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A Review of Modeling Approaches Accounting for Aerosol Impacts on Climate

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1. Introduction

Atmospheric aerosols are tiny particles suspended in the air, in solid as well as in liquid particle forms. Aerosols are known to cause serious air pollution problems and adverse health effects. Apart from these effects, aerosols have now been revealed as a key component in changing climate scenarios. Along with green house gases, aerosols also play an important role in modulating both the global and regional climate balance. Aerosols are found to influence the climate directly and indirectly through radiative forcing (Panicker et al. 2008). Aerosols directly influence the climate by scattering and absorbing incoming solar radiation and indirectly through modifying the cloud microphysical processes (Ramanthan et al. 2001). The quantitative estimation of aerosol radiative forcing is more complex than the radiative forcing estimation of greenhouse gases, attributed to the large spatio-temporal variability of aerosol particulates. This variability is largely due to the much shorter atmospheric lifetime of aerosols compared with the life time of important greenhouse gases. The typical life time of aerosols varies from days to weeks, where as greenhouse gases sustain in the atmosphere for years. The optical properties and microphysical processes of cloud aerosol interactions are also different among various aerosol species and hence are scarcely understood. The quantitative estimation of their effects, therefore, has been highly uncertain (Takemura et al. 2002). Intensive field experiments, new surface and remote-sensing observations, and improved representation of aerosol processes in models have provided new insights into the controlling mechanisms, radiative effects, and the influence of aerosols on climate (Bollasina and Nigam, 2006). The influence of anthropogenic aerosols on the Earth's radiation budget however is still considered as the largest uncertainty in radiative forcing under climate change (IPCC, 2007). According to the latest International Panel for climate change report (IPCC, 2007), the global mean direct aerosol radiative forcing is -0.5±0.4 Wm^{-2} and the estimate for the global annual radiative forcing of the first indirect effect is -0.7 Wm^{-2} with an uncertainty range of -1.8 to -0.3 Wm^{-2}. This negative radiative forcing is supposed to partly offset the the warming caused by greenhouse gases. The aerosol induced surface cooling namely 'White house effect', counter acting to greenhouse effect is revealed to generate a 'global dimming 'in the past century. It is proposed that this reduction of solar radiation at the surface and associated cooling can alter the tropospheric temperature profile and can even change the cloud processes and hence

precipitation patterns (Satheesh and Ramanathan, 2000). Absorbing aerosols such as black carbon are found to be responsible for a new phenomenon known as 'Atmospheric Brown clouds' (Ramanathan et al. 2005), which is considered as a threat for Himalayan glaciers due to heating in the lower troposphere, leading to melting of glaciers. Radiative effects of aerosols had generally been neglected in climate models while simulating different large scale phenomenon. However studies have pointed out that such omission of aerosol component could induce large bias in model outputs. Also recent studies proved that aerosols are influential climate components in modulating large scale phenomenon like Indian summer monsoon (eg: Lau et al. 2006; Menon et al. 2002). Several studies have been published in the aspect of aerosol radiative effects and their climate impacts. In this chapter we describe a compact review of aerosol radiative forcing studies reported using modeling approaches. Due to length constraint of the chapter, we present only most highlighted and recent findings in aerosol direct and indirect effect estimations carried out using atmospheric model simulations. Aerosol models vary from one dimension to three dimensions. This chapter focuses on the modeling aspects of aerosol optical properties and their direct and indirect radiative effects using one dimensional and three dimensional modeling studies. The chapter has been divided in to five sections including description of modeling of aerosol optical properties, aerosol direct radiative forcing estimates in local scale using one dimensional models, findings of aerosol direct radiative forcing in regional and global scales using three dimensional models, aerosol indirect forcing estimates in regional and global scale and the final section describes the important findings of role of aerosols in modulating the large scale phenomenon, the monsoon.

2. Modeling of aerosol optical properties

Aerosol models represent a simple, generalized description of typical atmospheric conditions (Shetle and Fenn., 1979). The definition of an aerosol model is a complex process because of the great variability in the physical, chemical, and optical properties of aerosols in both time and space. Two fundamental approaches toward defining an aerosol model exist: first, a direct measurement of all the necessary optical properties as a function of space and time and, second, a computation of the optical characteristics of aerosols after the microphysical properties have been collected and averaged by use of data derived from different sources (Levoni et al. 1997). The sparcity of adequate observational data sets makes the first approach much complex. Hence the second approach is used to model aerosol optical parameters. Several authors have developed models for atmospheric aerosols: beginning with the early works of Toon and Pollack (1976) and Fenn (1964). The aerosol component models has been popularized after the developmet of World Climate Research Program aerosol models (Deepak et al.1983) and the new version known as to as WCP-112 (WCP, 1986). In this section, we briefly decribe the fundamental aerosol optical models popularly used by aerosol community for modeling aerosol optical properties.

The essential aerosol optical parameters required for estimation of radiative forcing includes, Aerosol optical depth (AOD), Single Scattering Albedo (SSA), Asymmetry parameter (ASP) and Angstrom exponent (ANG). AOD represents the aerosol concentration in terms of attenuation of light. It is defined as the height integrated extinction coefficient and is a unit less quantity. A low value of AOD indicates an atmosphere with less aerosol loading and its typical value above 0.7 is considered as very high aerosol loading condition.

SSA indicates the aerosol radiative absorption nature,viz. absorbing type or scattering type. SSA is also a unit less quantity and its typical value above 0.9 indicates a majority scattering type aerosols (eg: sulphate, nitrate) and value below 0.8 represents significant presence of absorbing aerosols (eg: Black carbon, dust). ASP represents the direction of scattering by aerosols, (Panicker et al.2008; Pandithuarai et al.2004) ie. forward or back ward scattering. The value of ASP ranges between -1 to +1. The range -1 to 0 is indicates backward scattering by aerosols and 0 to 1 is assumed to be for forward scattering fraction of aerosols. Angstrom wavelength exponent indicates the size distribution of aerosol fractions. Higher value of ANG indicates an atmosphere with abundance of smaller particles (fine mode) and smaller values of ANG indicates the dominance of bigger particles (Coarse mode). The observations of these important aerosol optical parameters have been carried out using hand held/ automatic sunphotometers/radiometers. However when, the direct observations of these aerosol optical parameters are un available, chemical sampling data sets has been used to model the aerosol optical parameters. In this regard, one dimensional aerosol models has been utilized. In general, aerosol optical models utilize aerosol chemical data sets as inputs and provide aerosol optical parameters as output, which are necessary for estimating radiative forcing.

There are a few models, which utilizes aerosol chemistry data sets to derive aerosol optical properties. Out of these, Optical properties of aerosols and clouds (OPAC) is one of the most popular and widely used model. OPAC is a software package used to derive aerosol optical properties such as AOD, SSA, ASP, ANG and extinction coefficient at a given location. OPAC provides the optical properties of aerosol particles, water droplets and ice crystals, both in solar and terrestrial spectral range, and on the other hand include software to handle data (Hess et al., 1998). OPAC utilizes aerosol chemical composition data sets. It uses generally six different types of aerosol composition viz. Water soluble, Insoluble, soot, mineral aerosol, seasalt particles, sulfates chemistry data sets as its input (defaut or user defined). OPAC also has been characterized with ten different environmental conditions over continental and maritime regions. It provides outputs of aerosol optical parameters such as AOD, SSA,ASP, extinction coefficient, Angstrom expeont etc. at 8 different relative humidity conditions (0%, 50%, 70%, 80%, 90%, 95%, 98%, 99%).

Several investigators Several investigators utilize OPAC model to estimate aerosol optical properties from chemical composition data sets. A study by Panicker et al. (2010b) showed a promising comparison of aerosol optical properties derived potential comparison of OPAC derived AOD to Sun/Sky radiometer derived AOD. Another study by von Huene et al.(2011) also has reported fair comparison results between experimental aeorosol data sets and OPAC modeled aerosol components for different atmospheric environments. Several studies over the globe use Aerosol optical properties derived by OPAC as reference parameters for estimating aerosol raditive effects over the concerned environments. (eg: Satheesh et al. 1999; Ramachandran et al. 2006). A few literature report their radiative forcing computations using OPAC modeled aerosol optical poroperties (eg: Panicker et al. 2008; Sreekanth et al. 2007; Vinoj et al. 2004; Kim et al. 2006; Ramachandran et al. 2006). Satheesh et al. (1999) developed an aerosol optical model for natural and anthropogenic aerosols over Indian Ocean during Indian ocean experiment (INDOEX) based on OPAC model and was used to derive aerosol optical properties and hence the radiative forcing estimations during INDOEX. Smirnov et al. (2003) developed another model for accounting aerosol optical properties and size distributions exclusively over maritime regions using AERONET datasets.

Levoni et al. (1997) developed an optical aerosol model to derive aerosol optical properties from chemistry data sets. In this model, Users can select a default aerosol class or component or they can input a user-defined aerosol class or component by setting mixing ratios, size distribution, refractive indices of aerosol components, and mixing type. The user can choose a grid within the following parameter ranges: wavelength, 0.2–40 mm; scattering angle, 0°–180°; and RH, 0%–99%. It provides 15 different environmental conditions over continental and maritime areas. The model also has been provided with several aerosol scattering and absorbing species as its inputs (eg: Sulphate,Soot, Watersoluble, insoluble etc.) The main output parameters from this model includes, Extinction coefficient, scattering coefficient, SSA,ASP and phase function. This model found to have shown satisfactory comparison with well tested WCP-112 model (Levoni et al. 1997). The data sets described in this model has been used by several investigators for validation as well as for radative transfer calculations (eg: Guzzi et al. 2007; Nessler et al. 2005).

Global Aerosol Data Set (GADS) provides the aerosol optical parameters globally using aerosol chemical composition data sets. It is a completely revised version of the aerosol climatology by d'Almeida et al. (1991). GADS and OPAC use the same set of optical data of aerosol components. GADS provides aerosol optical parameters on a grid of 5 degrees longitude and latitude, with 7 differentiating height profiles. GADS consists of number distribution, mass per volume and optical properties of aerosols. In this package aerosol particles are described by 10 main aerosol components which are representative for the atmosphere and characterized through their size distribution and their refractive index depending on the wavelength. These aerosol particles are based on components resulting from aerosol emission, formation and removal processes within the atmosphere, so that they exist as mixture of different substances, both external and internal (Kopke et al. 1997). Typical components include water-soluble, water-insoluble, soot, sea-salt and mineral aerosols. The sea-salt particles are defined in two classes and the mineral particles in four. Aerosols are modeled as 10 components which are described with size distribution and spectral refractive index. From these chemical composition data sets, the optical properties are calculated with Mie-Theory at wavelengths between 0.25 μm and 40 μm and for 8 values of relative humidity similar as in OPAC, while over entire globe at 5^0 X 5^0 grid spacing. GADS has been cited several times in the literature (eg: Chin et al. 2003; Manoj et al.2010).

3. One dimensional modeling of direct aerosol radiative forcing

Direct Aerosol radiative forcing (DARF) indicates the reduction in surface reaching solar radiation due to its scattering and absorption by aerosols. Observed aerosol properties such as AOD, SSA and ASP and ANG have been the most important parameters required for estimating DARF. DARF is defined as the difference in solar fluxes (irradiance), with aerosol condition and fluxes with clean condition in the atmosphere. It requires, down welling and up welling irradiances to calculate radiative forcing and is calculated as,

$$DARF = [F\downarrow - F\uparrow]_{aerosol} - [F\downarrow - F\uparrow]_{no\ aerosol}$$

For calculating DARF, it is necessary to have the explicit data sets of aerosols, gaseous components, albedo of the observing surface, verical profiles of meteorological parametrs and aerosols. Radiative transfer models are used to compute the aerosol direct radiative forcing at any level in the atmosphere with the appropriate input values for aerosol

properties. The core of a radiative transfer model lies the radiative transfer equation that is numerically solved using a solver such as a discrete ordinate method or a Monte Carlo method. The radiative transfer equation is a monochromatic equation to calculate radiance in a single layer of the Earth's atmosphere. To calculate the radiance for a spectral region with a finite width, one has to integrate this over a band of wavelengths. The most exact way to do this is to loop through the wavelengths of interest, and for each wavelength, calculate the radiance at this wavelength. For this, one needs to calculate the contribution of each spectral line for all molecules in the atmospheric layer; this is called a *line-by-line* calculation.

In general, Radiative transfer models derive the radiative fluxes at specified spectral wavelengths. It derives fluxes at different levels with aerosol condition and no aerosol condition, difference of which, provides aerosol radiative forcing. A list of most important atmospheric radiative transfer models and their wavelength bands of simulation are depicted in table 1. Radiative transfer models in general uses a set of programs based on a collection of highly developed and reliable physical models, which have been developed by the atmospheric science community over the past few decades. The basic programs in radiative transfer codes consists of consists of (a) cloud model, containing the optical datasets of clouds,(b) Gas absorption model, describing the gaseous absorption in the atmosphere,(c) Extra terrestrial source spectra, consisting of model spectrums incorporating solar spectral wavelengths. (d)standard atmospheric models to characterize typical climate conditions (eg: Mc Clathey et al.(1972) contianing tropical, midlatitude winter and summer; sub artic winter and summer and artic winter and summer over the globe). The models also facilitate the option of using user defined atmospheric profiles of temperature and humidity for concerned environments. Also these models uses standard aerosol models for defining aerosol vertical profiles (eg: SBDART (Richiazzi et al. 1998) uses the MC Clathey et al. (1972) models, of vertical aerosol profiles for visibility 5 and 23 km).

Model name	Source	Spectral wavelength of simulation	Mode of operation
DISORT	Stamnes et al. (1998)	UV, Visible, IR	Offline
LBLRTM	Clought et al. (2005)	UV, Visible, IR	Offline
libRadtran	Mayer and Kylling (2005)	UV, Visible, IR	offline
MODTRAN	Berk et al. (1998)	UV, Visible, IR	offline
SBDART	Ricchiazzi et al. (1998)	UV, Visible, IR	offline
Fast Rt	Engelsen and Kylling(2005)	Exclusive for UV	online

Table 1. Popular atmospheric radiative transfer models and their wavelength bands of simulation.

Typically radiative forcing is estimated at the surface, Top of the Atmosphere (TOA) and in the atmosphere. DARF results in short wave region (0.3-3μm) report a negative forcing at the surface, attributed to radiation reduction at the surface by scattering and absorption of aerosols, depending on the aerosol species. The forcing at TOA also depends on aerosol species, which used to be positive for absorbing fractions and negative for scattering species. The difference between TOA and surface forcing, estimates the net gain of radiation by aerosols in the atmosphere, known as atmospheric aerosol forcing, which used to be a positive quantity in short wave domain. Several studies report aerosol shortwave radiative forcing estimates using ground based observations and also by modeling approaches. In this section, we brief the most important findings of one dimensional model based aerosol radiative forcing estimates over different regions in the globe.

Indian Ocean Experiment (INDOEX) (Jayaraman et al. 1998; Satheesh et al. 1999) was one of the initial attempts, which largely used the observed aerosol datasets in dimensional models to estimate regional aerosol radiative forcing. Tropospheric Aerosol Raditaive Forcing Observational experiment (TARFOX) over Atlantic Ocean (Hignett et. al., 1999) also contributed estimates of aerosol forcing using observation-model coupling analysis. Mean Clear-sky aerosol surface forcing reported was about -26W m^{-2} for Atlantic Ocean during TARFOX (Hignett et. al., 1999) and -29 W m^{-2} for tropical Indian Ocean during INDOEX (Satheesh and Ramanathan, 2000).

Conant (2000) showed an aerosol surface forcing of -7.6 ± 1.5 W m^{-2} during INDOEX period in the 400–700 nm spectral region (visible region of short wave band). He introduced two new promising methods for estimating Aerosol radiative forcing (ARF) and forcing efficiency. One a pure experimental method and another Hybrid method, utilizing Montercarlo radiative transfer model in conjunction with experimental data sets of observed fluxes. Both the methods found to show results with minimal bias. It is also shown that, a 0.1 change in aerosol optical depth produces a -4.0 ± 0.8 W m^{-2}; change in the 400–700 nm surface flux and 55% of this forcing is confined in the 400–540 nm region.

Satheesh et al. (1999) used Montecarlo radiative transfer model in conjunction with the INDOEX aerosol model and showed that anthropogenic aerosols reduces the incoming solar radiation up to -50 Wm^{-2} at the surface. Using OPAC in conjunction with SBDART, Vinoj et al. (2004) estimated radiative forcing over Bay of Bengal (BOB) and found that Regionally averaged aerosol (net) forcing over the Bay of Bengal was in the range -15 to -24 W m^{-2} at the surface, -2 to -4 W m^{-2} at the top of the atmosphere, leading to an atmospheric absorption of 13 to 20 W m^{-2}. Pandithurai et al. (2004) found a surface solar reduction of 33 Wm^{-2} over an urban Indian terrain, Pune. They used the observed aerosol optical properties from a Sun/Sky radiometer in SBDART to derve fluxes and hence forcing. The TOA forcing was found to be Zero, and the atmospheric absorption was found to be 33 Wm^{-2}. The surface aerosol forcing efficiency, which is the standardized aerosol radiative forcing for unit increase in AOD were computed using two methods and the forcing efficiency values found to be comparable ie. -88 and -84 Wm^{-2}, respectively, indicating a reduction of around 84 Wm^{-2} of short wave radiation at the surface for unit increase in AOD.

Aerosol forcing estimates across East Asia, which experiences large dust out breaks, have provided valuable information about the contribution of different chemical species to total forcing in the past decade. Kim et al. (2006) estimated DARF over a typical east Asian site

(Gosan, Korea) by using chemistry data sets in OPAC model in conjunction with a radiative transfer model (Fu–Liou RTM)(Fu and Liou, 1993). On estimating species segregated raditive forcing, they obtained the value of - 38.3Wm^{-2} at the surface attributable to mineral dust (45.7%). water-soluble components (sum of sulfate, nitrate, ammonium, and water-soluble organic carbon (WSOC)) induced a forcing of 26.8% and elemental carbon (EC) contributed up to 26.4% of the surface forcing. However, sea salt does not observed to play a major role in surface forcing. For the cases of Asian dust and smoke episodic events a diurnal averaged forcing of -36.2Wm^{-2} was observed at the surface over Gosan, contributed by mineral dust(-18.8Wm^{-2}), EC (-6.7Wm^{-2}), and water-soluble components (-10.7 Wm^{-2}). The results of this important study conclude that water-soluble and EC components as well as a mineral dust component are responsible for a large portion of the aerosol radiative forcing at the surface in the continental outflow region of East Asia. Another study by Li et al. (2009), estimated DARF using SBDRAT model over 25 stations in East Asia (China). ARF was determined at all the stations at the surface, inside the atmosphere, and at the top of atmosphere (TOA). Nationwide annual and diurnal mean ARF over China is found to be −15.7 ± 8.9 Wm^{-2} at the surface, 0.3 ± 1.6 Wm^{-2} at the TOA, and 16.0 ± 9.2Wm^{-2} in the atmosphere.

Extensive campaigns have been conducted to explore aerosol forcing over Middle East, where widespread sand/dust storm events are frequent. A typical study by Marcowicz. et al. (2008) found that relatively small value of the aerosol forcing efficiency (forcing per unit optical depth) at the surface (-53 W m^{-2}) persisting over United Arab Emirates (UAE)) during UAE2 campaign. They used MODTRAN based on DISORT method for the study and found a mean diurnal forcing of -20Wm^{-2} during campaign period. It is also found that aerosol forcing during the UAE2 campaign leads to a significant reduction of the incoming solar radiation at the surface (about 9%). The land–sea circulation found to have strong influence on the aerosol optical thickness and the aerosol diurnal variability. Larger aerosol radiative forcing is observed during the land breeze in comparison to the sea breeze. Markowiz et al. (2002) reported a radiative forcing estimate of -17.9 Wm^{-2} over mediteranian coast of Greece using MoDTRAn model, attributing the forcing to aerosols of anthropogenic origin. The study also revealed an increase of 11.3 W m^{-2} in the atmospheric solar absorption, and also an increase of 6.6 W m^{-2} in the reflected solar radiation at the top-of-the atmosphere. Thus giving observational proof for the large role of absorbing aerosols in the Mediterranean. This negative surface forcing and large positive atmospheric forcing values observed for the Mediterranean aerosols is nearly identical to the highly absorbing south Asian haze observed over the Arabian Sea. Another study over Mediterranean zone by Saha et al. (2008) discussed aerosol induced maintainance of summer heat waves over Europe. Using Global Atmospheric ModEl (GAME) (Dubuisson et al., 1996, 2004) they have reported the reduction of surface solar radiation by 26±3.9 W m^{-2} by aerosols during summer. This shortwave reduction at surface found to generate an atmospheric heating of 2.5 to 4.6 K day−1. Hence it is proposed that, this increase in heating rate could be one of the reason for maintenance of heat-waves frequently occurring over Mediterranean coastal region during summer. Marc et al. (2009) constrained the Impact of sea-surface dust radiative forcing on the oceanic primary production (PP) using GAME model. It is found that dust are able to induce a significant decrease of PP due to the attenuation of light by about 15–25% for dust optical depth (DOD) larger than 0.6–0.7 (at 550 nm). However for DOD lower than 0.2–0.3, the influence of dust on PP found to be weak (5%).

Regional estimates of DARF have been popularized after the establishment of Aerosol robotic Nerwork (AERONET), operated by NASA across various regions of the globe (http://aeronet.gsfc.nasa.gov/). AERONET has been active since 1993 (Smirnov et al. 2003). On parallel to AERONET, Chiba university of Japan established another aerosol network across Asia, known as SKYNET (http://atmos.cr.chiba-u.ac.jp/). Gonzi et al. (2007) reported DARF across 25 AERONET sites in Europe, spreading across the geographical borders of different European countries. They used sdisort radiative transfer code in libRadtran environment to simulate DARF. It is found that the annual median mean of this TOA, AERONET clear sky aerosol radiative forcing effect is around -3Wm^{-2} but with higher values in summer than in winter. The atmospheric aerosol forcing effect during summer is larger and has a typical median value of +3Wm^{-2}, essentially associated with high pollutant trapping in winter. The experiments were conducted for different albedo conditions and found to have a high sensitivity in TOA forcing with different albedo conditions. A median forcing efficiency (forcing per unit optical depth) of up to -25Wm^{-2} and -35Wm^{-2} were also found over Europe, respectively at TOA and surface.

SBDART model based studies were carried out across different parts of the world to estimate the contribution of most important absorbing aerosol species, Black carbon on the total aerosol short wave radiative forcing. It is revealed that, even though BC contributes only 3-6% of total aerosol mass, BC forcing contributes up to 55-80% of total aerosol atmospheric forcing (Sreekanth et al. 2007, Gaddavi et al.2010, Panicker et al. 2010a), attributed to strong atmospheric absorption by BC. This strong atmospheric warming along with surface cooling by BC aerosols can inhibit cloud formation processes by retarding convection by inducing lower atmospheric inversions.

Several studies across the globe have reported DARF in the short wave region. However, Aerosol long wave forcing effects has generally been neglected and estimates are sparse. Recent studies suggest that Aerosol long wave forcing is an important component in compensating short wave losses at the surface. It is also found that this long wave aerosol forcing has been of comparable magnitude as that of green house forcing at local scale (Vogelman et al.2003). Panicker et al. (2008) simulated aerosol long wave radiative forcing using SBDART model over a highly urbanized Indian city, Pune (A SKYNET Site). It is found that on contrary to short wave forcing, aeorols enhances the long wave radiation at the surface and compensates the shortwave cooling by up to 25%. It is also found that long wave radiaitve forcing is sensitive to temperature and humidity profiles. Increase in water vapour reduces aerosol long wave forcing while, an enhanced aerosol long wave forcing increases atmospheric temperature. Vogelman et al.(2003)using experimental data in conjunction with a radiative transfer model estimated a long wave forcing of up to 10 Wm^{-2} over pacific ocean during ACE-2 campaign. Dufresne et al. (2002) reported the long wave scattering effects of mineral aerosols. Using SBDART they showed that neglecting scattering by mineral aerosols in long wave region may unset estimates of long wave forcing, up to 50% at TOA and up to 15 % at the surface. It is also computed that for unit aerosol optical thinckness TOA forcing can reach up to +8 Wm^{-2}. Sathessh and Lubin (2003) analyzed the effect of wind speed in long wave forcing. It is showed that increased wind speed generating increased seasalt production can enhance long wave forcing due to absorption of long wave by sea salt aerosols. It is also found that even at moderate winds (6–10 m s^{-1}), the short wave forcing reduces by ~45% due to the dominance of sea-salt aerosols. At high winds (>10 m s^{-1}),

a major fraction of the long wave forcing is contributed by sea-salt (more than 70%). Hence it is proved that neglecting long wave forcing can make large bias in climate models.

4. Three dimensional modeling of direct aerosol radiative forcing

Direct Aerosol raditaive forcing has been modeled in regional as well as in global scales in order to find its reduction potential of green house warming. Global Modeling studies indicate that the aerosol radiative forcing effect is similar in magnitude, but opposite in sign, to the radiative forcing effect due to greenhouse gases (Charlson et al, 1992; Haywood and Boucher, 2000; Ramanathan et al, 2001; IPCC, 2007). This section briefly discusses the important three dimensional modeling results constraining important findings on global and regional scales.

Using a modeling approach, Haywood and Shine (1995) reported direct aerosol radiative forcing values of -2Wm^{-2} for an external mixture of soot and sulfate. Kiehl et al.(2000) estimated the direct and indirect radiative forcing due to sulfate aerosols using the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3). This model includes a sulfur chemistry model and predicts the mass of sulfate. The estimated global annual mean DARF forcing was found to be -0.56 W m^{-2}. Takemura et al.(2002) using a three-dimensional aerosol transport-radiation model coupled with a general circulation model reported the global annual mean values of the total direct radiative forcing of anthropogenic carbonaceous plus sulfate aerosols as -0.19 and -0.75 respectively under whole-sky and clear-sky conditions. They also described the global mean radaitve forcing induced by individual aerosol species segregated as sulphate, sea salt, soil dust and carbonaceous aerosols for clear as well as for all sky conditions. Chung et al. (2005) reported a global estimtate of direct aerosol radiatve forcing by integrating satellite and ground based observations with models of aerosol chemistry, transport, and radiative transfer models (GOCART and Montecarlo models). The typical value for the global top-of-atmosphere (TOA) aerosol radiative forcing effect obtained was in the range of -0.1 to -0.6Wm^{-2} for all sky conditions and around -1Wm^{-2} for clear-sky conditions. The global annual mean surface forcing values obtained were a found to be an order of magnitude greater than TOA values, showing -3.4 Wm^{-2} reductions at the surface and the corresponding global atmospheric aerosol forcing obtained was +3 Wm^{-2}. Verma et al. (2006) using a GCM simulation estimated the sulphate forcing. The model results indicate that the change in the sulfate aerosols number concentration is negatively correlated to the indirect radiative forcing. The model simulated annual mean direct radiative forcing ranged from -0.1 to -1.2Wm^{-2}. The global annual mean direct effect estimated by the model was -0.48Wm^{-2}. International panel for climate change (IPCC) from the forward global modeling approach concluded that the mean aerosol direct forcing value is -0.5±0.4 Wm^{-2} (IPCC, 2007). The independent contribution by different aerosol species in IPCC AR4 (2007) are, as follows, sulfate -0.4±0.2 Wm^{-2}; fossil fuel organic carbon -0.05± 0.05 Wm^{-2} ; fossil fuel black carbon 0.2± 0.15 Wm^{-2} ; biomass burning 0.03± 0.12 Wm^{-2}; Nitrate -1±0.1 Wm^{-2} ; mineral dust -1±0.2 Wm^{-2}.

The aerosol model, 'Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS)' (Takemura et al. 2002) has been now made available as an online tool for getting simulated global aerosol raditive forcing in daily as well as in monthly basis. Figure 1 shows global

distribution of clear sky aerosol direct raditive forcing in different months representative of different seasons viz. March (spring), June (summer), October (Autumn) and December (winter)during 2010 simulated by SPRINTARS. The model also has been used as a forecast model (Takemura et al. 2005) for aerosol raiative effects as well as air pollution transport studies. The details of model are available in, http://sprintars.riam.kyushu-u.ac.jp/indexe.html

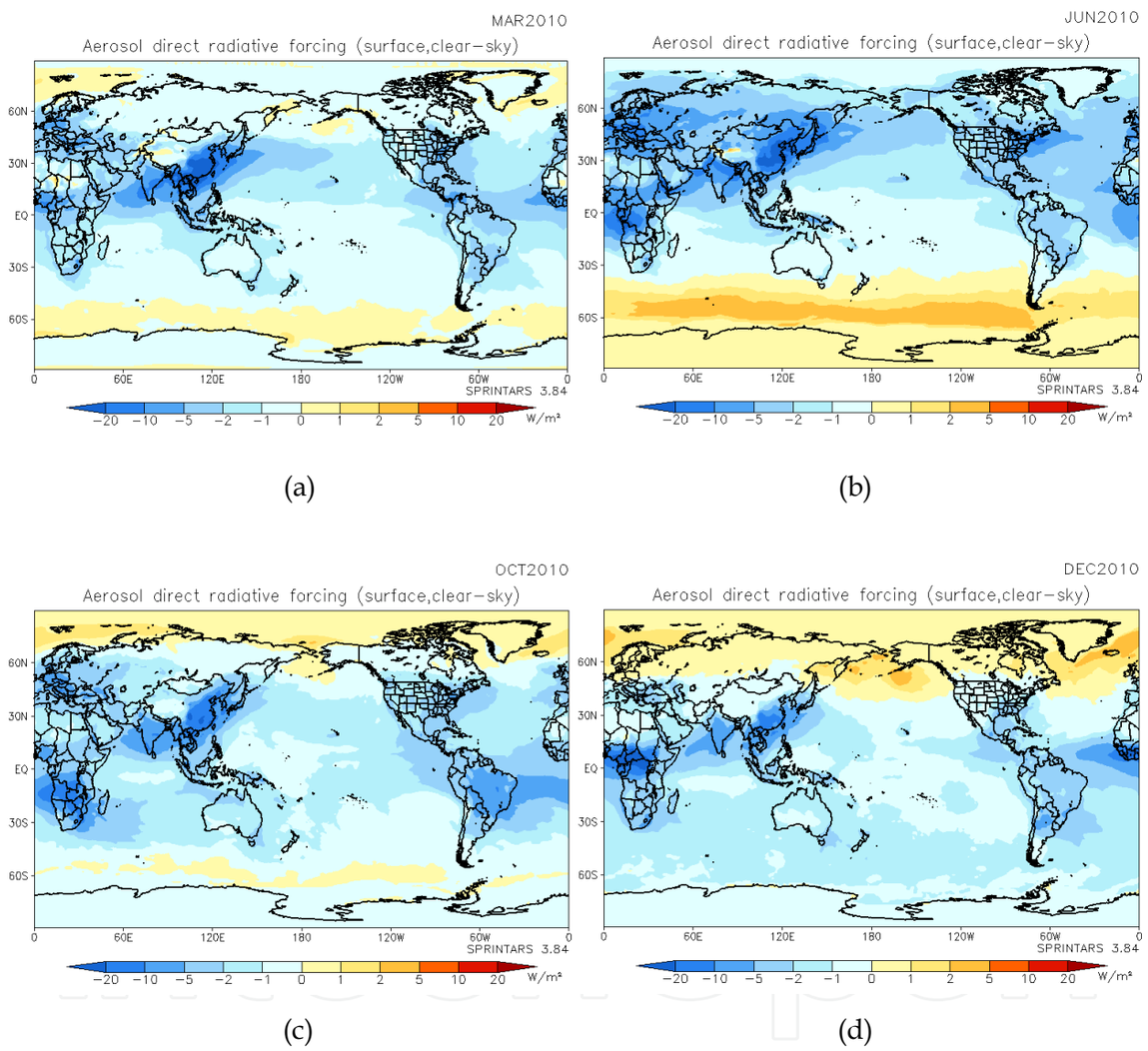

Fig. 1. Global aerosol clear sky direct radiative forcing distribution simulated by SPRINTARS in representative months during 2010 (a) March (Spring); (b) June (Summer); (c) October (Autumn); (d) December(winter).

Several modeling studies report the aerosol regional forcing over entire Europe. Based on a GCM (Global Circulation Model), Haywood and Ramaswamy (1998) estimated the radiative forcing for an external mixture of sulfate and black carbon (BC) aerosol to -5Wm^{-2} for Europe. Chung et al. (2005) reported the anthropogenic aerosol radiative forcing effect averaged over the year for clear-skies solely for Europe found to to lie between -2 and -

4Wm^{-2}. Based on a GCM in combination with a chemical aerosol model, Takemura et al (2002) specified the TOA aerosol radiative forcing effect to between -5Wm^{-2} and -10Wm^{-2} over the continent in summer months. Marmer et al. (2007) used a regional chemistry transport model REMOTE (Langmann, 2000) to analyze the seasonal variation of aerosol forcing over the entire European continent. Positive top-of-the-atmosphere forcing was simulated over eastern and southeastern Europe in spring and winter attributed to the contribution of black carbon. Its strength varies from +0.2 to + 1 W m^{-2}, depending on aerosol mixing assumptions. Sensitivity studies shows a mean European direct forcing of -0.3 W m^{-2} in winter and -2.5 W m^{-2} in summer, regionally ranging from -5 to + 4 W m^{-2}.

Using Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS), Takemura et al. (2003) simulated the DARF over Asia pacific region. On comparison, the SPRINTARS model showed promising results with the observed aerosol optical data sets. It showed a forcing of over -10 W m^{-2} at the tropopause in the air mass during the large-scale dust storm, to which both anthropogenic aerosols and Asian dust contribute almost equivalently. This study emphasizes the enhanced presence of strong absorbing aerosols over East Asian region. It suggests that, the enhanced presence of black carbon and soil dust aerosols, which absorb solar and thermal radiation, make strong negative radiative forcing by the direct effect at the surface, which can exceed the positive forcing by anthropogenic greenhouse gases over the East Asian region.

Dust strom outbreaks over Asia are a significant phenomenon both in pollution and climate perspectives. Park and Jeong (2008) simulated direct radiative forcing over Asia during dust storm events in 2002 using Asian dust aerosol model (ADAM) and a column radiation model. It is found that, the direct radiative forcing contributed by the Asian dust aerosol is about 22% of the mean radiative forcing at the surface (−6.8Wm^{-2}), about 31% at the top of atmosphere (−2.9Wm^{-2}) and about 13% in the atmosphere (3.8Wm^{-2}), suggesting relatively inefficient contribution of the Asian dust aerosol on the direct radiative forcing contrary to as anticipated. The aerosol direct radiative forcing at the surface is mainly contributed by the mixed type aerosol (30%) and the Secondary inorganic aerosol (SIA) (25%) while at the top of atmosphere it is mainly contributed by the SIA aerosol (43%) and the Asian dust aerosol (31%) with positively (warming) contributed by BC and mixed type aerosols. The atmosphere is warmed mainly by the mixed type aerosol (55%) and the BC aerosol (26%). Chung et al. (2010) using a modeling study using assimilation of avaialbe observed data sets showed that the all-sky aerosol forcing over Asia (60– 138E and Eq. −45 N) is −1.3Wm^{-2} (TOA), +7.3Wm^{-2} (atmosphere) and −8.6Wm−2 (surface). Zhang et al. (2009) used a modeling approach to study the effect of carbonaceous aerosol in south Asia. They concluded that the carbonaceous aerosol induced radiative forcing can cause the surface temperature to increase in southern china and india, and decreased the total cloud cover and precipitation over this area. However, the opposite effects are caused for most of northern China and Bangladesh. Carbonaceous aerosol was proposed to induce summer precipitation to decrease in southern China but increase in northern China by radiative forcing.

Very few modeling studies reports exclusive aerosol radiative forcing estimates across global oceans. One of such study by Bates et al. (2006) investigated DARF over three regions downwind of major urban/population centers over North Indian Ocean (NIO), the Northwest Pacific Ocean (NWP), and the Northwest Atlantic Ocean (NWA) using chemistry

transport models in conjunction with radiative transfer models. The resulting constrained clear-sky TOA anthropogenic aerosol forcng was −3.3±0.47, −14±2.6, −6.4±2.1Wm^{-2} for the NIO, NWP, and NWA, respectively. Malavelle et al.(2011) utilized RegCM3 model to assess optical properties and clear-sky direct radiative forcing (DRF) of mineral dust and carbonaceous aerosols over West Africa. The DARF calculations were found to be extremely sensitive to aerosol optical properties and underlying surface albedo. Over dark surfaces, the sum of shortwave (SW) and longwave (LW) top of the atmosphere (TOA) direct radiative forcing averaged found to −5.25 to −4.0 Wm-^{2} while over bright surfaces it was close to zero (−0.15 Wm-^{2}). They concluded that, large differences between SW surface and SW TOA direct radiative forcing indicates that SW absorption had an important influence on the radiative budget. The SW radiative heating rate associated with the aerosol reached 1.2 K/d at local noon (diurnal mean of 0.40 K/d) at surface levels and it showed peak values in high altitudes.

Few studies report the influence of aerosol forcing in snow cover. A typical study by Kim et al. (2006) employed the Mesoscale Atmospheric Simulation (MAS) regional climate model (Soong and Kim, 1996) to investigate the impact of direct aerosol radiative forcing on surface insolation and snowmelt in the southern Sierra Nevada Mountains in United States. They found interesting results on interaction of aerosol forcing on snow melt by modulating surface temperature. With a prescribed aerosol optical thickness of 0.2, it is found that direct aerosol radiative forcing influences spring snowmelt primarily by reducing surface insolation and that these forcing on surface insolation and snowmelt vary strongly following terrain elevation. The direct aerosol radiative forcing on snowmelt is notable only in high altitudes and is primarily via the reduction in the surface insolation by aerosols. The effect of this forcing on low-level air temperature is as large as -0.3°C, but its impact on snowmelt is small because the sensible heat flux change is much smaller than the insolation change. The direct aerosol radiative forcing on snowmelt was found significant only when low-level temperature is near the freezing point, between -3° and 5°C. The elevation dependency of the direct aerosol radiative forcing on snowmelt is claimed to be related with this low-level temperature effect as the occurrence of the favored temperature range is most frequent in high elevation regions. Takemura et al. (2009) using simulations by aerosol model SPRINTARS analyzed the radiative forcing effects of soil dust aerosols at the Last Galcial Maxima (LGM) period and found that the direct radiative forcings of soil dust aerosols at the LGM was close to zero at the tropopause and −0.4Wm^{-2} at the surface. These radiative forcings are about twice as large as those in the present climate, attributed to higher dust flux during LGM period due to extended arid regions and wind speed. It is suggested that atmospheric dust might contributed to the cold climate during the glacial periods.

Inter comparison experiments of modeling results are necessary to find the causes in creating discrepancy in forcing estimates. Recently Rind et al. (2009) carried out an inter comparison of most popular three dimensional models used for aerosol direct forcing estimates and concluded that the difference among models in the direct radiative forcing of sulfate aerosols are primarily associated with the loading, different size distribution of sulfate aerosols and different relative humidity influences. Ruti et al. (2011) carried out a detailed inter comparison of models used for African Monsoon Multidisciplinary Analysis (AMMA) campaign, deploying the inter comparison of chemistry transport and chemistry

climate models. Storelvmo et al. (2009) suggested that the discrepancy of 2 Wm^{-2} spread in present day aerosol short wave forcing in coupled global atmospheric-ocean models used in IPCC AR4 (IPCC, 2007) is attributed to the different methods used to calculate cloud droplet number concentration (CDNC) from aerosol mass concentrations.

5. Aerosol indirect effect: Observational and modeling perspective

Aerosols influence the climate indirectly by altering the cloud microphysics, known as Aerosol indirect effect (AIE). There are different types of AIE have been proposed (Twomey, 1974; 1977; Albrecht, 1989; Kaufman and Fraser, 1997). The first aerosol indirect effect also known as the cloud albedo effect and the Twomey effect (Twomey,1974; 1977), is the reduction of solar radiation reaching the surface due to an increase in cloud albedo. If cloud's liquid water content (LWC) is kept constant and cloud condensation nuclei (CCN) concentration is increased via an increase in aerosol concentration, there will be a corresponding increase in cloud droplet concentration and a decrease in the effective radius of the droplets. This change results in an increase in the cloud's surface area and in turn, an increase in the cloud's albedo. The overall impact is a cooling effect as less solar radiation reaches the surface. The second indirect effect, also known as the cloud lifetime effect (Albrecht, 1989), occurs due to a reduction in precipitation efficiency as a result of increased CCN. As in the first indirect effect, given a constant LWC and an increase in CCN, a cloud will have a higher concentration of cloud droplets with a smaller effective radius. Due to this decrease in cloud droplet size, the development of precipitation will be retarded and may be suppressed altogether (Panicker et al. 2010a). Semi-direct effect (Hansen et al., 1997; Kaufman and Fraser, 1997) involves the absorption of solar radiation by aerosols such as black carbon and dust. In the presence of clouds, these aerosols absorb shortwave radiation at cloud top, causing a local warming. The absorption increases the temperature, thus lowering the relative humidity and producing evaporation, hence a reduction in cloud liquid water and hence results in the early dissipation of clouds.

Since after reporting the first aerosol indirect effect (Twomey , 1974; 1977), several attempts has been made to measure the indirect effect. One of the promising ground based observational estimation of AIE was reported by Feingold et al. (2003). They used remote sensing data sets of sub cloud Raman lidar aerosol extinction and cloud droplet effective radius to constrain AIE using the formula

$$AIE = -\frac{d\ln r_e}{d\ln \tau_a}$$

Where τ_a is aerosol proxy and r_e is the cloud effective radius for fixed LWC. They Obtained AIE values between 0.07 and 0.11 over the ARM site for liquid water paths between 100 and 130 gm^{-2}. Based on remote sensing measurements Pandithurai et al. (2009) estimated an indirect effect on thin non precipitating cirrus clouds over East China Sea region. The indirect effect estimates are made for both droplet effective radius different liquid water path ranges and they range 0.02–0.18. Generally indirect effect values found to be are positive. However negative AIE also has been reportd over some parts of the world at certain environmental conditions (eg: Yuan et al., 2008). McComiskey

and Feingold (2009) proposed a method for estimating changes in radiatve forcing values from inferred AIE values by using a one dimension model (SBDART). Depending on anthropogenic aerosol perturbation, radiative forcing ranged from -3 to -10 W m^{-2} for each 0.05 increment in AIE, hence narrowing uncertainty in measures of AIE to an accuracy of 0.05.

A detailed review of AIE was presented by Lohman and Feichter (2005), in which they in depth discussed the Aerosol effects on different types of clouds and their magnitudes over land and oceans. Aerosol indirect effects are estimated from general circulation models (GCMs) by conducting a present-day simulation and a pre-industrial simulation in which the anthropogenic emissions are set to zero. The difference in the top-of-the atmosphere radiation budget of these multi-year simulations is then taken to be the anthropogenic indirect aerosol effect (Lohmann and Feichter 2005). The global radiative forcing due to AIE ranges between -0.5 to -1.9 Wm^{-2} by Twomey effect both at TOA and surface. However the second indirect values range between -0.3 to -1.4 Wm^{-2} at surface and TOA. Semi-direct effect values are found to range between -0.5 to +1 Wm^{-2} globally both at surface and TOA. Different simulations over land and ocenic areas (Menon et al. 2002; Quas et al. 2004., Takemura et al. 2005) confirmed a dominant AIE over land areas, attributed to enhanced anthropogenic aerosol loading. It is also found that the aerosol indirect effect is dominant over northern hemisphere (almost double) compared to southern hemisphere essentially due to large human inhabited land mass and associated anthropogenic aerosol emissions. From comparisons of different simulations, it is observed that, the magnitude of aerosol first indirect effect (Twomey effect) is larger than that of precipitation effect. There is a large discrepancy among modeling results of AIE. Lohmann and Feichter (2005) suggested that the main reason for this discrepancy between models could be associated with the dependence of the indirect aerosol effect on the background aerosol concentration. The latest estimates of IPCC AR4 reports global annual radiative forcing of the first indirect effect is -0.7 Wm_{-2} with an uncertainty range of -1.8 to -0.3 Wm^{-2} (IPCC, 2007).

Dispersion effect, describing the spread of cloud droplet number distribution and aerosol number density as defined by Liu and Daum (2002) found to offset the cooling of the AIE or Twomey effect by 10-80%. Liu et al (2008) demonstrated that the first aerosol indirect effect (AIE) is the algebraic sum of the conventional Twomey effect and dispersion effect and that dispersion effect is proportional to Twomey effect in magnitude. However the factors that determine the dispersion effect is poorly understood. A better understanding of the dispersion effect may improve the aerosol cloud interaction in Global Climate Models (GCMS), which in turn reduces the uncertainty in AIE estimates.

Lohmann et al. (2007) discussed a detailed review of different approaches for constraining anthropogenic aerosol influence on indirect effect in global models. They in depth discussed the methods to derive aerosol parameterization from theoretical principles and also from observations. SPRINTARS model (Takemura et al. 2002) has been one of the active tools for estimating the global distribution of Aerosol Indirect forcing. Figure 2 shows the latest global aerosol surface indirect forcing during 2010 in various parts of the globe during representative months in spring, summer, autumn and winter.

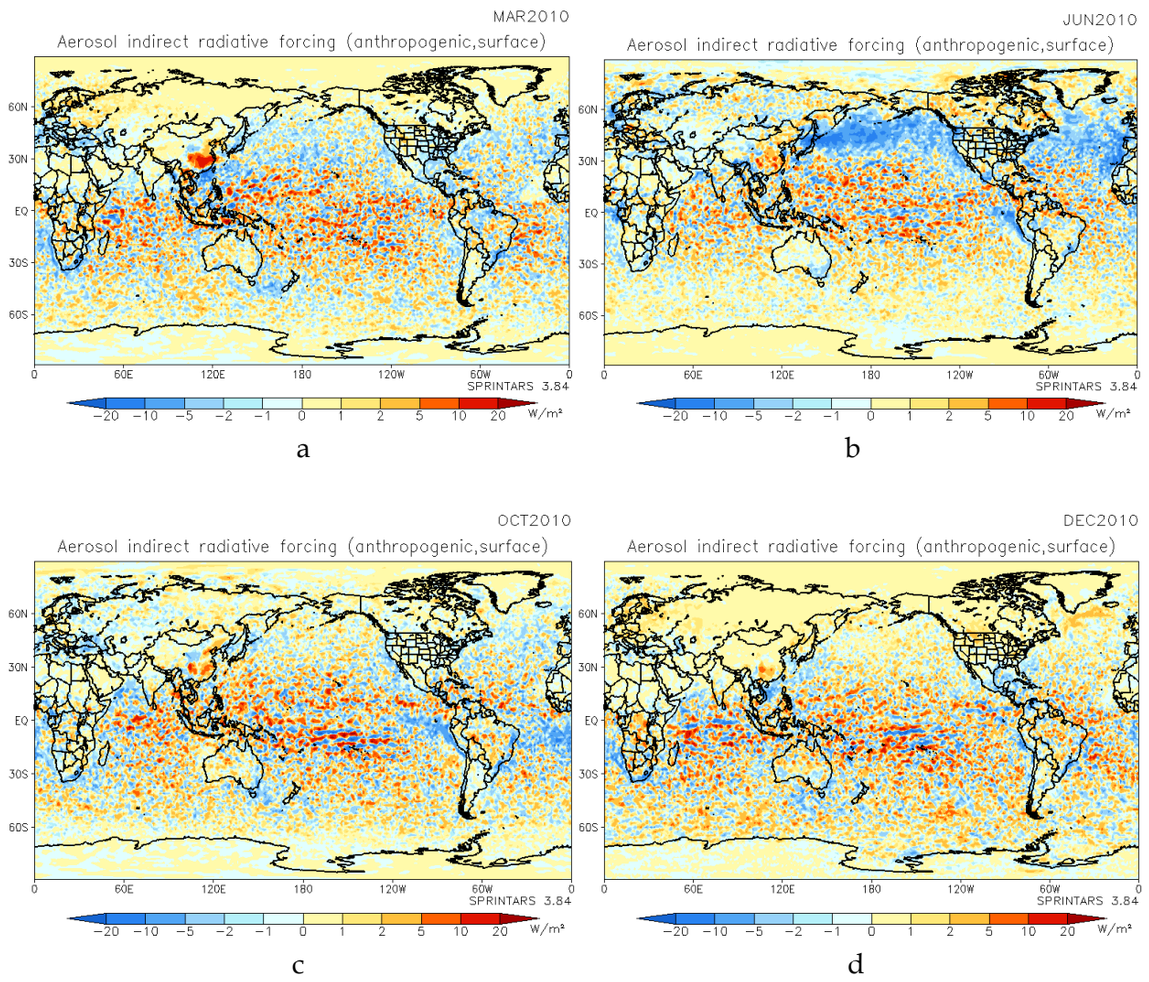

Fig. 2. Global aerosol clear sky indirect radiative forcing distribution simulated by SPRINTARS in representative months during 2010 (a) March (Spring); (b) June (Summer);(c) October (Autumn); (d) December(winter).

Myhre et al. (2007) used MODIS satellite data and two global models (Oslo CTM2 and CAMOslo) to investigate the relationship between AOD and cloud parameters. They found that there was an enhancement in cloud cover with increase in AOD. On analyzing the Angstrom exponent, it is concluded that hygroscopic growth is not likely to be a main contributor to the cloud cover enhancement; hence it could be attributed to the cloud life time effect. Strolvemo et al. (2006) compared the observed and modeled AIE values using MODIS satellite data and CAM-Oslo model over15 selected regions. They observed a large bias in Modeled and observationally estimated AIE values in both regional and global scales. Chylek et al. (2006) analyzed the AIE over Indian Ocean during pollution episodes. On contrary to the finding by Rosenfeld(1999), it is found that during pollution episodes, the radius of Ice crystals were shifted toward larger size than smaller size. ECHAM-4 modeling results of this study also reproduced an increase in ice crystal size. It is reasoned that this enhancement in ice crystal size could be associated with an"inverse aerosol effect', which need to be further investigated.

Recently Kurten et al. (2011) facilitated independent estimates for how the changes in the oxidant predicted by the TOMCAT chemical transport model (Chipper field, 2005) change the aerosol forcing. It is found that, a 10-fold increase in methane concentrations is predicted to significantly decrease hydroxyl radical (OH) concentrations, while moderately increases ozone (O3) concentration. These changes lead to a 70% increase in the atmospheric lifetime of methane, and an 18% decrease in global mean cloud droplet number concentrations (CDNC), and hence inducing an aerosol indirect effect. This CDNC change causes a radiative forcing that is comparable in magnitude to the longwave radiative forcing ("enhanced greenhouse effect") of the added methane. Hence it is suggested that, together, the indirect CH4-O3 and CH4-OH-aerosol forcing could more than double the warming effect of large methane increase.

Willox (2011) investigated the semi direct effect of smoke aerosols over clouds. By a model simulation experiment the negative radiative forcing associated with this semi-direct effect of smoke over clouds is estimated to be $-5.9\pm3.5 Wm^{-2}$. The average positive direct radiative forcing by smoke over an overcast scene is $9.2\pm6.6 Wm^{-2}$. Therefore it is suggested that the cooling associated with the semi-direct cloud thickening effect compensates for greater than 60% of the direct radiative effect.

Apart from the three important indirect effects reported above, Lohman et al. (2002) proposed a " glaciations indirect effect'. Here increases in ice nuclei in the present-day climate result in more frequent glaciation of supercooled clouds and increase the amount of precipitation via the ice phase. This reduces the cloud cover and the cloud optical depth of mid-level clouds in mid- and high latitudes of the Northern Hemisphere and results in more absorption of solar radiation within the Earth-atmosphere system. Therefore it is assumed that, this effect can at least partly offset the cloud lifetime effect. Two more indirect effects, viz. Riming indirect effect, and thermodynamic effects has been proposed (Lohmann and Feitcher. 2005). However further studies are required to confirm these climate effects.

6. Influence of aerosol radiative forcing on monsoon

Aerosols in the early 20th century have been considered only as particles inducing air pollution and detericious health effects. Later in mid 1960s it is revelaed that they influances the global climate by counter acting to global warming by enhancing global dimming. However recent studies suggest that aerosol contribution to the climate is more than what it was anticipated. Aerosols are found to influence the large scale phenomenon like monsoon by inducing atmospheric heating. Especially in this aspect, the influence of strongly absorbing species of aerosols such as black carbon in much debated. Studies using different general circulation models (GCMs) indicate that direct radiative forcing (DRF) of absorbing black carbon (BC) aerosols can influence the Indian summer monsoon.

Ramanathan et al. (2005) used the PCM ocean-Atmosphere coupled model to simulate the influence of Black carbon (BC) induced atmospheric brown cloud on monsoon. They found that an increase in the BC induced DRF over Indian Subcontinent and surrounding regions leads to a reduction of monsoon precipitation during June to September months while an enhancement to the pre-monsoon (March–April–May) precipitation. The study of Meehl et al. (2008) with a coupled model having more comprehensive treatment of aerosol-radiation interaction, supports the above findings. Collier and Zang. (2009) by a

GCM experiment showed that the, reduced shortwave aerosol heating and enhanced evaporation at the surface during April and May results in weakening of the near-surface cyclonic circulation and, consequently, has a negative feedback on precipitation during the active monsoon months of June and July. Menon et al. (2002) using a GCM simulation, showed that black carbon induced atmospheric warming changes the precipitation patterns over India and China. It is found that an atmosphere with enhanced BC, yield increased precipitation in southern China and over India and Myanmar where AOD was largest. There was a broad band of decreased precipitation to the south of the region with increased precipitation, with a lesser decrease to the north. Ji et al. (2011) using a coupled RCM-Chemistry aerosol model, showed that, in northeast India and Myanmar, aerosols lead the summer monsoon onset advancing 1–2 pentads, and delaying by 1–2 pentads in central and southeast India.

Lau et al. (2006) proposed one of the most debated mechanisms of aerosols influence on Indian monsoon. The hypothesis namely Elevated heat pump mechanism (EHP) was constrained with the NASA finite volume atmospheric general circulation Model simulation experiments over Indian region. They found that absorbing aerosols such as black carbon and dust, which accumulates over the foothills of Himalaya in Indo-Gangetic Plain (IGP) during pre-monsoon months (April-May) absorbs the solar radiation and heats the atmosphere. As the air warms, it rises over the Tibetan plateau; it draws in more moist air from Indian Ocean. Hence more moist air is drawn toward foothills of himalaya, producing anomalous rainfall. The increased condensation causes more upper troposheric heating, which draws in more low-level moisture from ocean and hence maintains a positive feedback namely heat pump. Hence according to this hypothesis, monsoon precipitation would be suppressed over central India due to aerosol-induced surface cooling. However, precipitation would come earlier and be enhanced over northern India and the southern slope of the Tibetan Plateau. Several modeling investigators supports this hypothesis adopts this idea in their research (e.g. Huang et al., 2007;;Meehl et al., (2008); Ramanathan and Carmichael, 2008; Randles and Ramaswamy, 2008). However debates have been enduring on this aspect. Bollasina et al. (2008) compared different studies of aerosol impact on the Asian Summer Monsoon and noticed that those using coupled ocean-atmosphere models yielded opposing results to those proposed by Lau et al. (2006). Kuhlmann and Quass. (2010) suggested three reasons for this discrepancy viz. simulation of Lau et al. (2006) was lacking interaction of atmospheric processes with the ocean, ignoring aerosol indirect effect and finally not considering vertical aerosol profiles in model. Kuhlmann and Quass. (2010) using CALIPSO satellite data of aerosol vertical profiles in conjunction with a radiative transfer model investigated the influence of aerosols in monsoon. They found that aerosol plumes reduce shortwave radiation throughout the Monsoon region in the seasonal average by between 20 and 30 Wm^{-2}. Peak shortwave heating in the lower troposphere reaches 0.2 K/day. In higher layers this shortwave heating is partly balanced by longwave cooling. Although high-albedo surfaces, such as deserts or the Tibetan Plateau, increase the shortwave heating by around 10%, the overall effect is strongest close to the aerosol sources. The simulated SW heating above the Tibetan Plateau does not exceed 0.05 K/day in the seasonal mean and is thus considerably weaker than in the surrounding regions. This result stands in contrast to the Elevated Heat Pump (EHP) hypothesis by Lau et al. (2006) who simulated SW heating of between 0.2 and 0.4 K/day above the Tibetan Plateau. Nigam and Bollasina (2010) confronted the observational feasibility of EHP hypothesis, and in response

Lau and Kim.(2011) defended their hypothesis by challenging the methodology of analysis prescribed in Nigam and Bollasina(2010).

Wang et al. (2009) explained the northward propagation of monsoon convective systems by coupling dynamic effects induced by aerosol heating. They used a community climate model (CCM3) to investigate the influence of absorbing aerosols on monsoon. The experiment was conducted for three different simulations for monsoon circulations viz. including only scattering aerosols, only absorbing aerosols, and both aerosols in the model. They found that, among different types of anthropogenic aerosols, scattering aerosols found to have only a very limited impact on monsoon circulation and precipitation. On the other hand, absorbing aerosols, with or without the co-existence of scattering aerosols, have a strong influence on the monsoon circulation and in the development of convective precipitation. They proposed that the influence of absorbing aerosols is reflected in a perturbation to the sub-cloud layer moist energy structure, initiated with a heating by absorbing aerosols of the planetary boundary layer, mostly over the land areas north of the Arabian Sea and also along the south slope of the Tibetan Plateau. This is then enhanced by the import of airmass with high water vapor concentration. The corresponding anomalous sub-cloud layer airflow that brings relatively humid air primarily originated from the Arabian Sea and hence the convective precipitation experiences a clear northward shift. Manoj et al. (2010) using a raditive transfer model (SBDART) in conjunction with MODIS/TOMS satellite data analyzed the influence of absorbing aerosols in modulating Indian summer monsoon break active cycles. It is shown those monsoon years, in which intense loading of absorbing aerosols were present over central India was able to heat the atmosphere over central India, creating enough pressure gradient between northern Indian Ocean and central India and could sustain the active condition after breaks. Whereas the monsoon years where less absorbing aerosols were present over central India, couldn't succeed in sustaining active spells after breaks.

Apart from these direct effects, aerosols also found to influence the Indian monsoon through indirect effect. Ravi kiran et al. (2009), Bhawar and Devara(2010), based on MODIS data qualitatively suggested that, there is a strong influence for aeorol- cloud interaction in influencing Indian summer monsoon. Patra et al. (2005) using MODIS satellite data in conjunction with a chemistry transport model (CTM) showed that prevailing monsoon dynamics in good and bad monsoon bringing air mass containg absorbing/ non absorbing aerosols can induce indirect effect and hence can influence precipitation. Bollasina et al. (2008) proposed that, Anomalous heating of the land surface by aerosol induced reduction in cloudiness (the "semidirect" effect) can increase in downward surface shortwave radiation. Stronger heating of the land surface in the month of May generates greater ocean atmosphere contrast and thus provides more monsoon rainfall in June. Panicker et al. (2010b) using MODIS data estimated AIE and found that there was a majority positive AIE (Twomey effect) in fixed Liquid and ice path bins during bad monsoons and a majority negative AIE (Anti-Twomey) effect in fixed cloud ice and water path bins during good monsoons, influencing the precipitation patterns. However more studies and more remote sensing observations are necessary to establish these results. An exclusive five year campaign Cloud aerosol interaction and precipitation enhancement experiment (CAIPEEX) based on aircraft observations of aerosol cloud parameters has been in operation over different Indian regions since 2009 to unravel the complex aerosol cloud interaction process on Indian monsoon.

7. Conclusions

Aerosols, which are tiny particles, present in the atmosphere, influence the climate through radiative forcing. Aerosol radiative forcing and associated surface cooling is found to compensate the green house gas warming in the past century. This chapter describes a brief review of aerosol radiative forcing estimates using modeling approaches. Aerosol models vary from one dimension to three dimensions. The one dimensional modeling studies on aerosol direct effects have been accelerated in the past two decades after the establishement of global aerosol networks across the world. Direct Aerosol radiative forcing has been estimated using ground based instruments in conjunction with radiative transfer models across maritime and continental environments in different parts of the globe. Several modeling studies reports the aerosol forcing estimates in regional as well as in global scales, both for combined fraction of aerosols and independently for different species. The latest estimate of aerosol radiative forcing by International panel for climate change (IPCC, AR4), reports a global mean aerosol direct forcing value of -0.5±0.4 Wm^{-2}. The independent contribution reported by different aerosol species in IPCC AR4 are, as follows, sulfate -0.4±0.2 Wm^{-2}; fossil fuel organic carbon -0.05± 0.05 Wm^{-2} ; fossil fuel black carbon 0.2± 0.15 Wm^{-2} ; biomass burning 0.03± 0.12 Wm^{-2}; Nitrate -1±0.1 Wm^{-2} ; mineral dust -1±0.2 Wm^{-2}. Global aerosol indirect effect estimates have still been a challenge, as the uncertainty levels are high. Latest estimate of the global annual radiative forcing of the first indirect effect by IPCC AR4 is -0.7 Wm^{-2} with an uncertainty range of -1.8 to -0.3 Wm^{-2}. Out of the main identified indirect effects, first and second indirect effects exert a negative forcing at surface and TOA. However, semi direct effect exerts a positive forcing at TOA and negative forcing at surface. Global modeling studies also have given a new insight in revealing the role of aerosols in modulating large scale phenomenon, such as monsoon. Different modeling studies confirmed that aerosol direct forcing is a key factor modulating onset, break phases of Indian summer monsoon. Aerosols are proposed to increase or decrease monsoon rainfall depending up on its species of origin and its amount of presence during the season. Several mechanisms have been proposed regarding the influence of direct aerosol radiative forcing on Indian summer monsoon. However still the uncertainty in aerosol forcing estimates, especially indirect effect and its possible influence on different large scale phenomenon remains un answered. Hence assimilation of real time data sets of aerosol optical properties and aerosol vertical profiles should be included in global models to overcome this uncertainty.

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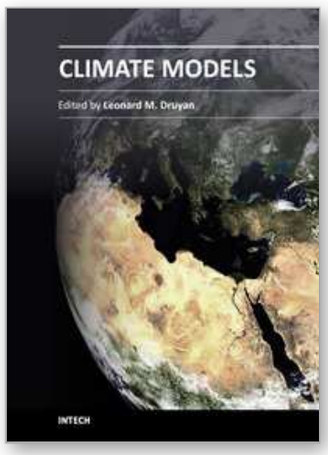

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