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Analysis of source regions for smoke events in Singapore for the 2009 El Nino burning season

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HIGHLIGHTS

- We evaluate Singapore as a receptor site for regional biomass burning aerosols.
- Sequential potential source regions were central Sumatra, southern Sumatra & Borneo.
- Smoke observed at the site was frequently transported above the boundary layer.
- Mixing into the boundary layer from aloft impacted surface aerosol observations.
- PBL/Free troposphere wind shear must be considered in analysis of aerosol transport.

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ABSTRACT

As part of the 7 SouthEast Asian Studies (7SEAS) program, a solar radiation and chemistry sampling site ("supersite") was developed at the National University of Singapore (NUS) to monitor regional air quality. The first intensive operations period for this site occurred between August and October 2009, a period that coincided with a moderate El Nino event and enhanced tropical burning, particularly in peatlands. We use data from this period to analyze the transport of biomass burning emissions in the Maritime Continent (MC) to the NUS supersite. An overview of the aerosol environment is provided for Singapore, followed by more detailed discussion of four aerosol events. The 2009 burning season was similar to those described in previous analyses, which showed that fire activity begins in the western half of the MC in Sumatra and propagates eastward in time. Similarly, agricultural burning occurs first, generally followed by deforestation and peatland fires. Some of the biomass burning emissions make their way into the free troposphere, where they are transported regionally by the prevailing wind patterns. Our analyses show that the seasonal winds at 850 hPa ($\sim$1500 m) shift transport patterns from source regions to the southwest of Singapore, to regions to the southeast over the course of the summer monsoon, patterns that allow Singapore to be impacted by peak burning regions in the MC. In contrast, winds at the surface are more typically from the south and southeast, demonstrating the prevalence of vertical wind shear over the region. As a result of the variable source regions influencing different levels of the atmosphere over Singapore, in-situ surface observations of aerosol mass concentrations are not always consistent with inferences of the presence of enhanced aerosol concentration from column optical depth. Our findings confirm the complexity of aerosol sources and transport over the MC, and the key role that biomass burning emissions play in influencing column aerosol optical depth and total particulate mass concentrations at the surface. The sea-level altitude of the NUS supersite means that non-local pollution transported above the boundary layer cannot be reliably sampled and characterized, but the combined effects of local emissions and downward-mixed, non-local pollutants in Singapore were consistently measured.

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1. Introduction

Southeast Asia's Maritime Continent is known for its high pollution loadings and complex meteorology (e.g., Balasubramanian et al., 2003; Oanh et al., 2006; See et al., 2007; Chang et al., 2011; Reid et al., 2012, 2013). Mega cities such as Jakarta, Singapore, and Kuala Lumpur exist in proximity to significant biomass burning sources from peatland destruction and agricultural maintenance (Streets et al., 2003; Stolle and Lambin, 2003; Giglio et al., 2006; Field and Shen, 2008; Reid et al., 2012). High population densities in mosaic landscapes exist on Java and Sumatra that lead to large-scale rural emissions (e.g., Yevich and Logan, 2003). Particle species from all of these sources mix in an environment of high humidity and solar radiation, leading to a chemically complex photochemical haze. This haze has been repeatedly identified as a broad threat to regional environmental quality (e.g., Siegert et al., 2001; Kunii et al., 2002; Sundarambal et al., 2010; Wang et al., 2013) and potentially climate (e.g., Rosenfeld, 1999; Hamid et al., 2001; Barbel, 2007; Tosca et al., 2010; Page et al., 2011).

The physical complexity of the Maritime Continent (henceforth MC) is coupled with daunting operability challenges. The region is covered with one of the highest cloud fractions in the world (e.g., ISCPP-Rossow and Schiffer, 1991; Reid et al., 2013), thereby defying monitoring by remote sensing. Siting and maintenance of equipment is difficult as sites with power and security are also often near significant local sources. This, coupled with the shear diversity of the socio-economic framework of the MC, leads to frequent questions of sampling representativeness (Reid et al., 2013).

The 7 SouthEast Asian Studies (7SEAS) project was created with the goal of linking aerosol, climate, and meteorology scientists in a grass-roots network dedicated to investigating the multi-faceted nature of aerosol particles in the Southeast Asian earth system (http://7-seas.gsfc.nasa.gov/; http://www.nrlmry.navy.mil/aerosol_web/7seas/7seas.html). The cornerstone of 7SEAS is a series of remote sampling sites over Southeast Asia and small intensive operations periods that can address the need for three-dimensional sampling, coupled with communal satellite and model products. One site which has seen a great deal of activity was established at the National University of Singapore (NUS), hosted jointly by the NUS Faculty of Engineering and the Center for Remote Imaging, Sensing and Processing (CRISP). Data previously collected in Singapore has led to a series of noteworthy papers which are among the few glimpses of MC atmospheric chemistry (e.g., Balasubramanian et al., 2003; See et al., 2006; He and Balasubramanian, 2009; He et al., 2010).

Here we evaluate the NUS supersite as a receptor for MC biomass burning during 7SEAS' first intensive trial operations from August to October 2009, when fire activity spiked due to El Nino conditions (Siegert et al., 2001; Fuller and Murphy, 2006; Field and Shen, 2008; Reid et al., 2012; Wang et al., 2013; Xian et al., 2013). While we briefly describe regional meteorology and observations from the site for context, the goal here is to understand the nature of the source–receptor relationship between biomass burning in the MC and the NUS supersite. Subsequent manuscripts by 7SEAS collaborators will discuss the nature of the Singapore aerosol environment and specific measurement results during this study in greater detail.

2. Methods

In this section we briefly describe measurements at the site, the trajectory tools used to establish potential source regions, and ancillary satellite and model data used to evaluate the source receptor relationship.

2.1. Description of the NUS supersite

In August 2009, aerosol and chemistry instrumentation was deployed to the NUS campus for the intensive operations period from August 5 to October 31, 2009. However, some data from preexisting instrumentation is included here for context. The site is located on an NUS rooftop above all other buildings for several kilometers and 1 km from the southern coast (Latitude 1.29 N; Longitude 103.77 E, 50 m altitude). Although the site was selected to be away from local sources, it is nevertheless located in a major city with significant shipping and petroleum industries. However, as we will show, major transport events increase optical depth and surface concentrations by integer factors.

Preexisting at the NUS site was a series of filter samplers and a sun photometer. In this work, we make use of filter gravimetry and aerosol optical depth (AOD) measurements, as well as ambient scattering from a nephelometer, to identify the start, end and relative magnitude of major aerosol events. The sun photometer was manufactured by CIMEL and was part of the Aerosol Robotic Network (AERONET; Holben et al., 1998, 2001). We use daily Level 2 data (cloud-cleared and manually quality controlled), processed with the Version 2 Direct Sun Spectral Deconvolution Algorithm (SDA) to provide 500 nm total, fine, and coarse mode AOD (O'Neill et al., 2003). Such data has a nominal uncertainty of ± 0.015, however, in locations such as Singapore, ubiquitous high thin cirrus can sometimes penetrate the cloud screening algorithm (Chew et al., 2011). Fortunately, the SDA largely sequesters this bias in the aerosol coarse mode. Additionally, we note that frequent heavy cloud cover over the Maritime Continent limits the number of valid AERONET and MODIS (discussed later) retrievals.

The Singapore National Environmental Agency (NEA) reports average PM_{10} mass concentrations from TEOM samplers and BAMS measurements across the city (available at: http://app2.nea.gov.sg/psi.aspx). At the NUS supersite, one in six day $PM_{2.5}$ filters were collected for 24-h (start/stop time $\sim$8AM LST) for gravimetric analysis, with additional daily samples collected when smoke impacts were thought to be occurring. Levoglucosan concentrations were measured for selected samples following the methods of Yang et al. (2013), and are used here as an indicator of smoke impacts. Samples were collected on 47-mm Teflon-coated glass fiber filters (Pall Corporation, USA) at a flow rate of 16.7 LPM. Gravimetric analysis was conducted at a relative humidity of $\sim$38%.

A TSI 3-wavelength nephelometer was used to measure light scattering coefficients at 450, 550, and 700 nm wavelengths. The data was corrected for Truncation/non-lambertian light source biases using the parameterizations of Anderson and Ogren (1998) and is reported as 30 min averages for the green channel only in order to estimate timing and magnitude of events.

2.2. Trajectory analysis

To assess Singapore as a receptor location we utilize backtrajectory analyses. Five-day backtrajectories originating from the NUS sampling location were generated using Version 4.9 of the NOAA HYSPLIT Lagrangian trajectory model (Draxler and Hess, 1997, 1998), driven by the Global Data Assimilation System (GDAS1) $1^\circ \times 1^\circ$ meteorological dataset provided by the NOAA Air Resources Laboratory. Eight trajectories per day (one every 3 h) were generated for starting receptor heights of 100 m and 1500 m above ground level. These correspond to the boundary layer and the middle of the convective boundary layer where smoke is frequently seen (Tosca et al., 2011; Campbell et al., 2013). We processed the backtrajectory endpoints using Residence Time Analysis (RTA) (Ashbaugh et al., 1985), to obtain probabilistic estimates of the transport pathways of air masses arriving at our sampling site