Role of the Madden-Julian Oscillation in the transport of smoke from Sumatra to the Malay Peninsula during severe non-El Nino haze events

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Introduction

This supporting information provides additional figures showing FRP and rainfall relationships over Riau during 2004-2013, satellite aerosol observations during June 2004, mean climatological winds, airmass backtrajectories, and additional time series depicting BSISO and the haze events of August 2006 and August 2009, as well as a description of discrepancies in daily satellite aerosol observations during the haze events discussed in the main text. Mean aerosol optical depth observations during 2005-2015 and before, during, and after each haze event are also included, as well as a description of relationships between the MJO and fire activity in Riau. Modeled surface PM2.5 from the NAAPS model overlain with NOGAPS 850 hPa winds before, during, and after each haze event are also shown. Finally, daily
snapshots of 850 hPa NOGAPS winds and CMORPH precipitation are included for each event indicating
the propagation of tropical cyclones near the South China Sea.
**Figure S1.** Top ten fire months in Riau during July 2002-August 2013 from Gaveau et al. [2014], as defined by monthly fire radiative power (FRP). Fire months are plotted against mean rainfall in Riau for the preceding two months following Gaveau et al. [2014]. High fire months that resulted in haze downwind in the Malay Peninsula are shown by black triangles.
Figure S2. Mean aerosol optical depths (AOD) from the MODIS instrument on board the Aqua satellite during June 2004. The top panel shows the mean AOD during June 1-16. There was no organized MJO signal in any phase during this time. The bottom panel shows mean AOD during June 17-30, when there was strong MJO activity in phases 4-7 (phase 6 during June 17-21 and phase 7 during June 22-30). Locations of Malacca and Singapore are shown in the white circles.
Figure S3. Surface PM$_{2.5}$ concentrations modeled with the Navy Aerosol Analysis and Prediction System (NAAPS; https://www.nrlmry.navy.mil/aerosol_web) overlain with 850 hPa winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) corresponding to time periods before (top) and during (bottom) MJO activity in phases 4-7 during June 2004 (see Figure S2). The right hand panels show the same figures plotted on a larger domain.
Figure S4. Climatological wind fields at 800 hPa and associated wind roses over Riau (white rectangle in bottom panel) for June, August, and October during 2004-2014. Wind roses for the three severe haze events discussed in this work - August 2005, October 2010, and June 2013 – are also shown on the far right. Percentages in wind rose plots indicate the percent days that winds emanate from a particular direction for that month; colors in these plots denote different ranges in wind speed.
Figure S5. MODIS AOD averaged before (top row), during (middle row), and after (bottom row) the MJO 4-7 periods during the haze events of August 2005 (left column), October 2010 (middle column), and June 2013 (right column). For August 2005, the corresponding dates are July 13-July 22 (before), July 23-August 10 (during), and August 11-August 20 (after). For October 2010, the dates are September 25-October 4 (before), October 5-October 21 (during), and October 22-October 31 (after); and for June 2013, the dates are June 2-June 11 (before), June 12-23 (during), and June 24-July 3 (after). MODIS AOD data used in this figure were processed with and downloaded from the Giovanni online data system, developed and maintained by the NASA GES DISC. We identified MJO 4-7 periods based on the RMM data available online from the Australian Government Bureau of Meteorology (www.bom.gov.au/climate/mjo).
Figure S6. Surface PM$_{2.5}$ concentrations modeled with the Navy Aerosol Analysis and Prediction System (NAAPS; https://www.nrlmry.navy.mil/aerosol_web) overlain with 850 hPa winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) corresponding to time periods before (top), during (middle), and after (bottom) MJO activity in phases 4-7 during the haze events of August 2005, October 2010, and June 2013 (see Figure S5).
Figure S7. MODIS AOD climatologies for August (top row), October (middle row), and June (bottom row) during 2005-2015. MODIS AOD data used in this figure were processed with and downloaded from the Giovanni online data system, developed and maintained by the NASA GES DISC.
Figure S8. Three-day back trajectories from Singapore, initialized at 1000 m on October 20, 2010 and June 18, 2013. The plots show that the air masses traversed Riau Province before reaching Singapore during both haze events. The figures above were produced with data from the NOAA Air Resources Laboratory HYSPLIT model [Stein et al., 2015], and processed with the AERONET Data Synergy Tool (http://aeronet.gsfc.nasa.gov). Similar backtrajectory analyses are not available for Malacca through this tool due to the lack of an accompanying AERONET station there.
Daily satellite observations of haze events

Figure S7 shows daily time series of MODIS Aerosol Optical Depth (AOD) from the Terra and Aqua instruments, observations of ultraviolet Aerosol Index (AI, Level 3) from the Ozone Monitoring Instrument (OMI), and active fire counts over Riau for the three haze events. In 2013, peak fire activity occurred on June 19, coincident in time with a strong enhancement in OMI AI. Neither MODIS AOD product, however, shows significant increases at that time. Similarly, in 2005, OMI AI responded readily to fire activity on August 7, with no clear corresponding increase in either MODIS AOD product until 2-3 days later. Satellite data are limited over Riau for much of October 2010, although OMI AI clearly increased on October 16 just after the onset of burning. MODIS AOD again showed no obvious enhancement until several days after fire activity begins in Riau.

The apparent discrepancies between daily OMI AI and MODIS AOD during haze events may be due to multiple factors, including 1) the representation in AOD retrievals of the optical properties of organic carbon, the dominant component of biomass burning aerosol [Jethva and Torres, 2011; Sayer et al., 2014] and 2) retrieval challenges associated with clouds [Reid et al., 2013]. The large variability in cloud cover, humidity, and wind-driven ocean aerosol fluxes associated with passage of the MJO could make monitoring the MJO-driven haze events discussed in this work especially challenging for the two MODIS instruments [Tian et al., 2008]. Although the twice-daily overpass schedule of the MODIS instruments currently offers the highest frequency in temporal coverage of any aerosol remote sensing product over Equatorial Asia, it is unclear how accurately MODIS AOD can monitor haze at the daily scale, at least in this region during MJO-influenced events.

AERONET AOD from Singapore during October 2010 and June 2013 are also shown in Figure S10. While some cloud-screened, quality-assured level 2 data are available during these months, many days are missing data, for example during the peak of the June 2013 haze on June 19-20. These data gaps, particularly during peak haze, make the use of AERONET to assess daily changes in haze levels problematic. In addition, AOD data represent total column aerosol concentrations rather than haze at the surface. For these reasons, we do not include AERONET observations in our analysis and instead rely on airport visibility data.
Figure S9. Daily observations of MODIS AOD over Riau (shown by red rectangle in Figure 3) from the Terra (red) and Aqua (orange) satellites compared with observations of OMI AI (purple) and MODIS active fire counts (grey bars) during the June 2013, October 2010, and August 2005 haze events. The threshold for AI detection by OMI is 0.5. To ease comparison among the different satellite products, 0.5 has been subtracted from all OMI AI values. MODIS AOD and OMI AI were processed using the NASA Giovanni online tool (https://giovanni.gsfc.nasa.gov/giovanni).
Figure S10. Daily observations of AERONET AOD in Singapore during the October 2010 and June 2013 haze events (http://aeronet.gsfc.nasa.gov).
Figure S11. Time series of daily fire counts and mean wind speed over Riau, and haze downwind in Malacca during October 2010. Fire count anomalies are shown by the red bars, westerly wind anomalies by the blue line, and visibility reduction anomalies in Malacca greater than 2 (“extreme haze”) by the black bars.
Figure S12. Same as Figure 5 but with the Boreal Summer IntraSeasonal Oscillation (BSISO) index instead of the MJO index. BSISO data (from http://iprc.soest.hawaii.edu/users/jylee/bsiso/) are available only through June 21, 2013.
Figure S13. Same as Figure S11 but for August 2006 and August 2009, two moderate haze events in Malacca.
Our analysis focuses on the link between the MJO-associated westerlies and the transport of haze to the Malay Peninsula. But the coincidence in timing of elevated windspeeds with fire counts in Riau for all three events (Figure 5) also suggests that the strong winds associated with RMM phases 4-7 may exacerbate existing fire activity in Riau. Such winds could increase the oxygen supply needed for combustion, speed up drying out of the ground, and promote the spread of fires [Huang et al., 2016]. In addition, Reid et al. [2012] demonstrated a relationship between RMM phases 5-8 and more frequent MODIS active fire counts in Riau, hypothesizing that the drier weather in Riau associated with RMM phases 5-8 may modulate the fire activity there, a result corroborated in Reid et al. [2015, 2016]. Large-scale subsidence associated with MJO-induced cyclogenesis (discussed in Section 3.5) may also exacerbate Riau fires. It is possible that a combination of elevated wind speeds and short-term dry weather due to the MJO amplified fire activity in Riau during the three haze events discussed here, counteracting the longer-term moist conditions preceding the fires in October 2010 and August 2005 and exacerbating the two month drought prior to June 2013 shown by Gaveau et al. [2014]. Detailed analysis of the effects of MJO on fire weather in Riau is beyond the scope of this paper.
Figure S14. Daily snapshots of CMORPH precipitation (http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html) and NOGAPS 850 hPa winds during August 2005. Tropical storms in or near the South China Sea are indicated by black arrows.
Figure S15. Same as Figure S14 but for October 2010.
Figure S16. Same as Figure S14 but for June 2013.