Atmospheric Environment 44 (2010) 1422–1427

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

# Aerosol transport model evaluation of an extreme smoke episode in Southeast Asia

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A R T I C L E  I N F O

*Article history:*
Received 31 August 2009
Received in revised form
24 January 2010
Accepted 29 January 2010

*Keywords:*
Biomass burning
Fire
Malaysia
Indonesia
Singapore
Aerosol
Aerosol transport modeling
Aerosol modeling
Emissions modeling
Smoke
Smoke emissions
Sumatra
Borneo

A B S T R A C T

Biomass burning is one of many sources of particulate pollution in Southeast Asia, but its irregular spatial and temporal patterns mean that large episodes can cause acute air quality problems in urban areas. Fires in Sumatra and Borneo during September and October 2006 contributed to 24-h mean $PM_{10}$ concentrations above 150 $\mu g\ m^{-3}$ at multiple locations in Singapore and Malaysia over several days. We use the FLAMBE model of biomass burning emissions and the NAAPS model of aerosol transport and evolution to simulate these events, and compare our simulation results to 24-h average $PM_{10}$ measurements from 54 stations in Singapore and Malaysia. The model simulation, including the FLAMBE smoke source as well as dust, sulfate, and sea salt aerosol species, was able to explain 50% or more of the variance in 24-h $PM_{10}$ observations at 29 of 54 sites. Simulation results indicated that biomass burning smoke contributed to nearly all of the extreme $PM_{10}$ observations during September–November 2006, but the exact contribution of smoke was unclear because the model severely underestimated total smoke emissions. Using regression analysis at each site, the bias in the smoke aerosol flux was determined to be a factor of between 2.5 and 10, and an overall factor of 3.5 was estimated. After application of this factor, the simulated smoke aerosol concentration averaged 20% of observed $PM_{10}$, and 40% of $PM_{10}$ for days with 24-h average concentrations above 150 $\mu g\ m^{-3}$. These results suggest that aerosol transport models can aid analysis of severe pollution events in Southeast Asia, but that improvements are needed in models of biomass burning smoke emissions.

## 1. Introduction

Smoke haze related to biomass burning is a recurring environmental problem in Southeast Asia which affects air quality not only in the source regions, but also in the surrounding areas. Biomass burning may be related to forest clearing, wildfires during drought years, or agricultural practice.

The forest clearing fires in the region are tightly linked to the monsoonal systems in the region (Fuller and Murphy, 2006). The southwest monsoon winds blow from April to September while the northeast monsoon occurs from November to February. From April through September, the east coast of Sumatra in Indonesia is sheltered from the southwest monsoon, resulting in a dry season. The territory of Kalimantan in Indonesia is also sheltered from the monsoon by the rest of the Indonesian Archipelago. It is therefore common for the locals to clear land for farming during the dry season. At the same time, accidental fires can be easily started in the forests, especially in Kalimantan.

From early July to October in 2006, biomass burning in Indonesia caused severe smoke haze over Southeast Asia, affecting many neighbouring countries such as Brunei, Malaysia, Singapore, and Thailand (NASA Earth Observatory, 2006, http://earthobservatory.nasa.gov/IOTD/view.php?id=7014). The situation was worsened by the El Niño-Southern Oscillation which delayed the monsoon season in the region (NOAA ESRL, http://www.cdc.noaa.gov/enso/impacts).

During the haze event, the air quality monitoring stations operated by Malaysia's Department of Environment (DOE) and Singapore's National Environment Agency (NEA) constantly monitored the situation and provided air quality advisories to the public. Needless to say, the smoke haze had a strong negative impact on air quality in the region.

The Navy Aerosol and Analysis System (NAAPS) is used by the US Navy for operational forecasting of air quality and visibility conditions. Satellite fire observations are used in real time to estimate smoke aerosol emissions, which are used as a boundary condition for NAAPS (Reid et al., 2009). In this study, we used a dataset of 24-h

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doi:10.1016/j.atmosenv.2010.01.043

average $PM_{10}$ data from Malaysia and Singapore to evaluate the capability of this modeling system to capture the onset, magnitude, and duration of severe smoke events.

## 2. Data and methods

### 2.1. Surface $PM_{10}$ data

The Malaysian Department of Environment (DOE) operates a network of 49 air quality monitoring stations in Malaysia. 35 of these stations are located in Peninsular Malaysia with 24 of them along the west coast, separated from the Indonesian island of Sumatra by the Straits of Malacca. The other 14 stations are situated in East Malaysia, north of the Indonesian territory of Kalimantan. More information about measurements and measurement locations is available online (Department of Environment, 2008: http://www.doe.gov.my/ms/content/air-quality-monitoring).

The NEA operates 13 air quality monitoring stations in Singapore (National Environment Agency, 2006) which is located at the southern tip of the Malay Peninsula. The air quality data is spatially averaged into 5 zones (north, south, east, west and central).

These air quality monitoring stations are positioned strategically in industrial, urban and sub-urban areas as well as along roadsides to monitor the ambient air quality. The concentrations of major criteria pollutants such as sulphur dioxide, nitrogen oxide, carbon monoxide, ozone and $PM_{10}$ are measured daily. The $PM_{10}$ measurements used in this study were obtained via the beta attenuation method.

Daily 24-h mean $PM_{10}$ observations (5 pm–5 pm local time for Malaysia and 4 pm–4 pm for Singapore) were acquired for 49 sites in Malaysia and 5 in Singapore with the site locations shown in Fig. 1. Measurements from Malaysia record only the most significant criteria pollutant for each 24-h period, which is not always particulate matter. We included only those sites and dates where particulate matter data were provided. For the 90-day study period from 1 September to 29 November 2006, 44 of 54 sites had at least 70 days of usable data.

### 2.2. FLAMBE smoke flux model

Smoke aerosol emissions were estimated using the Fire Locating and Monitoring of Burning Emissions (FLAMBE) smoke flux model (Reid et al., 2009; 2004). Fire locations and timing were derived from MODIS active fire detections (Giglio et al., 2003). Fire fuels were estimated using the Global Land Cover Classification (GLCC) (Loveland and Belward, 1997) global 1-km land cover database, version 2.0, and fire intensive properties (fuel loading, fuel consumption, emissions partitioning by species) were calculated based on the datasets of Reid et al., 2005. Section 4 includes further discussion of the components of this model in relation to the results of this study, as well as recommendations for model improvements.

### 2.3. NAAPS model

With its transition to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in October 2006, NAAPS is the U.S. Navy's (and the world's first) operational global aerosol forecast model. NAAPS produces 5-day forecasts of $SO_2$, sulfate, dust, biomass burning smoke and sea salt mass concentration with $1 \times 1$ degree resolution at 30 levels.

The NAAPS global model is a modified form of a hemispheric model of sulfate aerosols developed by Christensen, 1997. NAAPS is an offline model that utilizes the meteorological analysis and forecast fields from the Navy Operational Global Analysis and Prediction System (NOGAPS) (Hogan and Brody, 1993; Hogan and Rosmond, 1991). NAAPS includes wet deposition and dry deposition aerosol sinks. For additional details, see Zhang et al., 2008 and Xian et al., 2009.

Note that NAAPS simulates total particulate mass of each aerosol species. This total may include particles with diameters larger than 10 μm, and is therefore not an exact match to $PM_{10}$ observations. However, smoke particles with diameters larger than 10 μm are unlikely to be a significant fraction of the total smoke mass (Reid et al., 2005).

The lowest model layer in NAAPS has a thickness of approximately 30–40 m. However, representation of near-surface processes is limited by the coarse spatial resolution of the model as well as the rapid vertical mixing among the lowest model layers. Smoke aerosol particles are released into the boundary layer and lower free tropospheric layers of the NAAPS model. This parameterized description does not represent the complexity and range of smoke injection (see, e.g., Freitas et al., 2006); however it may be an acceptable description of the bulk behavior of the smoke source (Kahn et al., 2008).

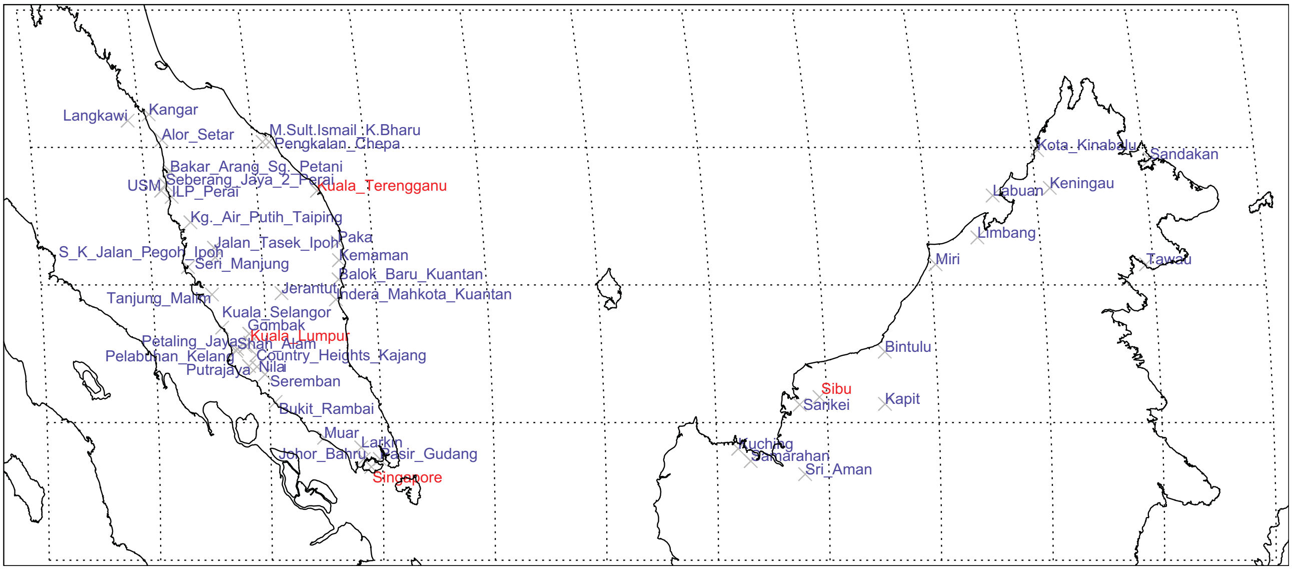

**Fig. 1.** Locations of $PM_{10}$ measurements used in this study. Five different stations in Singapore are included; a single label indicates the central point of these measurements. Locations of data shown in Fig. 4 are highlighted.