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Smoke aerosol transport patterns over the Maritime Continent

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ABSTRACT

Smoke transport patterns over the Maritime Continent (MC) are studied through a combination of approaches, including a) analyzing AODs obtained from satellite products; b) aerosol transport modeling with AOD assimilation along with the atmospheric flow patterns; c) analyzing smoke wet deposition distributions; and d) examining forward trajectories for smoke events defined in this study. It is shown that smoke transport pathways are closely related to the low-level atmospheric flow, i.e., during June–Sept, smoke originating from the MC islands with a dominant source over central and southern Sumatra, and southern and western Borneo, is generally transported northwestward south of the equator and northeastward north of the equator with the cross-equatorial flow, to the South China Sea (SCS), the Philippines and even further to the western Pacific. During the October–November transitional period, smoke transport paths are more zonally oriented compared to June–September. Smoke originating from Java, Bali, Timor etc, and southern New Guinea, which are in the domain of easterlies and southeasterlies during the boreal summer (June–November), is generally transported westward. It is also found that smoke transport over the MC exhibits multi-scale variability. Smoke typically lives longer and can be transported farther in El Niño years and later MJO phases compared with non El Niño years and earlier MJO phases. During El Niño periods there is much stronger westward transport to the east tropical Indian Ocean. Finally, orographic effect on smoke transport over the MC is also clearly discernable.

1. Introduction

The “Maritime Continent”, henceforth the MC, a term first coined by Ramage (1968) to describe the tropical Southeast Asia area extending across the Indonesian archipelago, Malay Peninsula and New Guinea, not only plays an important role in global circulation as a major heat source (e.g., Ramage, 1968; Neale and Slingo, 2003), but also is a major smoke aerosol source (e.g., van der Werf et al., 2004; Reid et al., 2009). The annual average carbon emission from biomass burnings over the MC is estimated to be about 11% of the global total and reaching 35–40% of the global value in the massive 1997 event when there were intensive fires all over the MC associated with El Niño (Page et al., 2002; van der Werf et al., 2006). Land use practices in the MC, involving biomass burning that converts forest and peatland into farmland (Page et al., 2002; Field et al., 2009), is a main contributor to smoke aerosol emission from year to year. Wildfires that burn in rainforest vegetations also contribute. Rainforest that normally experiences fire at intervals ranging from hundreds to thousands of years (Cochrane, 2003) now are more susceptible to fires owing to selective logging (Siegert et al., 2001).

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Smoke aerosols are known to directly affect human health, visibility in our daily life, and through direct and indirect effects impact temperature, atmospheric circulation, the formation of clouds and precipitation, and ultimately climate. Where these impacts occur is not only closely related to aerosol source but also aerosol transport. For example, air quality and visibility in Singapore are greatly affected by smoke originated from biomass burning in the coastal areas of southeast Sumatra and southwest Kalimantan (Koe et al., 2001). Aerosol and ozone concentrations in the Pearl River delta are greatly influenced by the upwind biomass burning in Southeast Asia (Deng et al., 2008). Large AODs are observed (Rajeev et al, 2000; Parameswaran et al., 2004), and significant radiative forcings (Podgorny et al., 2003; Thampi et al., 2009; Rajeev et al., 2008) are found in the east Tropical Indian Ocean resulting from the westward transport of smoke associated with Indonesian fires in 1997 and 2006.

Smoke transport pathways associated with MC fires have been studied in the past, but limited to case studies for certain time periods or locations (e.g., Koe et al., 2001; Rajeev et al., 2000). Still lacking is a systematic study or a study from a statistical point of view on the MC smoke transport patterns, which is what we intend to do in this work. This paper is the second in a series of three, where Reid et al. (2012b) first looked at fire activity and smoke AOD from climate point of view, we here perform large scale modeling over 2006 and 2007 aiming at generalizing smoke transport patterns in El Nino and Neutral years, and Wang et al. (2013-this issue) examine specific cases in 2006 at the mesoscale. We start with an overview of bulk fire activities for individual islands of the MC from 2003 to 2010 as a background introduction to smoke transport of the MC. Special focus is paid to atmospheric flow patterns and precipitation. Smoke transport patterns are explored through a combination of approaches, including a) analyzing AODs retrieved from satellite products; b) aerosol transport modeling with AOD assimilation, c) analyzing smoke aerosol wet deposition maps; and d) looking at bulk forward trajectories for smoke events defined by this study. Statistics of the lifetime of smoke events are also given based on model results. Because of large interannual variability in fire activities and smoke transport, particular attention is devoted to the years 2006 and 2007 as representatives of an El Nino year and a Neutral year respectively. Finally conclusions and discussions are given.

2. Data and methodology

The study area of the MC in this paper includes the equatorial island chain of Sumatra, Borneo, Sulawesi to New Guinea, and the southern island chain from Java, Bali to Timor. In order to show smoke transport patterns, a larger domain is generally used, i.e., 15S–20N, 85E–150E.

2.1. Fire and AOD data

For many reasons as stated in Reid, et al. (2009; 2012a), current state-of-the-science fire products can be considered only semi-quantitative in general, and only qualitative in the MC. Blocking and contamination of fire signals by cloud cover, variation in pixel geometry across the scan and satellite swath gap near the equator (Giglio et al., 2006), fires too small or burning temperature too low to be detected (e.g. Miettinen and Liew, 2009), etc., all affect active fire detections. Burn scar algorithms also require multiple looks and likely have a large threshold for operability. Estimation of smoke flux from these fire products introduces other uncertainties from variations in fire behavior as well as basic observational challenges such as attribution of fuels (Reid et al., 2009; Hyer and Reid, 2009).

For this study, we use the active fire hotspot data set of MODIS Terra (~10:30 LST) and Aqua (~13:30 LST) for 2003–2010, when both records exist (Justice et al., 2002; Giglio et al., 2003). We use a 9-day boxcar filter (i.e., 9-day center day average) on regional fire counts to generate our fire time series. This averaging smoothes orbit variations and provides some compensation for the region's high cloud cover. For smoke fluxes, we use the Fire Locating and Modeling of Burning Emissions (FLAMBE) system (Reid et al., 2009), which in this region is based upon the near real time University of Maryland/NASA MODIS fire products.

Satellite retrieved AOD data are obtained from three level-2 satellite products: the operational MODIS Dark Target (DT) collection 5 aerosol products from the Terra and Aqua satellites and the version 22 MISR aerosol product. For the MODIS DT products, AOD retrievals from the 0.55 μm spectral channel are used, and land data categorized as worse than "good" quality and ocean data categorized as worse than "marginal" quality by the QA flags are disregarded. When validated against AERONET data, the uncertainty of the MODIS DT products has an uncertainty of $\pm 0.03 \pm 0.05 \times \text{AOD}$ for over ocean retrievals and $\pm 0.05 \pm 0.15 \times \text{AOD}$ for over land retrievals (Remer et al., 2005; Remer et al., 2008). Similarly, for the version 22 MISR aerosol product, AOD retrievals from the 0.558 μm spectral channel are used, and only data categorized as "successful" are included. The uncertainty of the version 22 MISR AOD data, when compared to AERONET data, is 0.05 or $0.2 \times \text{AOD}$ (Kahn et al., 2010). In the SE Asian region, high cloud cover, complex lower boundary condition and variability in absorption challenge all satellite retrievals, leading to much larger uncertainties than as reported in global analyses (Reid et al., 2012a). Hence, here we treat these products as only semi-quantitative.

2.2. Meteorological data

For aerosol transport, the meteorological background, including flow pattern and precipitation, is essential. We use a one degree interpolation of the 0.5 degree reanalysis product of the Navy Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond, 1991) for wind field analysis. Multiple comparisons between NOGAPS fields to the NCAR reanalysis fields (Kalnay et al., 1996) in Southeast Asia show no substantial difference in winds.

For precipitation, we use the high resolution Climate Prediction Center (CPC) MORPHing technique product (CMORPH, Joyce et al., 2004). Unlike techniques which use IR data to help quantitatively derive precipitation where passive microwave data (PMW) data is not available (e.g., Huffman et al., 1997; Miller et al, 2001; Turk and Miller, 2005), CMORPH uses IR data only to propagate precipitation