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Analysis of Southeast Asian pollution episode during June 2013 using satellite remote sensing datasets

Krishna Prasad Vadrevu*, Kristofer Lasko, Louis Giglio, Chris Justice

Department of Geographical Sciences, University of Maryland College Park, 4321 Hartwick Road, College Park, MD 20740, USA

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A B S T R A C T

In this study, we assess the intense pollution episode of June 2013, in Riau province, Indonesia from land clearing. We relied on satellite retrievals of aerosols and Carbon monoxide (CO) due to lack of ground measurements. We used both the yearly and daily data for aerosol optical depth (AOD), fine mode fraction (FMF), aerosol absorption optical depth (AAOD) and UV aerosol index (UVAI) for characterizing variations. We found significant enhancement in aerosols and CO during the pollution episode. Compared to mean (2008–2012) June AOD of 0.40, FMF-0.39, AAOD-0.45, UVAI-1.77 and CO of 200 ppbv, June 2013 values reached 0.8, 0.573, 0.672, 1.77 and 978 ppbv respectively. Correlations of fire counts with AAOD and UVAI were stronger compared to AOD and FMF. Results from a trajectory model suggested transport of air masses from Indonesia towards Malaysia, Singapore and southern Thailand. Our results highlight satellite-based mapping and monitoring of pollution episodes in Southeast Asia.

1. Introduction

Vegetation fires are an immense source of air pollution in several tropical countries. In particular, biomass burning in Southeast Asia is extensive and an important source of trace gases and aerosols (Folkins et al., 1997; Chan et al., 2006; Hyer et al., 2013). In the region, fire is used as a management tool for clearing land through slash and burn agriculture (Tomich et al., 1998), disposing of agricultural residues (Dobermann and Fairhurst, 2002; FAO, 2013) and for clearing forests for developing palm oil plantations by private companies (Greenpeace, 2013; Miettinen et al., 2011). The fire season in this region coincides with the dry weather season and the southwest monsoon. Earlier researchers reported several biomass burning-related haze episodes from the region during August to September 1982, September 1983, September 1987, August 1990, August–September 1991, August–October 1994, August–October 1997 (Nichol, 1998; Radojevic, 2003; See et al., 2006). During the air pollution events, aerosols and pollutants can be transported long distances and persist for weeks to months, impacting not only air quality but also human health, biogeochemical cycles, atmospheric chemistry, weather and climate (Radojevic, 2003).

Among Asian countries, Indonesia accounts for 15.7% of total fires (Vadrevu and Justice, 2011). For Indonesia, the most recent, significant recorded haze episode occurred during 1997/1998 from the combination of human factors and dry conditions during an El Niño-Southern Oscillation cycle. During that time, the haze persisted for weeks in Indonesia and in the neighboring countries of Singapore and Malaysia (Murdiyarso et al., 2004). It is estimated that more than 11 Mha of forest were burned (Siegert, 2001; Taylor, 2010). Close to the vegetation fires at Palangkaraya on Kalimantan and Jambi on Sumatra up to 4000 $\mu g/m^3$ total particulate matter was measured, exceeding the Indonesian national ambient air quality standard by a factor of 15 (Heil and Goldammer, 2001). In Indonesia, peatland fires are common (Nara et al., 2011; Hyer et al., 2013). Peatlands occupy 170,000–270,000 km^2 (Heil and Goldammer, 2001) and it is estimated that they store 57,367Gt of carbon (Page et al., 2011). Thus, peatland fires release huge amounts of carbon into the atmosphere. Most of the peatland fires are attributed to anthropogenic factors, however, they get aggravated by the coincidence of dry season (Usup et al., 2004). During recent times, one of the major projects that led to peatland degradation was the Mega Rice Project in central Kalimantan, Indonesia. The project aimed to create large rice cultivation area, however, it failed and resulted in the drainage of 1 Mha of unmanaged peatlands. The drained peatlands are highly susceptible to fires as they are relatively dry with a low water table, enabling combustion of top peat layers (Miettinen et al., 2011). Fires from the peatlands are hard to detect from space, as peat fires are typically low temperature smoldering fires involving both above-ground as

* Corresponding author.
E-mail addresses: krisvkp@umd.edu, krisvkp@yahoo.com, krivadrevu@gmail.com (K.P. Vadrevu).

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well as below-ground organic matter (Langmann and Heil, 2004; Hyer and Chew, 2010).

During last year, an intense haze event occurred from June 18th–July 1st 2013, in Indonesia that spread to other neighboring countries, including Brunei, Indonesia, Malaysia, Singapore and southern Thailand. The main source for the pollution was attributed to fires in the Riau Province, Indonesia (Eastasia forum, 2013). In the province, several residents had to flee their homes due to respiratory problems and a local airport had to be closed due to poor visibility caused by haze (Eastasia forum, 2013). The smoke plumes traveled large distances and as a result, Malaysia had to declare an emergency in two southern regions after the country's air pollution reached hazardous levels. As a result of the haze event, the pollution index in the capital Kuala Lumpur reached 200 indicating "very unhealthy" conditions and in Johar State, it reached greater than 700 indicating "hazardous" conditions. Similarly, Singapore was shrouded with haze as the pollution index reached 371 on the June 20th, 2013. The haze also affected some provinces in southern Thailand and parts of Brunei. Important reasons for the fires were attributed to palm oil, pulp and paper companies which are involved in forest clearance and developing plantations (Greenpeace, 2013). It is inferred that the Indonesia-caused air pollution event reached the worst levels in nearly 16 years after the major 1997/1998 haze episode.

Remote sensing data with its multi-temporal, multi-spectral, repetitive and synoptic coverage can provide useful information on land use/cover and pollution monitoring. In particular, remote sensing of the troposphere can yield useful measurements on atmospheric composition which can range from regional to global scales, that are not easily obtained from in situ observing systems (Monks and Bierle, 2011; Ichoku et al., 2013). However, the potential of remote sensing datasets in capturing air pollution events needs a thorough investigation, as pollutants can have short residence times. Further, most of the emission sources are located close to the ground, whereas, satellite detection is mostly based on the absorption spectra of atmospheric constituents (Richter and Wagner, 2011) and pollutants may not be always associated with ground sources due to dispersion. Satellite observations can be a powerful tool for monitoring of atmospheric pollution if they can be related to the underlying emission sources.

In this study, we evaluate the potential of remote sensing datasets in capturing the air pollution episodes (June, 2013) in Southeast Asia. We use remote sensing data for capturing the changes in atmospheric composition and degradation due to fires in the region. We focused on aerosol physical and optical properties as well as Carbon monoxide (CO) retrieved from MODIS, OMI and MOPITT data corresponding to the pollution event. We also used meteorological data and a Lagrangian particle dispersion model to characterize the influence of wind direction and long range transport of pollutants. In view of the growing incidence of forest fires and the resulting haze events in the region, there is a need to explore remote sensing data for capturing synoptic pollution events. The results from such an exercise can provide valuable insights useful for pollution control measures.

2. Study area

The study area includes Indonesia, Singapore, Brunei and peninsular Malaysia (Fig. 1). The region is home to 250 million people and is experiencing increasing economic development. The weather is hot and humid all year round, and the dry period is from June till October, during which most biomass burning take place. Mostly, the dry seasons in the study area are attributed to the El Niño-Southern Oscillation (ENSO) (Corlett, 2011), however, even during this period, rainfall exceeds evaporation in many parts of the region in normal years (Meittinen et al., 2004).

3. Datasets and methodology

3.1. Active fires

For characterizing the vegetation fires in the region, we used daily active fire detections from the MODIS instruments onboard the Aqua and Terra satellites. The two MODIS sun-synchronous, polar-orbiting satellites pass over the Equator at approximately 10:30 a.m./p.m. (Terra) and 1:30 p.m./a.m. (Aqua) with a revisit time of 1–2 days. The MODIS Advanced Processing System (MODAPS) processes the resulting data using the enhanced contextual fire detection algorithm (Giglio et al., 2003) combined into the Collection 5 Active Fire product. For this study, we analyzed the yearly data (2003–2013) for Indonesia and also daily data for local provinces during June, 2013 to characterize fires. The algorithm routinely detects fires of at least 1000 m^2. However, under ideal observing conditions such as near nadir, little or no smoke, relatively homogenous land surface, flaming fires one tenth of that size can be detected. Further, the smallest size of a flaming fire that can be detected is 50 m^2 under pristine conditions (Giglio et al., 2013). In many cases a large fire event consists of several small active fires burning simultaneously (Morisette et al., 2005).

3.2. Post-fire vegetation loss in Riau Province

For assessing the vegetation changes before and after fire, we used the MODIS Aqua vegetation indices 16-day L3 Global 250 m SIN Grid product version 5 (MYD13Q1). Accordingly, we obtained scenes before and after the peak fire event on June 2nd (t_1) and June 18th (t_2) respectively; time period one is a composite of normalized difference vegetation index (NDVI) with data from June 2nd till June 17th while time period two has data ranging from June 18th till July 3rd. The NDVI ranges from 0 to 1 with 0 indicating very low vegetation (or none) to 1 indicating very high vegetation vigor or greenness. For the northern region of Riau Province where most fire hotspots were observed, the NDVI data for time period two were obtained after June 25th i.e., the end of the fire episode (Fig. 2d). A change was computed between the two time periods as.

$$\text{NDVI Change} = \text{Time period}_{(2)} - \text{Time period}_{(1)}$$

Negative values are indicative of a decrease in NDVI which is indicative of a disturbance and degradation or loss of vegetation while positive values are attributed to and associated with vegetation growth/regrowth increasing leaf area index, and other factors (Carlson and Ripley, 1997).

3.3. Aerosol optical depth (AOD) ($_a$)

AOD is a measure of atmospheric extinction through a vertical column of atmosphere as retrieved by satellites visible channel corresponding with Beer–Lambert's law. The higher the AOD value, the more aerosols are within a column; thus lower visibility within that column. Biomass burning activities are expected to increase AOD's compared to the background. The aerosol properties are derived by the inversion of the MODIS-observed reflectance using pre-computed radiative transfer look-up tables based on aerosol models (Remer et al., 2005). For this study, we specifically used the MODIS Collection 5.1 monthly product (MYD08_M3.005) for June, 2008–2013 and daily product (MYD08_D3.005) for June 2013 for characterizing the spatial and temporal variations in relation to fires.

3.4. Fine mode fraction (FMF)

Aerosol fine mode fraction is the ratio of small mode optical depth (thickness) to the total AOD. In the aerosol research, quantifying the particle size distribution is critical to estimating the Earth's energy balance (Kleidman et al., 2005) and FMF is useful for the same. MODIS provides the aerosol fine mode fraction at 550 nm and we used the level 3 version 5.1 daily product (MOD08_D3.051) corresponding to the study area.

3.5. Aerosol absorbing optical depth (AAOD) at 500 nm

The aerosol absorption optical depth is measure of concentration of near-UV absorbing aerosol particles such as smoke and mineral dust and is retrieved from the Ozone Monitoring Instrument (OMI). The OMI measures the solar light backscattered by the earth's atmosphere and surface (Bucsela et al., 2008). The instrument consists of two spectrometers, one measuring the UV spectral range from 270 to 365 nm in two sub-ranges (UV1: 270–314 nm, resolution: 0.42 nm, sampling: 0.32 nm; UV2: 306–380 nm, resolution: 0.45 nm, sampling: 0.15 nm), the other measuring the UV–visible spectrum from 350 to 500 nm (resolution: 0.63 nm; sampling: 0.21 nm). We used the AAOD daily product at 500 nm (OMAERUVd.003).

3.6. UV Aerosol Index (UVAI)

is an index that detects the presence of UV-absorbing aerosols such as dust and soot. UV Aerosol index (AI) is based on a spectral contrast method in a UV region where the ozone absorption is very small. It is the difference between the