaysia AOD		EOF2 (12%)	Northwest PM ;(+), Southeast PM ;(-)	-
	2015	EOF1 (60%)	Central PM ;(+)	10th Sept. –31st Oct.
		EOF2 (11%)	Northwest PM ;(+), Southeast PM ;(-)	-
	2016	EOF1 (41%)	Central PM ;(+)	10th Aug. – 10th Oct.
		EOF2 (14%)	Northwest PM ;(+), Southeast PM ;(-)	-

From Figure 3, it can be seen that the AOD varied the most over South Sarawak from mid of Sept. to mid of Oct. in East Malaysia (EM). It could be seen as the transboundary haze from Indonesia as aerosols are mainly concentrated in Kalimantan from Figure 2. In 2015, aerosols were apparently transported further north in Sarawak with strong AOD correlation between mid-September and end of Oct. In 2016, the 1st EOF mode demonstrates the arrives of aerosols in Sarawak coastline in Aug. In West Malaysia (WM), AOD varies the most from mid-Sept. to late Oct. (Aug. to early Oct.) in 2014 and 2015 (2016). In 2014, southern PM (Selangor and Melaka) exposed to a haze event from Sept. to Oct. with a PC value greater than 0.8. In 2015, the situation worsened as the it spreads across the entire central PM. For 2016, the spatial distribution of first mode consists with the fire spots in Figure 1, where the haze is mainly due to local biomass burning rather than transboundary haze. From second EOF mode, Southeast Sarawak, Sabah and PM show the negative correlation with Northwest Sarawak, Sabah and PM, and the value of PC changes alternately between positive and negative on the time-axis. This AOD pattern depicts how the BB aerosols moves in Malaysia.

Consider the EOF2 of WM in 2015, a negative PC is noticed in late Aug., followed by a positive PC in early Sept., then a negative PC dominates until mid-Oct. and then changes back to a positive PC. In accordance with the AOD spatial distribution, haze reach Southeast PM (blue) in end of Aug. and travel to Northwest PM at early Sept. Another group of haze particles travels from Sumatra to Southeast PM between mid-September and mid-October, then reaches Southeast PM and forms precipitation there by referring to Figure 4. By comparing the time for major variation occurs between AOD and precipitation, heavy rainfall occurs on average 60, 30 and 60 days after the haze episodes in 2014, 2015 and 2016, respectively in both EM and WM. By following the spatial-temporal pattern in the 1st EOF mode in Figure 3, more heavy rainfall events observed in Oct. and Dec. (Dec.) over Northwest Sarawak (East PM). From the second EOF mode, Southwest East (West) Malaysia shows a strong negative spatial correlation with Northeast East (West) Malaysia in 2014 and 2015. The negative correlation pattern in 2014 differs between 2015 and 2016.

Table 2. 1st and 2nd principal modes of EOF analysis on rainfall from Aug. to Dec. from 2014 to 2016 in East and West Malaysia

EOF (Eigencoefficient)			Major variation	
			Region ;(+ or - PC)	Period
East Malaysia Rainfall	2014	EOF1 (20%)	Northwest Sarawak ;(+)	11st Nov. –31st Dec.
		EOF2 (8%)	Southwest Sarawak ;(-), Sabah ;(+)	-
	2015	EOF1 (22%)	Northwest Sarawak ;(-)	20th Oct. –15th Dec.
		EOF2 (9%)	Northwest Sarawak ;(+), Southeast Sabah ;(-)	-
	2016	EOF1 (22%)	Northwest Sarawak ;(-)	20th Oct.; 10th Dec.; 25th Dec.

		EOF2 (8%)	Northwest Sarawak, Sabah ;(-)	-
West Malaysia Rainfall	2014	EOF1 (27%)	Southeast PM ;(+)	15th Nov.; 15th Dec.- 31st Dec.
		EOF2 (14%)	Northeast PM ;(+), Southwest PM ;(-)	-
	2015	EOF1 (18%)	Northeast PM ;(+)	20th Oct. –1st Dec.
		EOF2 (9%)	Northeast PM ;(+), Southwest PM ;(-)	-
	2016	EOF1 (24%)	Northeast PM ;(+)	20th Oct. – 10th Nov.; 25th Nov – 10th Dec.
		EOF2 (9%)	Northwest PM ;(+), Central-East PM ;(-)	-

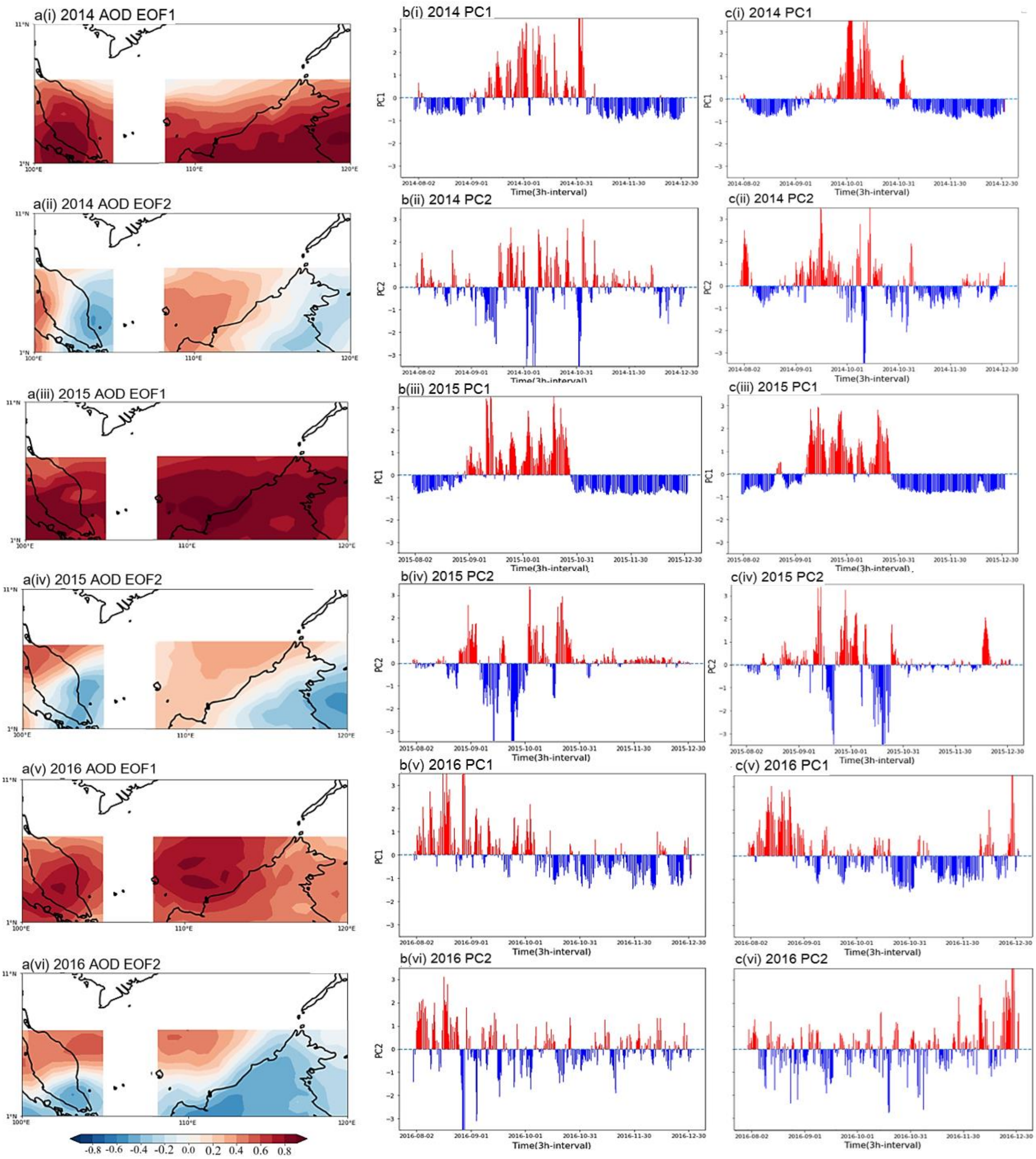

Figure 3. 1st and 2nd principal modes of EOF analysis on AOD from Aug. to Dec. from 2014 to 2016 in East and West Malaysia. Column a present the two EOF modes; column b present PC in 3-hr interval corresponding to the EOF mode over West Malaysia; column c present PC in 3-hr interval corresponding to the EOF mode over East Malaysia.

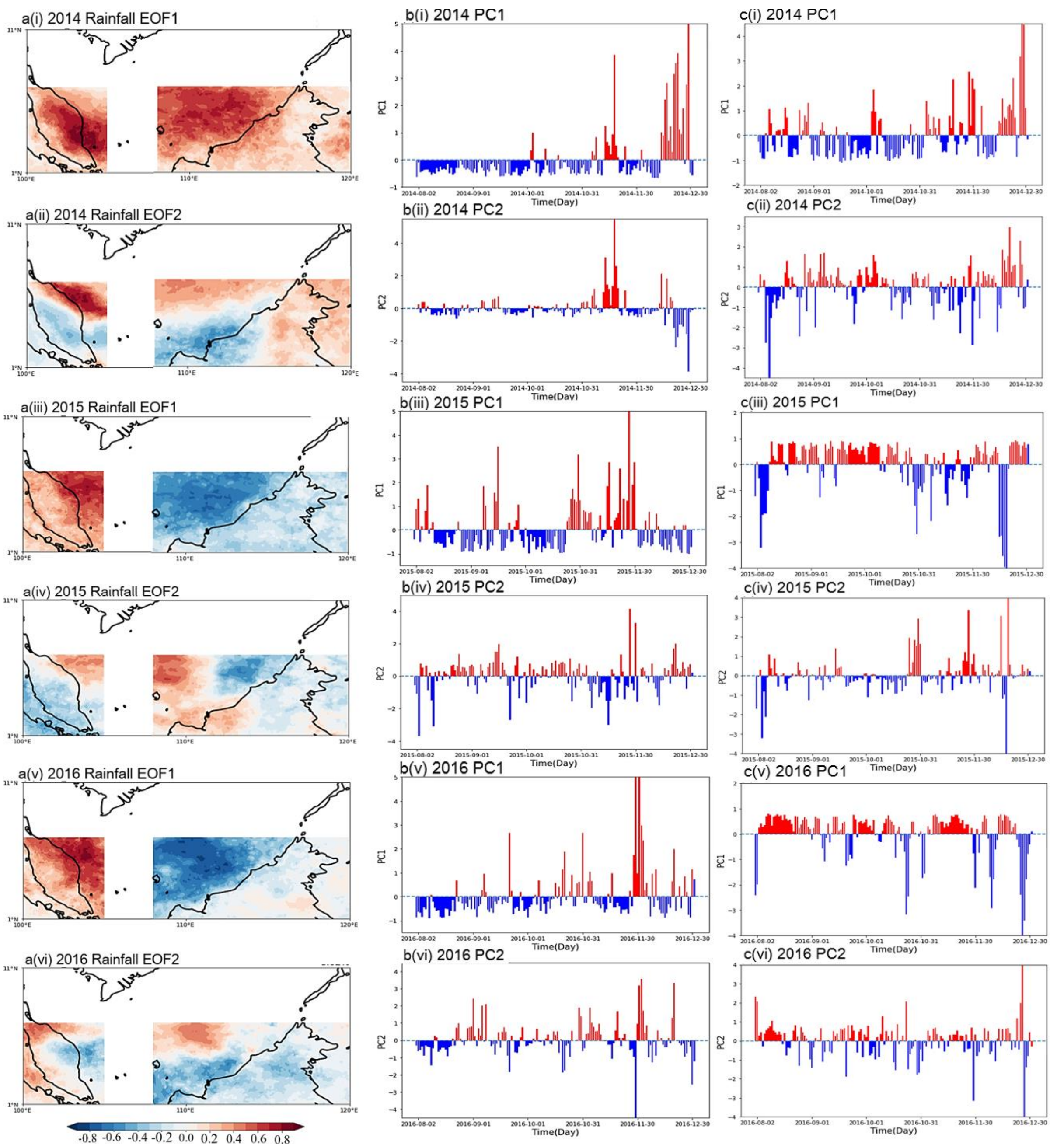

Figure 4. 1st and 2nd principal modes of EOF analysis on rainfall from Aug. to Dec. from 2014 to 2016 in East and West Malaysia. Column a present the two EOF modes; column b present PC in 1-day interval corresponding to the EOF mode over West Malaysia; column c present PC in 3-hr interval corresponding to the EOF mode over East Malaysia.

3.3 Comparison between AOD and Precipitation EOF modes

In order to have better understanding on the relationship between BB haze and rainfall, detailed discussion will be carried out in this section. The first EOF mode pattern of AOD and rainfall are used to discuss as they cover the highest percentage of dataset. Average precipitation over WM and EM during and after haze period were produced as Figure 5, and Table 3 summaries the location and period of high rainfall intensity (red spots) and low rainfall intensity (dark blue) during and after haze period form the figures. In EM, rainfall has been suppressed in regions (Southeast Sarawak) with large AOD concentrations as shown in 2014 and 2015. In 2014, a transboundary haze was observed between mid-September and mid-October, which suppress the local rainfall event at Southeast Sarawak and produce a precipitation with intensity of 30 mm at coastline after 60 days. In 2015, large amounts of aerosol reached Sarawak between mid-September and late October and formed into could droplet but did not rain down immediately. The monsoonal wind circulation transports some cloud droplets to the SCS, but the majority remain where they are and rise to greater amplitude. As the result indicated in Figure 5, heavy rainfall event occurs at two locations after 30 days. 2016 is thought to have been less influenced by the haze particle since rainfall intensity did not alter much throughout and after the haze event.

As for the spatial-temporal rainfall pattern during and after the haze event in WM, rainfall over Southwest PM (high aerosol concentration) is noticeably lower in 2014 than in the Northwest PM (low concentration of aerosols). A heavy rainstorm with maximum intensity of 50 mm that occurs between Kuala Terengganu and Kuantan two months after the haze episode. Theoretically, one of the probable explanations of this intense rainfall event may be that a lot of small CCN droplets migrate from the Southern PM to the Northwest PM, then accumulate and rain down. The government must establish emergency plans for such catastrophic events since they might cause significant losses due to agriculture damage and urban floods.

Table 3. Summary of AOD and rainfall in East and West Malaysia during and after haze period from 2014 to 2016

Region				Period
2014 East Malaysia	During Haze Episode	Largest AOD variation	South Sarawak	15th Sept. – 20th Oct.
		High rainfall intensity	Coastal area of Sabah	
		Low rainfall intensity	South Sarawak	
	After Haze Episode	High rainfall intensity	Northwest Sarawak, SCS	10th Nov. – 31st Dec.
		Low rainfall intensity	Sabah	
2015 East Malaysia	During Haze Episode	Largest AOD variation	Northwest Sarawak	15th Sept. – 31st Oct.
		High rainfall intensity	Sarawak	
		Low rainfall intensity	Southeast Sabah	
	After Haze Episode	High rainfall intensity	Sarawak, SCS	20th Oct. – 15th Dec.
		Low rainfall intensity	Sabah	
2016 East Malaysia	During Haze Episode	Largest AOD variation	Northwest Sarawak	1st Aug. – 1st Sept.
		High rainfall intensity	Southeast Sabah	
		Low rainfall intensity	East Sarawak	
	After Haze Episode	High rainfall intensity	Coastal area of Northwest Sarawak and Southeast Sabah	20th Oct. – 25th Dec.
		Low rainfall intensity	Sabah	
2014	During	Largest AOD variation	Southwest PM	

West Malaysia	Haze Episode	High rainfall intensity	Coastal area of Southwest PM,	10th Sept. – 10th Nov.
		Low rainfall intensity	Southeast PM	
	After Haze Episode	High rainfall intensity	East PM	15th Nov. – 31st Dec.
		Low rainfall intensity	West PM	
2015 West Malaysia	During Haze Episode	Largest AOD variation	Central PM	10th Sept. – 31st Oct.
		High rainfall intensity	Coastal area of West PM	
		Low rainfall intensity	Central-South PM	
	After Haze Episode	High rainfall intensity	Northwest PM	20th Oct. - 1st Dec.
		Low rainfall intensity	Central PM	
2016 West Malaysia	During Haze Episode	Largest AOD variation	Central PM	10th Aug. – 10th Oct.
		High rainfall intensity	Coastal area of Southwest PM	
		Low rainfall intensity	Central PM	
	After Haze Episode	High rainfall intensity	Coastal area of East PM	20th Oct. – 10th Dec.
		Low rainfall intensity	Central PM	

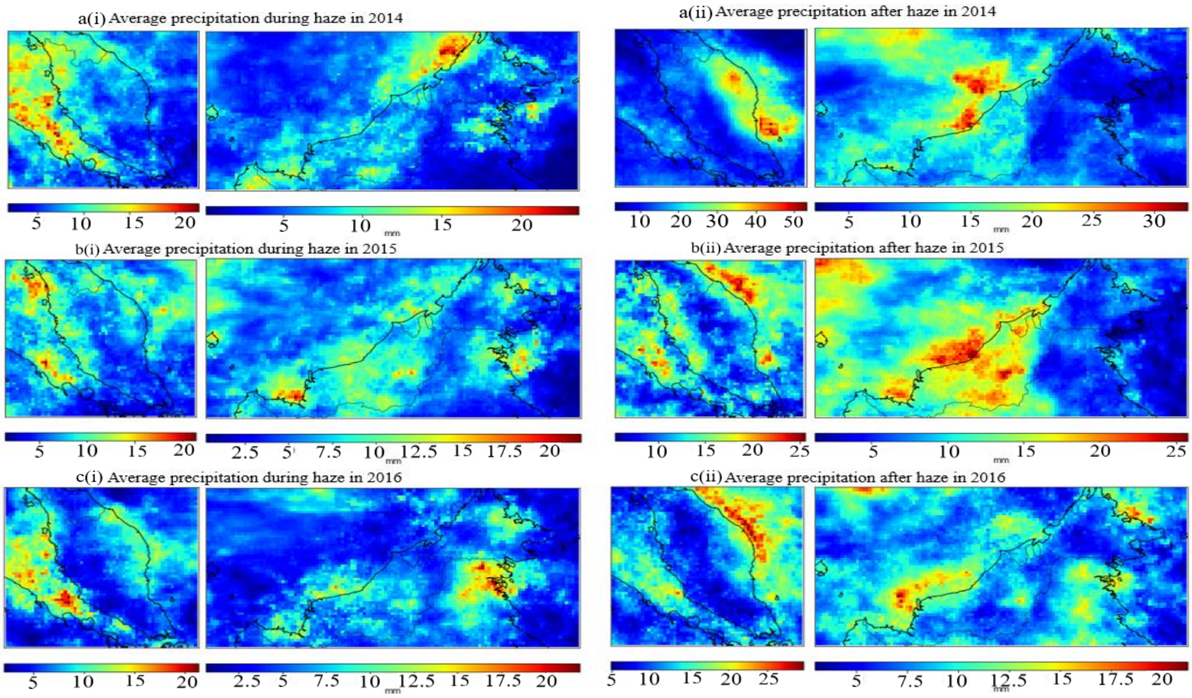

Figure 5. Average rainfall (mm) of East and West Malaysia during (i) and after (ii) the haze period from 2014 to 2016

4. Conclusion

This study has looked at both the spatial and temporal effects of biomass burning on precipitation in Malaysia. The haze episode in 2015 and 2014 was chosen as the primary research subject, and the reference year without haze, 2016 is selected in this study. Empirical orthogonal function (EOF) analysis was carried out to extract the strongest spatial-temporal model from Aerosol Optical Depth and Global

Precipitation Measurement dataset. The discussion focusses on the result of the EOF first mode of AOD and precipitation as it covers the largest portion of dataset. In East Malaysia in 2014, high concentrations of aerosols suppressed precipitation in South Sarawak from mid-September to mid-October. In the following 60 days, these aerosols continue migrate north and rain down in Northwest Sarawak. 2016 is also depicted with a two-month delay in rainfall activity. A similar pattern of aerosol transport was discovered in 2015 which travel from Southeast to Northwest with a 30-days delay. In West Malaysia, aerosols have been observed to arrive in Southwest PM and suppress local precipitation, then move to Northwest PM with an extreme rainfall event with delay of 60 days, 30 days, and 60 days after the haze episode in 2014, 2015, and 2016, respectively. Using this conclusion, the Malaysian government may briefly identify the impacted range of a haze event and warn towns and villages inside the range of the possibility of drought during the haze episode since precipitation has been suppressed in the short term, as well as floods after 30 - 60 days.

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