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Attribution of aerosol radiative forcing over India during the winter monsoon to emissions from source categories and geographical regions

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ABSTRACT

We examine the aerosol radiative effects due to aerosols emitted from different emission sectors (anthropogenic and natural) and originating from different geographical regions within and outside India during the northeast (NE) Indian winter monsoon (January–March). These studies are carried out through aerosol transport simulations in the general circulation (GCM) model of the Laboratoire de Météorologie Dynamique (LMD). The model estimates of aerosol single scattering albedo (SSA) show lower values (0.86–0.92) over the region north to 10°N comprising of the Indian subcontinent, Bay of Bengal, and parts of the Arabian Sea compared to the region south to 10°N where the estimated SSA values lie in the range 0.94–0.98. The model estimated SSA is consistent with the SSA values inferred through measurements on various platforms. Aerosols of anthropogenic origin reduce the incoming solar radiation at the surface by a factor of 10–20 times the reduction due to natural aerosols. At the top-of-atmosphere (TOA), aerosols from biofuel use cause positive forcing compared to the negative forcing from fossil fuel and natural sources in correspondence with the distribution of SSA which is estimated to be the lowest (0.7–0.78) from biofuel combustion emissions. Aerosols originating from India and Africa-west Asia lead to the reduction in surface radiation (−3 to −8 W m^{-2}) by 40–60% of the total reduction in surface radiation due to all aerosols over the Indian subcontinent and adjoining ocean. Aerosols originating from India and Africa-west Asia also lead to positive radiative effects at TOA over the Arabian Sea, central India (CNI), with the highest positive radiative effects over the Bay of Bengal and cause either negative or positive effects over the Indo-Gangetic plain (IGP).

1. Introduction

Human activities causing release of greenhouse gases and aerosols are the main drivers of climate change (Forster et al., 2007). Anthropogenic aerosols alter the earth's energy balance by changing radiative fluxes both at the surface and at the top of the atmosphere (Bellouin et al., 2005) and hence exert radiative forcing of climate. Aerosols reduce the solar radiation reaching the earth's surface by absorbing and scattering respectively the incoming solar radiation and hence cause negative radiative forcing at the surface. Additionally, aerosols such as black carbon absorb solar radiation resulting in a positive radiative forcing at the top-of-atmosphere (TOA). The change in the radiative flux due to aerosols is a function of the atmospheric loading of aerosols and the sign of radiative forcing at the TOA will depend upon the aerosol single scattering albedo as well as the albedo of underlying surface and the distribution of solar zenith angle, the balance between absorption and scattering being the key. On the other hand, the regional climate response to the variation (spatial and temporal) in aerosol radiative effects will depend on the intensity of radiative–convective coupling between the surface and the atmosphere which could be different during the different seasons over the tropical and non-tropical world regions (Ramanathan and Carmichael, 2008). This could lead to climate response due to aerosols which could be different regionally and globally. In this context, it is necessary to examine the radiative effects due to aerosols on a regional basis.

The recent field campaigns over the Indian Ocean [e.g. the Indian Ocean Experiment (INDOEX) and the Indian Space Research Organisation-Geosphere Biosphere Programme (ISRO-GBP) land- and ship-campaigns] have shown large aerosol negative radiative forcing at the surface and a relatively large atmospheric heating compared to the top-of-atmosphere (Ramanathan et al., 2001;

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Jayaraman et al., 2006). The globally and annually averaged direct aerosol radiative perturbation in the Laboratoire de Météorologie Dynamique General Circulation Model (LMD-ZT GCM) have been discussed by Reddy et al. (2005). Recent modelling studies using region-tagged emissions in the LMD-ZT GCM (Verma et al., 2008) showed that the emissions from different regions have disproportionate effects on the surface and columnar loadings of different aerosol species over the Indian subcontinent and ocean. For instance, the surface black carbon (BC) concentrations are mainly contributed from Indian regions while the BC column is more contributed from Africa-west Asia. Hence it is necessary to understand the radiative effects due to aerosols originating from different emission sectors and geographical regions. Modelling studies carried out to understand impact on global annual mean radiative forcing due to aerosol emissions (Koch et al., 2007) or both aerosol emissions and greenhouse gases (Unger et al., 2009; Aunan et al., 2009) originating from sectors such as, residential, industrial, transport, power, biomass showed different extents of radiative effects at the top-of-atmosphere. Using Goddard Institute for Space Studies (GISS) GCM, Koch et al. (2007) showed a significant influence of inter-regional transport of aerosols on aerosol chemical composition over the Arctic and Atlantic oceanic regions. It is required to understand the radiative effects due to aerosols originating from different geographical regions of the world, including those originating from different parts of India and emission sectors (natural and anthropogenic sources) specifically over the Indian subcontinent and ocean. In the present work, we examine the spatial distribution of aerosol radiative effects over the Indian subcontinent and ocean through aerosol transport simulations in the LMD-ZT GCM with the emissions tagged by geographical regions and fuel sectors corresponding to the northeast (NE) Indian winter monsoon when the Indian subcontinent and ocean has the highest pollution loading potential from anthropogenic sources. The specific objectives of the study include the following: (i) evaluate the aerosol single scattering albedo due to contribution from different emission sectors and geographical regions to assess the relative importance of scattering or absorbing aerosols. (ii) analyse the spatial distribution of aerosol radiative effects from different emission sectors and geographical source regions within and outside India.

2. Method of study

Aerosol transport simulations for the period from January to March 1999 (corresponding to the NE Indian winter monsoon) are carried out in the LMD-ZT GCM, version 3.3. A description of the atmospheric model is given in Li (1999) and a specific description of aerosol treatment and atmospheric transport is given in Boucher et al. (2002) and Reddy et al. (2004). Two sets of experiments were carried out for the present work, where aerosols were either tagged by regions or sources. Details of the experimental setup are given in Verma et al. (2007). Fig. 1 shows the masked regions on GCM zoom grid, which include the Indo-Gangetic Plain (IGP), central India (CNI), south India (SI), northwest India (NWI), southeast Asia (SEA), east Asia (EA), Africa-west Asia (AFWA), and rest of the world (ROW). In the region-tagged simulations, the aerosol transport and atmospheric processes are simulated for each geographical region with the emissions outside that region being switched off. In the source-tagged simulations, the aerosol transport and atmospheric processes are simulated for each of the sector – biofuel (BF), fossil fuel (FF), and natural source. The sectors for the biofuel source included wood and crop-waste for residential cooking and heating. The sectors for the fossil fuel source are coal-fired electric utilities, diesel transport, brick kilns, industrial, transportation, and domestic. The natural source included sulphur from

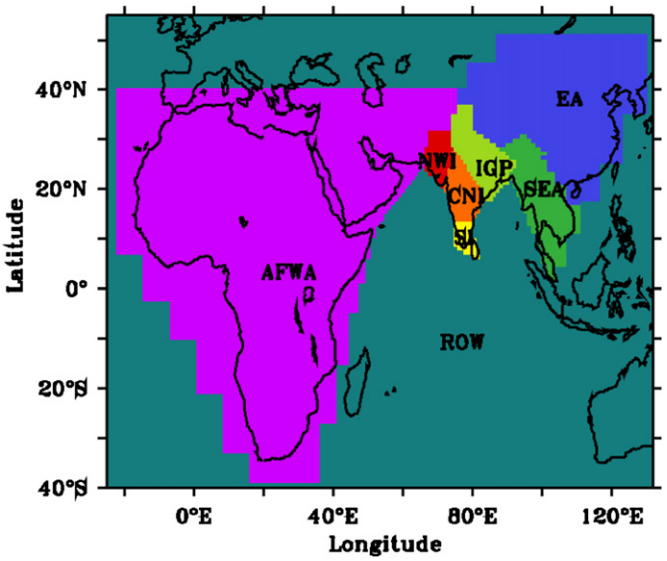

Fig. 1. Masked regions on GCM zoom grid representing tagged source regions taken under study; the classification of source regions are as following with different colours indicated in bracket: 1. IGP (light green) 2. CNI (orange), 3. SI (yellow), 4. NWI (red), 5. SEA (green), 6. EA (blue), 7. AFWA (pink), 8. ROW (dark green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

volcanic and biogenic sources, terpenes from the vegetation or natural OM, dust from arid regions, and sea-salt. Aerosol emissions over India [SO_2, BC, and organic matter (OM), and inorganic matter (IOM) (fly-ash emissions from coal combustion)] are from the high-resolution ($0.25^\circ \times 0.25^\circ$) emission inventories of Reddy and Venkataraman (2002a, 2002b). Emissions of SO_2, BC, and organic carbon (OC) from fossil fuel and biomass sources over Asia are from Streets et al. (2003). Global carbonaceous aerosol emissions used here are the same as described by Reddy and Boucher (2004). Carbonaceous aerosols are predominantly emitted in the hydrophobic form, but some fraction of the emissions may be in hydrophilic form as well. Here, we assume that black carbon (BC) emissions from both fossil fuel and biomass burning occur as 80% hydrophobic and 20% hydrophilic, whereas organic matter (OM) emissions occur as 50% hydrophobic and hydrophilic. The ageing process of BC and OM is represented by a transfer of the hydrophobic to hydrophilic form with an exponential lifetime of 1.63 days. Aerosol scheme is a mass-only scheme. Aerosol optical properties (mass extinction efficiency, single scattering albedo, and asymmetry factor) for all aerosol species are computed using Mie theory with prescribed size distributions and refractive indices. We consider the relative humidity (RH) effects on particle size and density of sulphate, hydrophilic OM, and sea-salt. The refractive index of sulphate, hydrophilic OM, and sea-salt as a function of RH are calculated as the volume weighted average of the refractive indices of each of the aerosol species and water. Aerosol optical properties for all aerosol species are computed assuming an external mixing.

The radiative code in the LMD-ZT GCM consists of improved versions of the parametrization of Fouquart and Bonnel (1980) (solar radiation) and Morcrette (1991) (terrestrial radiation) as described in Reddy et al. (2005). The model accounts for the diurnal cycle of solar radiation and allows fractional cloudiness to form in a grid box. The reflectivity and transmissivity of a layer are computed using the random overlap assumption (Morcrette and Fouquart, 1986) by averaging the clear and cloudy sky fluxes weighted linearly by their respective fractions in the layer. For each