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Clear sky direct radiative effects of aerosols over Southeast Asia based on satellite observations and radiative transfer calculations

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ABSTRACT

Using the Moderate Resolution Imaging Spectroradiometer (MODIS), Clouds and the Earth's Radiant Energy System (CERES) instrument, and a radiative transfer model (RTM), we provide a quantitative assessment of regional cloud-free diurnally averaged shortwave Aerosol Radiative Effects (AREs) at the top of atmosphere (TOA) and at the surface over Southeast Asia (SEAS, 10°S–20 N and 90°E–130°E). The spatial and temporal variations of the annual ARE are calculated based on satellite and ground-based measurements, supplemented by radiative transfer simulations. During 2001–2010, our results indicate that the *TOA* diurnally averaged ARE is -5.6 ± 0.8 Wm^{-2} over land and -4.8 ± 0.7 Wm^{-2} over ocean, respectively. In contrast, the *surface* ARE is -13.8 ± 3.2 Wm^{-2} based on radiative transfer calculations. For aerosol layers of 2 km in height with midvisible optical depth of 1.41 and single scattering albedo of 0.91, the shortwave radiative heating can exceed 0.8 K/day. Our results indicate significant inter-annual variability of aerosol radiative properties, which is extremely large over major emission outflow regions like SEAS. This study suggests that an integrated system of satellite data, model calculations coupled with ground-based and meteorological data sets is needed to assess Aerosol Radiative Effects on regional earth-atmosphere energy budgets.

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1. Introduction

Although the impact of greenhouse gases on climate has been extensively studied, the role of aerosols also has measurable and equally significant impact on climate (Kaufman, Tanre, & Boucher, 2002). However, scientific understanding of the radiative effects due to atmospheric aerosols from regional to global scales is still uncertain, especially in regions with complex emission sources and land ecosystems such as Southeast Asia (SEAS) (IPCC, 2007; Reid et al., 2013). Previous studies have indicated that natural and anthropogenic aerosols alter the radiative energy budget by scattering and absorbing incoming solar radiation (the direct radiative effect) and also modify cloud properties (the indirect radiative effect) (Davison, Roberts, Arnold, & Colvile, 2004; Rajeev, Parameswaran, Nair, & Meenu, 2008). Depending on aerosol properties and the underlying surface albedo, the top of atmosphere shortwave aerosol direct radiative effects (ARE_{toa}) can be positive (warming effects) or negative (cooling effects). By absorbing incoming solar radiation, aerosols such as soot can both warm the atmosphere and cool the surface, whereas highly scattering type aerosols (e.g. sulfate) can cool the Earth's surface by reflecting more solar insolation and thereby increasing the planetary albedo (Eck, Holben, Slutsker, & Setzer, 1998; Satheesh & Ramanathan, 2000). Prior studies indicate that globally averaged ARE_{toa} values are negative but vary regionally depending on surface and aerosol characteristics (Yu et al., 2006). Large uncertainties are associated with current estimates of ARE_{toa}, that are largely due to the heterogeneous spatio-temporal distributions, magnitudes of aerosol loadings, uncertainties in characterizing microphysical and optical properties, and challenges in assessing their interactions with clouds.

Recently there has been a renewed emphasis on observational studies to provide better estimates of aerosol loading and ARE_{toa} that can be used for validating and constraining numerical models (Kahn, 2012). Observational estimates based on satellite and ground observations can provide reliable monitoring of aerosol emissions, transport, and its microphysical and optical properties, which can then provide realistic representations of regional aerosols in numerical models. Measurements of aerosol physical and chemical properties are also available from field campaigns conducted in major aerosol regimes over the world. These measurements can be used in radiative transfer models (RTMs) to estimate ARE_{toa} and surface radiative effect ARE_{sfc} (Christopher et al., 2000; Fu & Liou, 1993). However, only a very few direct measurements of atmospheric composition, aerosols, or cloud properties are available over SEAS. Satellite remote sensing can therefore serve as a useful tool to understand the impact of aerosols on climate (Reid et al., 2013).

Satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) can provide routine global measurements of aerosol properties (e.g. aerosol optical

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depth). These observations can be used in conjunction with broadband data sets from Radiation Budget instruments such as Clouds and the Earth's Radiant Energy System (CERES) to estimate ARE_{toa} (Zhang, Christopher, Remer, & Kaufman, 2005a). Although previous studies have assessed ARE_{toa} over regions with high smoke aerosol concentrations such as Africa and South America (Sakaeda, Wood, & Rasch, 2011; Sena, Artaxo, & Correia, 2013), the spatial and temporal distributions of ARE_{toa} that are mainly caused by biomass burning smoke and industrial pollution over SEAS have not been studied in much detail. The ubiquitous cloud cover, sharp gradients in surface features, and complex aerosol characteristics increase the difficulties in conducting in-situ and remote sensing observations. By using observations from MODIS, CERES and AERONET along with calculations from the RTM, this study provides quantitative evaluation of regional cloud-free diurnally averaged ARE_{toa} and ARE_{sfc} over the entire SEAS region during a 10 year period from 2001 to 2010.

The major goals of this study are to:

a) Assess the ARE_{toa} in cloud free conditions using multi-year observations from MODIS and CERES instruments on board the Terra satellite;
b) Calculate ARE_{sfc} using satellite and AERONET data in radiative transfer calculations;
c) Compare these assessments with previous research;
d) Use aerosol vertical distribution to assess profile of radiative heating rates.

2. Data and area of study

2.1. Southeast Asian meteorology and aerosol particles

The study area includes the SEAS region between 10°S–20°N and 90°E–130°E which covers tropical to subtropical regimes (Fig. 1a, b

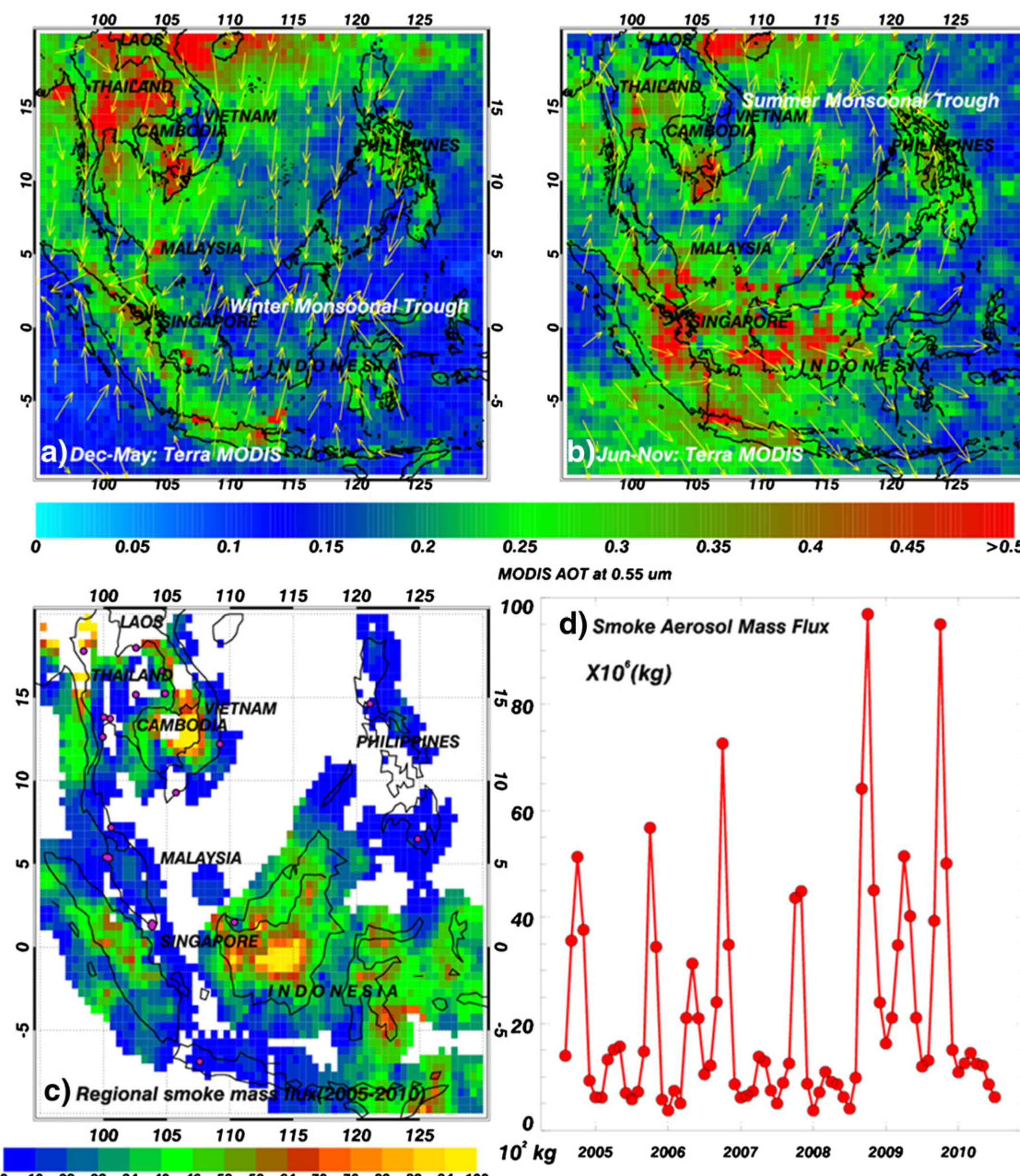

Fig. 1. Seasonal averaged aerosol optical depth (AOD) composites from MODIS collection 5.1 (550 nm) MOD04 products for each 0.5 × 0.5 degree grid point for (a) December to May and (b) June to November during the whole study period from 2001 to 2010. Also with NOGAPS winds at 850 hPa averaged over each period and plotted to show monsoonal characteristics (c) 0.5° × 0.5° spatial distributions of annual mean FLAMBE smoke aerosol mass fluxes, with ground-based AERONET sites (purple points). (d) The monthly variations of regional FLAMBE smoke aerosol mass fluxes (×10^6 kg) from 2005 to 2010.

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