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Key Points:
- Three recent, severe haze events in the Malay Peninsula cannot be explained by El Nino-positive Indian Ocean Dipole conditions
- All three events are associated with anomalous westerly wind speeds occurring over Riau as the Madden-Julian Oscillation moves across Indonesia
- Late phases of the MJO are associated with the transport of extreme smoke pollution from Riau province to the Malay Peninsula

Supporting Information:
- Supporting Information S1

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Role of the Madden-Julian Oscillation in the Transport of Smoke From Sumatra to the Malay Peninsula During Severe Non-El Niño Haze Events

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Abstract In June 2013, the Malay Peninsula experienced severe smoke pollution, with daily surface particulate matter (PM) concentrations in Singapore greater than 350 μg/m^3, over 2 times the air quality standard for daily mean PM_{10} set by the U.S. Environmental Protection Agency. Unlike most haze episodes in the Malay Peninsula in recent decades (e.g., the September 2015 event), the June 2013 haze occurred in the absence of an El Niño, during negative Indian Ocean Dipole conditions, with smoke carried eastward to the Peninsula from fires in the Riau province of central Sumatra. We show that June 2013 was not an exceptional event; inspection of visibility data during 2005–2015 reveals two other severe haze events in the Malay Peninsula (August 2005 and October 2010) occurring under similar conditions. Common to all three events was a combination of anomalously strong westerly winds over Riau province concurrent with late phases of the Real-Time Multivariate Madden-Julian Oscillation Index, during negative phases of the Indian Ocean Dipole. Our work suggests that identifying the meteorological mechanism driving these westerly wind anomalies could help stakeholders prepare for future non-El Niño haze events in Singapore and the Malay Peninsula.

1. Introduction

During 18–23 June 2013, Singapore experienced one of its worst air pollution events on record, with daily surface particulate matter (PM_{10}) concentrations exceeding 350 μg/m^3 on 20 June as measured by the Singapore National Environment Agency (http://www.nea.gov.sg/; Hertwig et al., 2015). This level of pollution is 2 times the 150 μg/m^3 air quality standard for daily PM_{10} designated by the U.S. Environmental Protection Agency. The pollution was severe across much of the southern Malay Peninsula, with daily PM concentrations reaching 400 μg/m^3 as far away as Port Dickson, ~300 km to the northwest of Singapore (Hertwig et al., 2015). Subsequent research has attributed the June 2013 haze across the Malay Peninsula to smoke from agricultural fires in the Riau province of central Sumatra (Gaveau et al., 2014; Kusumaningtyas & Aldrian, 2016), ~100-km upwind (Figure 1).

The Malay Peninsula is typically most affected by severe smoke during September–October under El Niño phases of the El Niño Southern Oscillation (ENSO; Rasmusson & Wallace, 1983, and references therein) and positive Indian Ocean Dipole (pIOD; Saji et al., 1999) conditions, which together lead to drought and enhanced fire potential across Indonesia (Field & Shen, 2008; Field et al., 2016). The prevailing southerlies during the Southwest Monsoon carry smoke from burning in southern Sumatra to form intense haze events downwind in August to early October—for example, September 1997 (Koe et al., 2001). Kalimantan (Indonesian Borneo) fires can also impact the Malay Peninsula in October in association with a weakened or transitioning monsoon (Reid et al., 2012; Xian et al., 2013), most notably in October 2015. In contrast, the intense haze in June 2013 occurred under ENSO-neutral conditions during a negative phase of the IOD (nIOD), which is often associated with increased precipitation over Indonesia (Li et al., 2003), and well before the more typical agricultural burning in Riau initiates in August (Reid et al., 2012). At least two other significant haze events in the region not associated with El Niño-pIOD conditions have recently occurred, affecting (1) Kuala Lumpur, a dense urban area northwest of Singapore, in August 2005 (Aglionby, 2005; Forsyth, 2014),

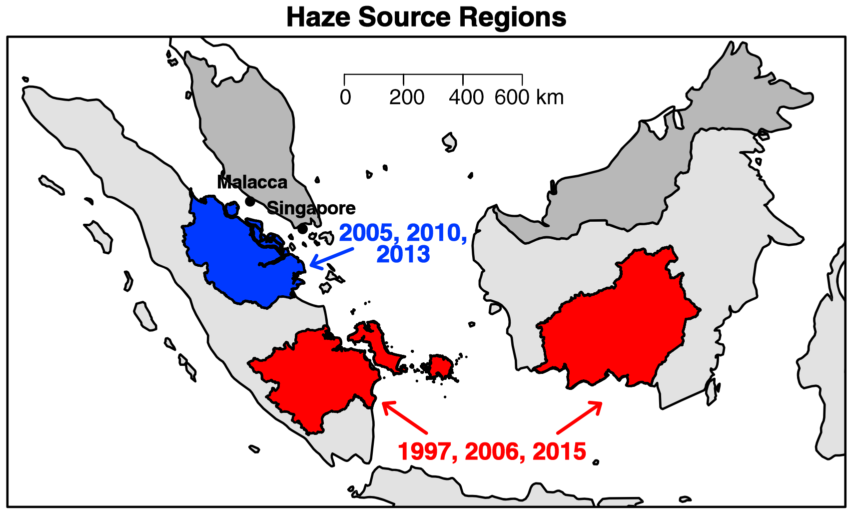

Figure 1. Provinces contributing to severe haze in Equatorial Asia. Riau province, where fires associated with haze in the Malay Peninsula occurred during August 2005, October 2010, and June 2013, is shown in blue. In red are provinces associated with burning during the El Niño-pIOD events in 1997, 2006, and 2015 (from west to east: South Sumatra/Bangka-Belitung, Central Kalimantan). Other Indonesian provinces are shown in light grey; Malaysia is dark grey. Singapore and Malacca are denoted by black circles.

and (2) Singapore in October 2010 (Salinas et al., 2013). To our knowledge, no study has examined the common characteristics in the smoke transport patterns during these three, meteorologically similar haze events. In this work we use visibility data from two sites in the Malay Peninsula together with observations of fire activity in Riau and assimilated meteorology to investigate the drivers of smoke transport to the Malay Peninsula during August 2005, October 2010, and June 2013. In particular, we examine the influence of the phase of the Madden-Julian Oscillation (MJO) on smoke transport from Sumatra to the Malay Peninsula during these events. Better understanding of the meteorological mechanisms that lead to extreme ENSO-neutral haze events in the Malay Peninsula could provide a means to predict when such events are likely to occur in the future.

Fires for land clearing and management have increased rapidly in Indonesia since the 1970s, particularly in coastal peat swamps (Page et al., 2009). Emissions of particulate and gaseous pollution from peat fires are estimated to be twice those emitted from other tropical forest fires (Levine, 1999; Page et al., 2002). The extreme haze events that sometimes accompany agricultural fires in Indonesia exert a severe toll on human health because of the very high population density. Estimates of premature mortality across Equatorial Asia from the severe smoke pollution events in 1997 and 2015 range from 12,000 to 300,000 excess deaths per event (Crippa et al., 2016; Johnston et al., 2012; Koplitz et al., 2016; Marlier et al., 2013). These events also weaken local economies through airport closures, suspended economic activity, and reductions in tourism (Glover, 2006). Understanding the meteorological pathways of severe haze events in this region has particular importance as the population continues to grow rapidly, and land clearing for agricultural use expands. By 2030, fire emissions from agricultural activities in Sumatra are expected to more than double (Marlier et al., 2015a).

While the regional smoke events of 1997, 2006, and 2015 have received significant attention, there is far less literature documenting drivers of severe smoke episodes during nondrought conditions in Indonesia, such as the June 2013 haze in Singapore. Gaveau et al. (2014) quantified a relationship between fire radiative power (FRP) and Riau precipitation and found that high fire activity in northern Riau during June 2013 followed a 2-month drought there. Gaveau et al. (2014) further proposed that monsoonal westerlies typical at that time of year carried the June 2013 smoke across the Straits of Malacca to the Malay Peninsula, leading to the severe haze in Singapore and the surrounding area. The Gaveau et al. (2014) relationship of FRP with precipitation in Riau leaves two issues unresolved. First, two outliers in the plotted relationship, October 2010 and August 2005, suggest that other factors play a role in driving fires in this region (Figure 3 in Gaveau et al., 2014). In both these cases, anomalously high fire activity followed a 2-month period of relatively high precipitation. Second, two other high fire months identified by Gaveau et al. (2014), June 2005 and July

2006, also occurred during months with monsoonal westerlies, but unlike in June 2013, the fires in these months did not lead to severe haze in the Malay Peninsula. In this work we build on Gaveau et al. (2014), focusing primarily on the second of these two unresolved issues by identifying meteorological patterns associated with efficient transport of dense smoke from Riau to the Malay Peninsula. While we will investigate haze transport during the events of October 2010 and August 2005 in detail, the purpose of this paper is not to explain the drivers of fire activity in Riau, which are complex and have been explored previously (e.g., Gaveau et al., 2017; Reid et al., 2012).

In addition to the ENSO and IOD systems, the meteorology of Equatorial Asia is influenced by many other phenomena spanning a range of spatial and temporal scales (Reid et al., 2012; Xian et al., 2013). Of these, perhaps the most prominent driver of intraseasonal (i.e., daily to weekly) variability in winds and precipitation is the MJO. The MJO is a large-scale envelope of convection that propagates eastward across the Indian and Pacific Oceans with a period of 30–90 days (Madden & Julian, 1972, 1994). Typically, a well-organized MJO system is composed of two relatively dry regions of suppressed convection on either side of a region of strongly enhanced convective activity and increased precipitation. The western dry side is the drier and more persistent of the two. The patterns of low-level air flow associated with these alternating zones of enhanced and suppressed convection lead to near-surface easterly wind anomalies on the eastern edge of the convective MJO center, while the western edge is characterized by near-surface westerly anomalies, also known as westerly wind bursts (Lin & Johnson, 1996; Moum et al., 2014; Tian & Waliser, 2014; Woolnough et al., 2007; Zhang, 2005). As a result, the dry western side of a propagating MJO event is more likely to strengthen surface winds near Riau and the Malay Peninsula as the convective phase passes out of the Maritime Continent. MJO activity over Indonesia has also been linked to the formation of tropical cyclones in the western Pacific, which themselves can influence regional wind and precipitation patterns (Maloney & Hartman, 2001).

Previous efforts have explored the implications of the MJO for air quality in Equatorial Asia. MJO precipitation patterns have been linked to intraseasonal PM variations in Malaysia (Juneng et al., 2009). Reid et al. (2012) showed that fire activity in Riau is less sensitive to ENSO compared to the peatlands of southern Sumatra and central Kalimantan and that the later, drier phases of the MJO correlate with enhanced fire activity in Riau compared to earlier phases. These later MJO phases have also been linked to extended smoke particle lifetimes over Indonesia due to reduced wet scavenging (Xian et al., 2013). Later MJO phases have also been shown to correlate with increased tropical cyclone activity in the South China Sea, whose upper level outflow can enhance large-scale subsidence across Equatorial Asia leading to drier conditions and prolonged smoke events (Reid et al., 2012, 2015, 2016; Xian et al., 2013). While the influence of the MJO on fire activity in Riau has been established (Reid et al., 2012), to our knowledge, no research to date has explored in detail connections between the MJO and eastward smoke transport during the extreme haze events of August 2005, October 2010, or June 2013.

This work provides new evidence linking the MJO to smoke delivery from Riau downwind to the Malay Peninsula during the extreme haze events of August 2005, October 2010, and June 2013—events that are counter to the prevailing view that El Niño and pIOD conditions are the dominant drivers of severe haze in Indonesia. We investigate the MJO influence only on haze transport to the Malay Peninsula and not on the initiation or exacerbation of fires in Riau. Our analysis builds directly on previous work (Gaveau et al., 2014; Reid et al., 2012, 2015, 2016; Xian et al., 2013) to offer further insight into the meteorological mechanisms leading to the haze events downwind, information that could help guide ongoing efforts to improve forecasting the MJO system. Such advancements would be of great value to policymakers as they take steps to prepare for extreme haze events in the future.

2. Data and Methods

To identify episodes of extreme haze in the Malay Peninsula, we use 2005–2015 hourly visibility data, averaged to daily means, from Changi Airport in Singapore and from the Malacca site in the Iowa Environmental Mesonet Automated Surface Observing System network (mesonet.agron.iastate.edu/request/download.phtml). Visibility data are often used as a proxy for particulate matter haze (Field et al., 2016) and provide more information specific to ground level air quality than column aerosol measurements such as those from satellite or the Aerosol Robotic Network. Kusumaningtyas and Aldrian (2016) found

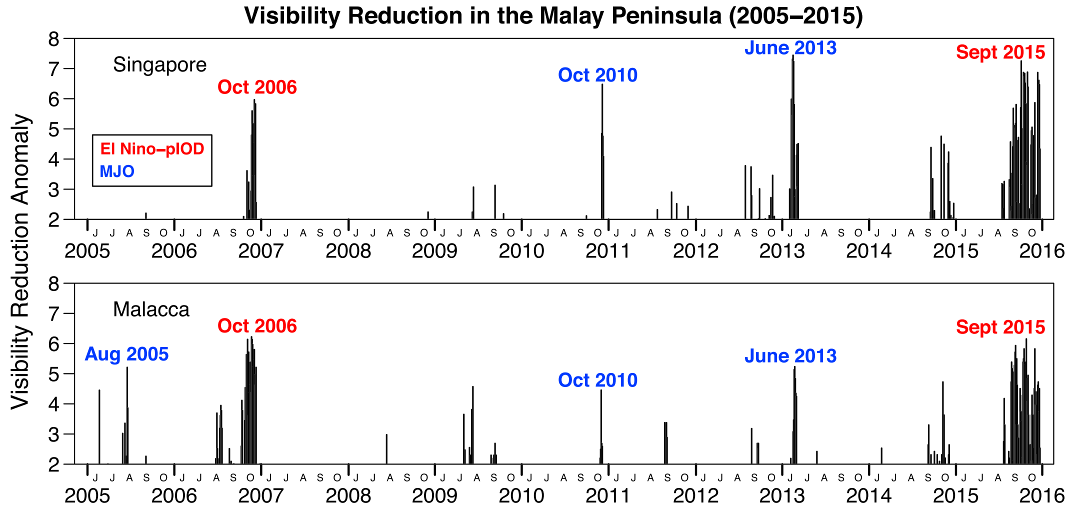

Figure 2. Time series of extreme anomalies in daily visibility reduction recorded in Singapore (Changi Airport) and Malacca during June–October 2005–2015. Station locations are shown in Figure 3. Anomalies are constructed by subtracting daily visibilities from the maximum visibility reported at each site and then normalizing the resulting time series. The panels show only extreme values of visibility reduction, defined as normalized anomalies greater than 2 (i.e., in the 95th percentile), which we use as a proxy for severe haze. Haze events driven by El Niño and positive Indian Ocean dipole conditions are indicated by red text; those events associated with strong MJO activity are in blue. Visibility data are from the Iowa Environmental Mesonet Automated Surface Observing System (ASOS) network.

that reductions in visibility at Changi Airport correlated well with observed $PM_{2.5}$ concentrations in Singapore during the June 2013 haze event. We define visibility reduction at each site as the daily visibility value subtracted from the maximum visibility reported throughout the time series. Daily anomalies of visibility reduction are calculated by subtracting daily values from the long-term mean and normalizing by the standard deviation. The maximum visibility reported in the raw Malacca data decreases in a nonphysical manner for unknown reasons during 2007–2009 and again during 2013. To avoid artificially inflating visibility reductions from the earlier years with higher reported maximum visibility, we removed the artificial trends in maximum visibility by inspection from the Malacca time series before performing the visibility reduction anomaly calculations. (The 95th percentile peaks in the Malacca data shown in Figure 2 are noticeable even before detrending, so this manipulation does not affect our results.) There is no change in the maximum visibility at the Singapore site at any point during the 2005–2015 time period. We classify days with normalized anomalies greater than 2 (i.e., in the 95th percentile) as *extreme haze* days.

We use daily fire location and FRP data from Moderate Resolution Imaging Spectroradiometer (MODIS; MCD14ML Collection 6, available online at https://earthdata.nasa.gov/firms) to track fire activity in Riau. While these data have been shown to be uncertain over Equatorial Asia, satellite-derived active fire hot spot observations nevertheless offer the most comprehensive coverage of fire activity in Indonesia (Hyer et al., 2013; Reid et al., 2013).

To characterize the wind patterns during August 2005, October 2010, and June 2013, we rely on assimilated 800-hPa wind fields from the National Aeronautics and Space Administration (NASA) Goddard Earth Observing System-5 (2004–2011, 0.5° × 0.666°) and from the Modern-Era Retrospective Analysis for Research and Applications-2 (2012–2014, 0.5° × 0.625°). Both sets of meteorology are from the NASA Modeling and Assimilation Office. Wind fields at this pressure level are generally representative of transport patterns in the lower troposphere (although the complex terrain of Indonesia and associated surface wind shear can create challenges for climate models in this region).

To demonstrate the spatial extent and direction of smoke plumes over Riau and the Malay Peninsula during the August 2005, October 2010, and June 2013 haze episodes, we use aerosol optical depths (AOD) from MODIS v6 (Level 3) on the Aqua satellite (Levy et al., 2013; Remer et al., 2005). The MODIS AOD products used in this work were processed using the Goddard Earth Sciences Data and Information Services Center Interactive Online Visualization and Analysis Infrastructure (https://giovanni.gsfc.nasa.gov/giovanni).

The progression of the MJO across the Indian Ocean Basin can be described by an index based on a pair of empirical orthogonal functions that combine information on 850-hPa zonal winds, 200-hPa zonal winds, and outgoing longwave radiation (http://www.bom.gov.au/climate/mjo; Wheeler & Hendon, 2004). The index, known as the Real-Time Multivariate MJO (RMM) Index, consists of two principal components, RMM1 and RMM2, calculated by projecting daily meteorological data onto the two empirical orthogonal functions, resulting in eight phases tracking the MJO from the African coast (phase 1) eastward to the Pacific Ocean (phase 8; Zhang, 2013). MJO patterns in which the RMM amplitude ($\sqrt{\mathrm{RMM1}^2 + \mathrm{RMM2}^2}$) is greater than 1 are considered to be *organized* or *strong*. Haze transport from Riau province to the Malay Peninsula is most likely affected by MJO phases 4–7, when areas of westerly wind anomalies preceding suppressed convection are located over Indonesia (Wheeler & Hendon, 2004). As we will show, however, the spatial patterns of winds and precipitation during each MJO phase can vary to some extent by season.

3. Results

3.1. Extreme Haze in the Malay Peninsula During 2005–2015

We first examine the non-El Niño haze events in the context of other haze episodes in the Malay Peninsula over the time period of the visibility data (2005–2015). Figure 2 shows daily visibility reduction anomalies greater than the 95th percentile value, a proxy for extreme haze days, in Singapore and Malacca during 2005–2015. Here we focus our analysis on the June–October time frame because conditions are relatively dry then and the prevailing wind flow is conducive to transport of smoke from fire regions in Indonesia to the Malay Peninsula (Okamoto et al., 2003). The four most significant haze events in Singapore over the past decade occurred in October 2006, October 2010, June 2013, and September–October 2015. The Malacca time series reveals the same four peaks, with the October 2010 and June 2013 events somewhat less extreme than those in Singapore and with an additional event in August 2005.

As discussed in section 1, the October 2006 and September–October 2015 events are well understood to be the consequence of strong El Niño-pIOD conditions, which led to drought and increased fire activity across Indonesia, primarily in southern Sumatra and Kalimantan (Field & Shen, 2008; Huijnen et al., 2016; Koplitz et al., 2016; van der Werf et al., 2008). We therefore focus our analysis on the three extreme haze events that cannot be explained by the El Niño-pIOD paradigm: August 2005, October 2010, and June 2013. While other haze events are evident in Figure 2, in this work we focus only on these three most severe episodes.

3.2. Fire Activity in Riau

Table 1 lists the top 10 fire months in Riau during 2002–2013 in terms of monthly FRP, as identified by Gaveau et al. (2014). These authors analyzed ~130 fire events in northern Riau over the July 2002 to August 2013 time period and diagnosed a negative relationship between mean rainfall in the preceding 2 months and monthly FRP. Mean May–June precipitation was particularly low in 2013 (~125 mm), while FRP in June 2013 reached the highest level of the 2002–2013 period (~270 GW). Table 1 also indicates the IOD conditions associated with these fires. None of these high fire events occurred during El Niño-pIOD conditions, and in fact, the October 2010 and August 2005 events occurred during times of anomalously high rainfall, demonstrating a fundamental difference between the drivers of high fire activity in Riau compared to southern Sumatra and Kalimantan. Reasons for this difference remain unclear, although a longer history of anthropogenic alteration of the landscape may have left Riau more vulnerable to fires, even in ENSO-neutral conditions (Gaveau et al., 2014; Page et al., 2009). More widespread slash/stack-and-burn activity compared to Sumatra and Kalimantan also makes burning in Riau a possibility throughout the year (Reid et al., 2013), and the relatively wet conditions in Riau preceding the October 2010 and August 2005 events likely increased the amount of vegetative fuel present during these burns.

As expected, the relationship between FRP and precipitation from Gaveau et al. (2014) explains the majority of the high fire months in Riau (Figure S1 in the supporting information); 7 of the 10 high fire months saw less than 160 mm of mean rainfall in Riau over the previous 2 months. However, the Gaveau relationship between FRP and rainfall makes clear that high fire activity in Riau, while likely leading to intense haze locally, is not always associated with strong and sustained ($>$2 days) haze downwind in the Malay Peninsula. It is also evident from this relationship that sustained haze downwind in the Malay Peninsula can occur in the absence of severe drought and with only moderate fire activity—two of the four months with sustained haze in the

Table 1
Top 10 Fire Months in Riau During July 2002 to August 2013 From Gaveau et al. (2014), as Defined by Monthly Fire Radiative Power (FRP) and the Corresponding Number of Haze Days on the Malay Peninsula

High fire month	Riau fire days during RMM phases 4–7	Seasonal wind direction[a]	nIOD[b]	Haze score	Malay Peninsula haze (days)
June 2004	10	WSW	Yes	3	>2[c]
June 2013	8	WSW	Yes	3	18
October 2010	7	WSW	Yes	3	9
August 2005	5	WSW	Yes	3	7
July 2006	1	WSW	No	1	0
June 2005	0	WSW	Yes	2	1
February 2005	13	NNE	Yes	2	2
January 2005	12	NNE	Yes	2	0
March 2006	4	NNE	No	1	0
March 2005	0	NNE	Yes	1	2

Note. Fire months are grouped by season (June–November first and then December–May) and ordered within each group by number of days with high fire activity in Riau occurring during RMM phases 4–7. We define high fire activity as FRP $>$ 1 standard deviation above the 2005–2015 mean and consider only well-organized MJO events with amplitude greater than 1 during phases 4–7. We assign a *Haze score* of 1 for each of three conditions conducive to smoke transport from Riau to the Malay Peninsula: at least 2 days of high fire activity in Riau during RMM phases 4–7, nIOD conditions, and prevailing seasonal winds from the west-southwest (WSW). The total Haze score for each month ranges from 1 to 3 and is listed in the fifth column. RMM = Real-Time Multivariate; MJO = Madden-Julian Oscillation.
[a]Seasonal winds during boreal winter (December–May) are typically from the north-northeast (NNE), blowing away from the Malay Peninsula toward Sumatra (Xian et al., 2013). [b]Column 4 indicates whether or not the high fire months coincided with nIOD conditions (Dipole Mode Index < -0.1). Values of indices are from http://stateoftheocean.osmc.noaa.gov/. [c]Visibility data are not available for 2004. Satellite aerosol observations and modeled $PM_{2.5}$ concentrations during June 2004 indicate haze in the Malay Peninsula during RMM phases 4–7 (Figures S2 and S3).

Malay Peninsula, October 2010 and August 2005, occurred during positive 2-month rainfall anomalies over Riau. While August 2005 also saw moderately high FRP (fifth highest), fire activity during October 2010 was relatively weak, tied for ninth out of the 10 events listed.

The significant fire activity of January–March 2005 and March 2006 led to little or no haze in the Malay Peninsula, probably because the prevailing northeasterly winds make sustained haze transport from Riau to the region unlikely at this time of year. March 2014, not included in the Gaveau et al. (2014) analysis, was also a high fire month in Riau (Gaveau et al., 2017; Kusumaningtyas & Aldrian, 2016) but again did not lead to sustained haze at either Singapore or Malacca (Nuryanto, 2015). Two other major Riau fire episodes—June 2005 and July 2006—also did not lead to severe haze in the Malay Peninsula, even with favorable winds prevailing. Malacca experienced haze for 1 day in June 2005, but that was before the onset of peak fire activity in Riau (not shown). Importantly, neither June 2005 nor July 2006 saw sustained fire activity concurrent with organized MJO activity in RMM phases 4–7 (Table 1). We explain the relevance of RMM phases 4–7 for smoke transport to the Malay Peninsula in later sections.

Table 1 also shows qualitative *haze scores* for each of the high fire months in Riau identified in Gaveau et al. (2014). We assign these scores based on the presence (score of 1) or absence (score of 0) of several meteorological conditions that we identify as common to all three severe haze events observed downwind in the Malay Peninsula: (1) prevailing wind conducive to westerly haze transport (i.e., seasonal winds not from the east), (2) more than two high fire days in Riau occurring during RMM phases 4–7, and (3) nIOD conditions present during that month. Summing across the individual scores for each condition leads to a total haze score for that month out of 3 possible points. While the assignment of these haze scores is somewhat arbitrary, the goal is to visualize in a simple way the interactions between these complex meteorological systems that did or did not result in haze transport downwind during each of the Riau fire events examined. As shown in Table 1, only the high fire months with a combined haze score of 3 resulted in sustained haze downwind either Singapore or Malacca, which was recorded in visibility data from these sites during three of the months (August 2005, October 2010, and June 2013). These three ENSO-neutral but severe events, which we investigate in detail below, share the same pattern of nIOD conditions and multiple high fire days concurrent with RMM phases 4–7. June 2004, the only other event with a haze score of 3, followed a similar meteorological pattern, and satellite observations show enhanced aerosol plume over the Malay Peninsula in late June, when the RMM was again in phases 4–7 (Figure S2). Modeled surface $PM_{2.5}$ concentrations (Figure S3) and news

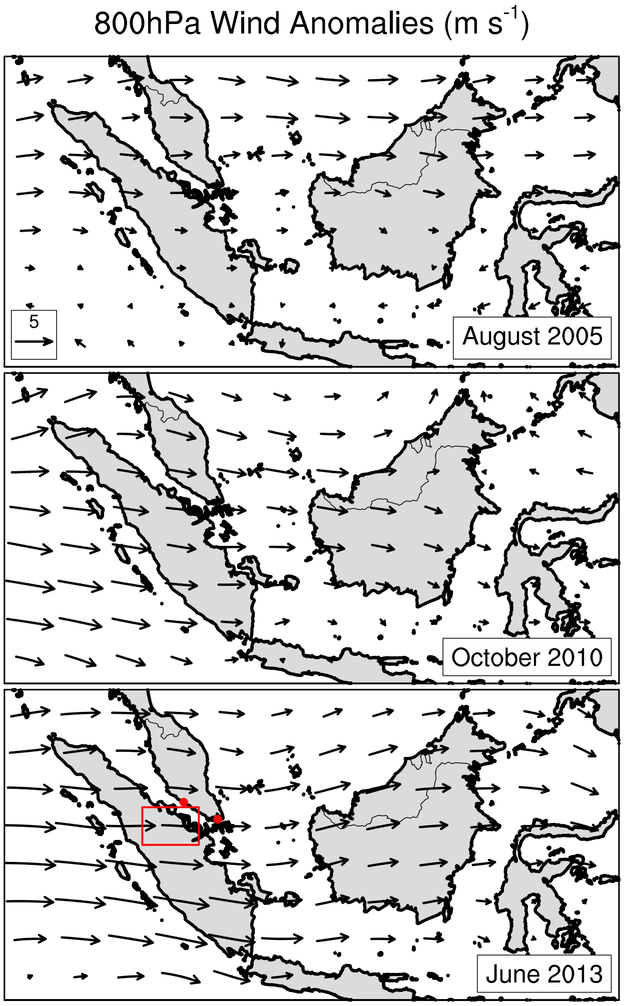

Figure 3. Monthly wind anomalies in the lower troposphere (800 hPa) during August 2005, October 2010, and June 2013 compared to their respective 2004–2014 averages. For reference, a vector corresponding to an anomaly of 5 m/s is shown inset in the top panel. Wind data are from the NASA Global Modeling and Assimilation Office, with data for 2004–2011 from GEOS5 at the native 0.5° × 0.67° horizontal resolution and data for 2012–2014 from MERRA-2, regridded from 0.5° × 0.625° to 0.5° × 0.67° for consistency with GEOS5. Corresponding figures showing monthly climatologies and wind roses over Riau for 2004–2014 are shown in the supporting information (Figure S4). Red circles indicate the visibility data sites for Malacca (2.3°N, 102.2°E) and Singapore (1.4°N, 104.0°E). The red rectangle denotes the domain for northern Riau wind and fire data in Figure 5. NASA = National Aeronautics and Space Administration; GEOS = Goddard Earth Observing System; MERRA = Modern-Era Retrospective Analysis for Research and Applications.

reports during June 2004 also suggest severe smoke transport to Kuala Lumpur from Riau during this time (BBC News, 2004). However, because no visibility data are available prior to 2005 at either Singapore or Malacca, we were unable to consistently include the June 2004 event in our analysis of smoke transport to the Malay Peninsula.

3.3. Wind Anomalies and Smoke Plumes During August 2005, October 2010, and June 2013

Figure 3 shows monthly mean wind anomalies in the lower troposphere (800 hPa) during August 2005, October 2010, and June 2013 compared to the 2004–2014 average for those months. During all three months, a significant westerly wind anomaly appeared over Riau province and most of the Malay Peninsula, ranging in speed from ~2–3 m/s in August 2005 to 5 m/s in June 2013. During August 2005 and June 2013, these anomalies strengthened the west-southwesterlies prevailing in the May–September time frame (Okamoto et al., 2003). The strong westerly winds observed during October 2010 were particularly unusual; due to the location of the Intertropical Convergence Zone at this time of year, winds are typically weak and southerly over Riau (Figure S4). During August 2005, the spatial pattern of the wind anomalies was shifted northward compared to that in October 2010 and June 2013. This shift likely reflects some combination of the seasonal behavior of the MJO and MJO-induced tropical cyclone formation near the South China Sea, as we explain below.

Figure 4 shows MODIS AOD averaged during the times of extreme haze in the Malay Peninsula, as diagnosed in the visibility record: 2–12 August 2005, 18–22 October 2010, and 16–28 June 2013. Corresponding figures showing AOD and modeled surface $PM_{2.5}$ concentrations before, during, and after the MJO phases 4–7 periods are shown in Figures S5 and S6. AOD climatologies for August, October, and June are shown in Figure S7. The satellite AOD data clearly show well-defined smoke plumes originating in Riau and moving almost directly eastward, consistent with the wind anomalies in Figure 3. Back trajectories initialized at Singapore using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (Stein et al., 2015) during the October 2010 and June 2013 events also indicate transport from Riau (Figure S8). The northward shift of the most intense haze from Singapore to Malacca in August 2005 is also apparent in Figure 4. Although the monthly mean AOD products from MODIS capture smoke plumes during all three haze events (Figure 4), an assessment of daily AOD compared to observations of the ultraviolet Aerosol Index from the Ozone Monitoring Instrument (OMI; Torres et al., 2002, 2007) and active fire counts in Riau suggests that MODIS cannot consistently detect the onset of these events at the daily scale (Figure S9), discussed in more detail in the supporting information (Jethva & Torres, 2011; Reid et al., 2013; Sayer et al., 2014; Tian et al., 2008).

3.4. The Role of the MJO in Haze Transport

Figure 5 shows a time series of RMM phase, westerly wind strength and fire activity in Riau (averaged over the domain shown in Figure 3), and visibility reduction in the Malay Peninsula leading up to and during the three severe ENSO-neutral events: June 2013 and October 2010 in Singapore and the August 2005 event which mainly affected Malacca. We focus on the westerly wind strength (i.e., only show anomalies in the zonal wind component) because the receptors of interest in our analysis, Singapore and Malacca, are located almost directly due east of the smoke source region Riau province. As explained previously, there are multiple features of the MJO system that can influence westerly wind strength over Riau—our goal in this section is simply to demonstrate a link between later phases of the MJO and changes in wind strength over Riau that led to smoke transport to the

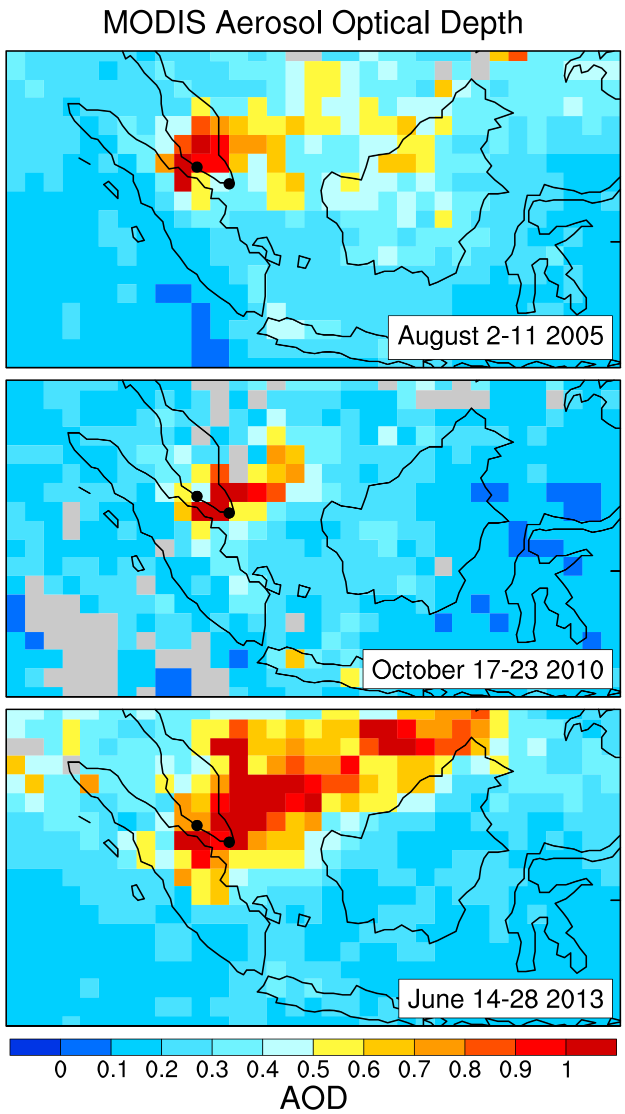

Figure 4. Mean aerosol optical depth (AOD) from the MODIS instrument on board the Aqua satellite during the haze events of 2–11 August 2005, 17–23 October 2010, and 14–28 June 2013. Grey pixels indicate missing data. Locations of Malacca and Singapore are shown as black circles. MODIS = Moderate Resolution Imaging Spectroradiometer.

Malay Peninsula, rather than attribute the observed wind changes to specific mechanisms within the complex MJO system. We go on to discuss which MJO-related mechanisms may have driven the wind changes in the next section. Also, while explaining the causes of fire activity in Riau is not the focus of this paper, we describe some of the possible connections between the MJO and fire activity in Riau in the supporting information (Gaveau et al., 2014; Huang et al., 2016; Reid et al., 2012, 2015, 2016).

3.4.1. June 2013

We begin with a description of June 2013, as the pollution episode in Singapore is most severe in this event. On 10 June, immediately prior to the Singapore haze event, westerly wind speeds over Riau increased by ~4 m/s above the 2004–2014 June average as the RMM entered phase 4. Fire activity in Riau began increasing around 14 June, several days after the onset of the strong westerlies, peaking on 19 June. As the RMM progressed through phases 5 and 6, the westerly winds remained anomalously strong, transporting smoke from the fires toward Singapore, which experienced peak pollution during 16–23 June. Wind speeds, fire activity in Riau, and haze levels in Singapore all dropped significantly as the RMM left phase 7 on 23 June, returning to normal levels several days later when the RMM exited phase 8. This sequence of events is consistent with the diagnosis of Hertwig et al. (2015), who attributed both the strong winds and the sudden increase in precipitation near Riau on 23 June to the presence of a tropical cyclone near Indonesia at this time. We return to this issue in section 3.5.

3.4.2. October 2010

A similar sequence of phenomena led to the intense haze during October 2010. Again, anomalously strong westerlies over Riau coincided with a strong RMM index entering phase 4 (Figure 5). Severe haze began in Singapore on 20 October, 3 days after the enhanced fire activity in Riau (15–17 October) and while westerly wind speeds over Riau were still moderately enhanced. The westerly wind anomaly in Riau remained apparent until 22 October, when the RMM index weakened. Unlike the June 2013 event, the haze in Singapore lagged the peak fire activity in Riau by several days in October 2010. A similar lag occurred between the Riau fires and haze in Malacca (Figure S11). The reason for these lags is not clear, although could be related to the timing of tropical storm formation near the South China Sea (section 3.5).

3.4.3. August 2005

The haze event in the Malacca-Kuala Lumpur region during August 2005 was again characterized by strong westerlies over Riau, which began to strengthen on 27 July just as the RMM index entered phase 5. As in the June 2013 event, westerly wind speeds during August 2005 remained elevated as haze arrived in Malacca on 2 August and peaked on 10–11 August. The strong westerlies dropped off abruptly after the RMM index exited phase 8 on 12 August. In this case, the first sign of haze in Malacca appears to have preceded fire activity in Riau, which began on 5 August and quickly ramped up. This apparent discrepancy may be due in part to uncertainty in the fire counts.

The absence of haze in Singapore during August 2005 could be explained by two different phenomena. First, during boreal summer (May–October), the east-west trajectory of the MJO (and therefore MJO-related changes in wind direction) slowly shifts toward the north, with August–September marking the time period of peak shift. This northerly summertime MJO is sometimes called the boreal summer intraseasonal oscillation (BSISO; Lee et al., 2013). The timing and strength of the BSISO during August 2005, as well as during two other more moderate haze events in Malacca during August 2006 and August 2009, are consistent with this hypothesis (Figures S12 and S13). Second, two separate tropical storms, one during 1–5 August and one during 8–12 August, are visible in the western Pacific around the time of the August 2005 haze event

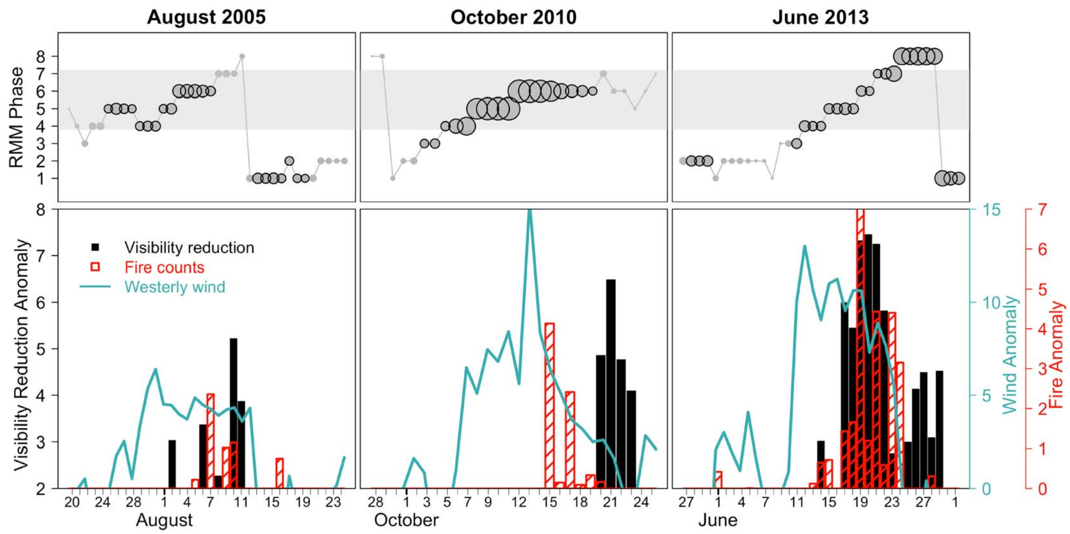

Figure 5. Time series of MJO phase, daily fire activity, and wind speed over Riau and visibility reduction anomalies downwind in Malacca (August 2005) and Singapore (October 2010 and June 2013). MJO phase is shown in the top panels by the Real-Time Multivariate MJO (RMM) index, with symbol size scaled by the amplitude of the RMM signal ($\sqrt{\mathrm{RMM1}^2 + \mathrm{RMM2}^2}$) on that day. Symbols denoting *strong* MJO occurrences (amplitude greater than 1) are outlined in black. Grey shading indicates the MJO phases associated with strong westerlies and precipitation deficits over Riau (phases 4–7). The bottom panels show fire count anomalies (red bars), westerly wind anomalies (blue line), and visibility reduction anomalies greater than 2 (i.e., *extreme haze*) in the Malay Peninsula (black bars). Fire and wind anomalies represent daily averages calculated across the domain shown in Figure 3. Fire anomalies were calculated compared to the 2005–2015 mean. Wind anomalies were calculated with respect to monthly average 2004–2014 values. MJO = Madden-Julian Oscillation.

(Figure S14). The northward propagation of low-level wind fields related to these storms may have influenced smoke transport between Riau and the Malay Peninsula during this time. We discuss relationships between the MJO, tropical cyclone activity, and smoke transport in Equatorial Asia in the next section.

3.5. MJO-Induced Cyclogenesis

Our results provide evidence of relationships between MJO phases 4–7, westerly winds enhancements over Riau, and smoke transport to the Malay Peninsula. The close coincidence in time between the RMM phases 4–7 signal and intense westerly winds over Riau suggests that these winds originate from the MJO system. While the western MJO edge is associated with westerly wind bursts, MJO phases 6–7 may also increase the probability of tropical cyclone formation in the southwest Pacific (Diamond & Renwick, 2014; Maloney & Hartman, 2001). Previous work has hypothesized that MJO-induced tropical cyclones in the South China Sea may induce large-scale subsidence and lead to enhanced smoke transport across Southeast Asia (Reid et al., 2012, 2015, 2016; Xian et al., 2013). For example, Hertwig et al. (2015) attributed the severe haze in Singapore during June 2013 to the presence of a tropical cyclone (Tropical Storm Bebinca) in the South China Sea on 21 June. Figure 5 also shows elevated haze in the Malay Peninsula during 20–23 October 2010, almost precisely when Typhoon Megi passed through the South China Sea during 18–23 October of that year (Ko et al., 2014). Another tropical storm, Typhoon Sanvu, entered the South China Sea on 11–12 August 2005, around the time of peak haze in Malacca on 10–11 August.

For all three haze events, the enhancements in westerly winds over Riau shown in Figure 5 occurred 10–12 days prior to the tropical cyclones named above entering the South China Sea, suggesting that other components of the MJO system (e.g., low-level westerly winds bursts near the western edge) may have also been involved in initiating smoke transport from Riau to the Malay Peninsula prior to the formation of the tropical cyclones downwind. However, as shown in Figures S14–S16, there were other tropical depressions in the area of the South China Sea on 1–5 August 2005 (Tropical Storm Matsa), 13–17 October 2010 (Tropical Storm Megi as it was strengthening), and 6–12 June 2013 (Tropical Storm Yagi) and 16–21 June 2013 (Tropical Storm Leepi). The timing of these other storms is more consistent with the elevated westerly winds over Riau during each haze event and further supports the hypothesis that MJO-induced tropical cyclone activity is related to haze transport during these events. Continued investigation of the connections between the MJO system, tropical cyclone activity near the South China Sea, and westerly wind strength over Riau is needed to fully understand this system and would benefit the representation of MJO-related smoke transport from Riau to the Malay Peninsula in air quality forecasting models.

3.6. The Role of the Negative Indian Ocean Dipole in Haze Transport

Westerly transport of smoke during all three events may have also been strengthened by the nIOD conditions, which were particularly strong in October 2010 and June 2013. A negative IOD phase is characterized by warm sea surface temperature anomalies around Sumatra, which enhance near-surface westerlies (Saji et al., 1999; Wilson et al., 2013). Although mechanisms governing the formation, strength, and propagation of the MJO are uncertain, one hypothesis is that the MJO is driven by moisture availability (Del Genio et al., 2015; Wang et al., 2015). Under this hypothesis, the warmer sea surface temperatures in the eastern Indian Ocean characteristic of nIOD provide a source of energy that strengthens the MJO (Wilson et al., 2013, and references therein). While the timescales of variability are quite different between the IOD and MJO systems, such a relationship between the nIOD and strong MJO activity compared to positive or neutral IOD conditions has been observed during August–November (Wilson et al., 2013). Given the consistent pattern of nIOD conditions during all three severe haze events discussed in this paper, we conjecture that background nIOD conditions may have also influenced smoke transport to the Malay Peninsula during these episodes, either directly by strengthening westerly winds over Indonesia or indirectly by modulating the intensity of the MJO events. However, there is little evidence to date directly documenting the influence of the nIOD on MJO-related haze in Indonesia.

4. Discussion and Conclusions

The conventional view holds that extreme haze events in the Malay Peninsula are associated with strong El Niño-pIOD conditions, when drought exacerbates burning in southern Sumatra and Borneo and smoke is transported north to the Peninsula by weak southeasterly winds. Here we demonstrate that three of the five most extreme haze events of the last decade in the Malay Peninsula occurred during non-El Niño conditions and that these three haze events occurred as a consequence of anomalously strong westerly winds traversing Riau province and carrying intense haze across the Straits of Malacca. We find that these anomalous westerlies are likely driven by passage of the MJO, corresponding to an organized RMM index in phases 4–7. Unlike southern Sumatra and Kalimantan, Riau experiences frequent agricultural fire activity throughout the year (Gaveau et al., 2014; Reid et al., 2012), and so bursts in westerly winds related to passage of the MJO can transport smoke from Riau to Singapore and other densely populated areas of the Malay Peninsula, even in the absence of extreme drought conditions.

The role of the MJO in smoke transport across Equatorial Asia has been documented before (Reid et al., 2012, 2015, 2016; Xian et al., 2013). Our work builds on previous research by connecting three recent extreme haze events in the Malay Peninsula to the MJO and by diagnosing MJO-enhanced westerly winds over Riau as a key driver of these events. Our results suggest that the connection between later phases of the MJO and westerly wind strength over Riau represents an important mechanism of severe smoke exposure in the Malay Peninsula of which June 2013 is just one example. The link between the MJO and smoke delivery to the Malay Peninsula during August 2005, October 2010, and June 2013 demonstrated in this work is consistent with the relationship between MJO-induced tropical cyclone activity and smoke transport in Equatorial Asia previously identified by Reid et al. (2012, 2015, 2016) and Xian et al. (2013), although more work is needed to mechanistically link the MJO, tropical cyclone formation, and westerly wind strength over Riau to smoke transport during these extreme events. The nIOD conditions common to all three events are also in direct contrast with those of the more widely publicized haze events of 1997, 2006, and 2015, when pIOD conditions prevailed. In fact, nIOD conditions may promote MJO-related haze events, although more evidence is needed to understand how interactions between the IOD and MJO influence smoke transport from Riau to the Malay Peninsula. While the duration of MJO-related haze events is relatively short—on the order of days compared to the multiweek time frames typical of El Niño-pIOD events—the intensity of smoke concentrations during these events is just as severe and could have serious implications for acute smoke-related public health impacts in the Malay Peninsula.

There are several sources of uncertainty inherent in our analysis. First, the three MJO-related haze events reveal differences in the sequential timing of relevant phenomena—that is, the RMM entering and exiting phases 4–7, the westerly wind enhancements over Riau, and the smoke delivery downwind to the Malay

Peninsula. Some of these differences may be traced to uncertainties in quantifying the RMM index. The RMM index can sometimes be contaminated by other large-scale systems influencing winds and precipitation (e.g., Kelvin waves). Other methods for tracking the MJO exist—for example, following the progression of large precipitating areas using satellite data (Kerns & Chen, 2016)—and might classify the events discussed here differently. Better understanding of the timing of haze in the Malay Peninsula relative to the RMM signal and conditions in Riau would benefit future efforts to forecast such haze. Also, although we identify a consistent pattern of smoke transport across multiple haze events that appear to be related to the MJO, predicting when such conditions will lead to haze downwind in the Malay Peninsula is currently very difficult given (1) the complexity of fire dynamics and uncertainty in fire source attribution in Riau and (2) the relatively limited time frame of visibility data at the Singapore and Malacca sites. Second, our assessment does not account for local influences on the visibility measurements unrelated to smoke from Riau. However, by confining our examination to only the 95th percentile values in the visibility reduction time series, we likely exclude most of these localized influences, including changes in sea salt and relative humidity. Third, while we observe a consistent pattern of nIOD conditions during all three severe haze events in the Malay Peninsula, more work is needed to robustly characterize the influence of the IOD on the MJO and on haze transport to the Malay Peninsula. Finally, the fire observations that we rely on for our analysis are also subject to uncertainty (Reid et al., 2013, and references therein). For example, thick smoke can obscure hot spots at the surface, leading to underestimates in fire counts. Fires in degraded peat, the dominant land cover type across much of Riau, often smolder at low temperatures, making them difficult to detect via satellite (Elvidge et al., 2015). Accurately quantifying fire activity from space remains a persistent problem for fire science in Indonesia.

Despite the broad environmental impacts of the MJO, accurately forecasting individual MJO events and projecting the effect of climate change on MJO frequency remain a challenge. The fundamental mechanisms governing the formation and propagation of the MJO are still a matter of debate (Crueger & Stevens, 2015), limiting the accuracy to which the MJO can be represented in climate models (Kim et al., 2011). The response of MJO strength and organization to mountainous terrain, such as that along the coast of Sumatra just to the west of Riau, is also uncertain (Kim et al., 2016; Peatman et al., 2014), complicating the forecast of individual MJO events passing over Riau. Improving scientific understanding of these and other aspects of MJO dynamics is a top research priority in the tropical meteorology community and is a major focus of an upcoming international field campaign, Years of the Maritime Continent, planned for 2017–2019 (http://www.bmkg.go.id/ymc/).

Future trajectories of land use change in Riau may result in increased fire emissions due to continued agricultural management and expansion (Marlier et al., 2015a, 2015b, 2015c). Recent work also suggests an increased frequency of MJO events in a warmer, more moist climate (Arnold et al., 2015), which would make extreme haze occurrences over the Malay Peninsula increasingly likely. The MJO, in turn, may also influence both the IOD and ENSO systems (Zhang, 2013). For example, strong MJO activity in boreal spring is often followed by an El Niño event within 6 months to a year (Hendon et al., 2007). March 2015 saw record-breaking MJO activity, which may have amplified the development of the strong El Niño during September–October of that year (Marshall et al., 2016). Better representation of the MJO in models might therefore improve our ability to forecast not only future MJO-related haze events as discussed in this work but also El Niño-pIOD haze events such as those of 1997, 2006, and 2015.

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