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Aerosols impact on climate, air quality and health

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Abstract
Suspended particles in the atmosphere (aerosol) emitted by natural and anthropogenic activities effect climate, air quality and health. Black carbon (BC), optically absorbing form of carbonaceous aerosols, emitted by various combustion processes reduce the incoming solar radiation and causes heating of the particles and local warming of the boundary layer of the atmosphere. Recently, BC has been used as an indicator of exposure to diesel soot, which has been classified as a toxic air contaminant and a suspected carcinogen. BC is responsible for change in surface albedo and the single scattering albedo (SSA). The SSA determines the degree of absorption and is a very important parameter in term of their radiative effects. Generally, for non dust aerosol SSA decreases with wavelength and for dust aerosols increases with wavelength. One of the most important properties of aerosols is the aerosol optical depth (AOD) helps in deriving information of the optical properties and size distribution of the particles. AOD value is used to estimate aerosol radiative forcing. The largest contribution to global annual average AOD (0.12 at 550 nm) is from natural (58%), fossil fuel (26%) and biomass burning (16%). Aerosols impact climate by modifying cloud properties. Aerosols in the range of 0.3 to 1 µm in diameter reduce visibility and it below 0.1 µm get deposited in the lung and causes several respiratory problems.

Keywords: aerosol, black carbon, aerosol optical depth, single scattering albedo

Introduction
The suspension of solid and liquid particles in the air is called aerosols. Aerosols are emitted in to the atmosphere by natural (sea salt and wind borne dust) and anthropogenic activities (fossil fuel combustion [diesel and coal], open biomass burning, and cooking with bio-fuel etc). Based on the formation processes, aerosols are divided into primary and secondary. Primary aerosols (sea-salt emission from ocean surface, mineral dust emission from arid regions, and fly ash emission from the industrial activities) are emitted directly at the sources and secondary aerosols (sulfate aerosols from dimethyl sulfide emitted by oceanic phytoplankton) are formed from gaseous precursors through various gas and aqueous phase reactions. Aerosols are removed from the atmosphere through dry and wet deposition and its life time in the atmosphere depends on size of the particles. The life time of the aerosols in the atmosphere is few minutes to several weeks (Seinfeld *et al.* 1998) [23]. Aerosols are important atmospheric components both due to their impact on air quality and climate.

A category of aerosols, black carbon (BC), is optically absorbing and graphitic form of carbonaceous aerosols which is emitted into the atmosphere by various combustion processes such as industrial pollution, outdoors fires, traffic, and household burning of coal and biomass fuels (Haywood and Ramaswamy, 1998) [12]. BC doesn't exist freely in the atmosphere; it is always bonded with some other aerosols particles such as sulphates, organics etc. Atmospheric aerosols containing BC can absorb in so far as 20-25% of the incoming solar radiation which leads to heating of the particles and local warming of the boundary layer of the atmosphere (Herrmann and Hänel, 1997) [13] and thus most likely changing the temperature profile in the troposphere, which in turn affects the cloud microphysical properties and there by rainfall mechanism (Menon *et al.* 2002) [17]. It has been also reported that when BC become hydrophilic it acts as a cloud condensation nuclei (Twomey, 1977) [28] and therefore affects cloud cover and lifetime. Thus, the fraction of BC in total aerosol load in the atmosphere is critical to the aerosol radiative forcing at the Earth's surface and also at different level in the atmosphere. When atmospheric BC suspended near clouds then it contribute to cloud evaporation, termed as 'semi-direct effect' (Hansen *et al.* 1997) [9]. The enhancement in BC fraction can also change the surface albedo and the single scattering albedo (SSA) of the atmosphere, which leads to change in sign of aerosol radiative forcing (Solomon, 2007) [24]. When BC is deposited on snow then after receiving radiation it promotes snow-melt (Flanner *et al.* 2007) [5] and further contributes to warming. Recently, BC has been used as an indicator of exposure to diesel soot (Fruin *et al.* 2004) [7], which has been classified as a toxic air contaminant and a suspected carcinogen.

Aerosol characteristic
Aerosol is characterized by its optical, physical and chemical properties. The interaction of aerosols with radiation is studied by using three optical parameters: aerosol optical depth (AOD, τ), the single scattering albedo (SSA) and the phase function. Among these, one of the most important properties of aerosols is the Aerosol optical depth (AOD). It is dimensionless quantity that quantifies how efficiently a beam of radiation is weakened. It is defined as attenuation of solar radiation when passing through the atmosphere by scattering and absorption due to aerosols.

The aerosol optical depth τ is a vertical integral of the aerosol extinction coefficient from the earth surface (Sfc) to the top of

the atmosphere (TOA), as follows:

$$\tau_\lambda = \int_{Sfc}^{TOA} k\lambda\rho dz$$

AOD is not a function of height. AOD is AAOD (Absorption Aerosol Optical depth) plus SAOD (Scattering Aerosol Optical Depth). AAOD (τ_a) is the vertical integral of the aerosol absorption coefficient. In other words AOD is column-integrated aerosol amount in an optical sense. When aerosol mass amount is doubled, AOD should also be doubled. It helps in deriving information of the optical properties and size distribution of particles as well as studying the diurnal and seasonal variability of aerosols by measuring AOD at different spectral wavelengths. AOD value is used to estimate aerosol radiative forcing. The largest contribution to global annual average AOD (0.12 at 550 nm) is from natural (58%), fossil fuel (26%) and biomass burning (16%).

Single scattering albedo is defined as the ratio of scattering coefficient to the extinction coefficient, measuring the relative importance of scattering and absorption. The SSA determines the degree of absorption and is a very important parameter in term of their radiative effects.

The angular distribution of scattering radiation is described by the phase function. It is a ratio of the scattered intensity at a specific direction to the integral of the scattered intensity in all directions. The phase function is defined in terms of asymmetry parameter (g). The value of g is 1 for completely forward scattering and 0 for symmetric scattering (e.g. Rayleigh scattering). Its value lies in the range of 0.5 to 0.8. It is most important input parameter for radiative transfer calculations.

The optical properties aerosol varies with the wavelength of radiation. The wavelength –dependence of aerosol optical depth is represented by Angstrom exponent. The high value of Angstrom exponent indicates small size particles and low value indicates large size particles. Generally, at visible wavelength, for non dust aerosols the SSA decreases with wavelength and for dust aerosols increases with wavelength (Dubovik *et al.* 2002) [2]. The asymmetry parameter decreases with wavelength because of decrease in scattering-effective particle size (Hansen and Travis, 1974) [10]. Aerosol optical properties also depend on the size distribution i.e. any factors that affect size distribution will impact the optical properties. Among which relative humidity (RH) is one critical factor. Some aerosols are hygroscopic in nature i.e. they grow as they take up water vapor. As a result, their size increases then their refractive indices change which in turn leading to change in their optical properties. When RH increases twice, then the scattering cross section of sulfate-dominated aerosols doubles, whereas it increases by only 10-40% for same RH ranges (Kaufman *et al.* 1998) [15]. For hygroscopic aerosol, SSA increases with RH and g increases with RH and particle size.

The physical characteristic of aerosols depends on concentration and size distribution. The concentration is expressed in number, area volume and mass concentrations. Aerosols particles present in the atmosphere have widely variable shape and their dimension is characterized by particle diameter. One of the most important parameters which describe the behavior of aerosols, affecting their life time, physical and chemical properties is particle size. The distribution of aerosol particles is defined by their number, surface or volume. On the basis of particle distribution, atmospheric particles are divided into nucleation mode, accumulation mode and coarse mode. Aerosol particles which have diameter below 0.1 µm constitute the nucleation (Aitken) mode. The smallest range of particles which have diameter below 0.01 µm is called ultrafine, produced by homogeneous and heterogeneous nucleation process. These particles are produced during gas-to particle conversion or during condensation of hot vapor in combustion process. The lifetime of these particles is very short (minutes to hours) due to their rapid coagulation or random impaction onto surfaces. The larger aerosol particles which have diameter in the size range 0.1 to 1 µm is called accumulation mode. The lifetime of these particles in the atmosphere is 7 to 10 days due to which it is transported to long distance from their sources. These particles are mainly formed by coagulation process or coagulation of vapors onto existing particles. They are also emitted into atmosphere from different sources, mainly from incomplete combustion. They are removed by wet deposition. The aerosol particles which have diameter greater than 1.0 µm are called coarse mode particles. These particles are emitted into atmosphere during mechanical process from both natural and anthropogenic sources (e.g. sea-salt particles from ocean surface, soil and mineral dust, biological materials). They have short atmospheric lifetime due to relatively large mass and because of this rapid sedimentation.

The chemical composition of atmospheric aerosol is very complex and variable in nature. Each particle has individual composition due to various sources of emission and transformation. Generally, it is composed of sulphate, nitrate, ammonium, sea salt, crustal elements and carbonaceous compounds (elemental and organic carbon) and other organic materials. Fine particles predominantly have sulphate, nitrate, ammonium, elemental and organic carbon and certain trace metals (e.g. lead, cadmium, nickel, copper etc.). The primary components of coarse particles have dust, crustal elements, nitrate, sodium, chloride and biogenic organic particles (e.g. pollen, spores, plant fragments etc.).

Aerosol Impact on climate

Aerosols impacts on climate are generally classified as direct or indirect with respect to radiative forcing of the climate system. Aerosols scatter and absorb the solar and thermal infrared radiation, thus alter the radiative balance of the Earth-atmosphere system is termed as direct effect (Haywood and Boucher, 2000) [11]. Direct radiative forcing is defined as change in net radiative balance due to the perturbation by aerosols holding all atmospheric variables fixed (Haywood and Boucher, 2000) [11]. The difference between the TOA forcing and the surface forcing is known as atmospheric forcing.

Aerosols modify the microphysical and hence the radiative properties and life time of clouds is called aerosol indirect effect. Aerosol indirect effect is split into two effects: the first indirect effect and the second indirect effect. In first indirect effect (Twomey effect), whereby an increase in aerosols causes an increase in droplet concentration and a decrease in droplet size for fixed water content (Twomey, 1974) [27]. In second indirect effect, whereby decrease in cloud droplet size affects the precipitation efficiency, tending to increase the water content, the cloud life time and the cloud thickness (Pincus and Baker, 1994) [19]. The first and second indirect

effects are also known as 'cloud albedo' and 'cloud lifetime'. The third assessment report of IPCC find out that the Twomey effect of anthropogenic aerosol particles amounts to 0 to -2 W/m^2 in the global mean (Ramaswamy *et al.* 2001) [21]. Absorbing aerosols, particularly BC impact climate after deposition to bright surfaces. When BC deposited onto snow and ice surfaces, it reduces the albedo of snow through which causes additional warming of climate (Hansen and Nazarenko, 2004) [8]. Earlier (Flanner *et al.* 2007) [5] had reported that the snow-albedo forcing and associated feedbacks from all anthropogenic BC emission result in global warming (annual mean temperature) of between 0.1 and 0.15^{0}K, while (Jacobson, 2004) [14] find out that fossil and biofuel sources individiually result in a warming of 0.03 to 0.11^0 K. On the whole impact of anthropogenic aerosol is cooling impact on climate. The fourth assessment report of IPCC estimated that total forcing of 1.2 W/m^2 from anthropogenic aerosol, partly satiating the warming of 2.6 W/m^2 from long lived greenhouse gases (Forster *et al*. 2007) [6].

Aerosol Impact on Air Quality and Health

Aerosol impact on air quality has become matter of concern for everyone. According to the reports, aerosols play very crucial role in air quality. The impact of gaseous and particulate pollutant is measured by the effect on pollution receptors. For example, deposition of acidic pollutants on building can deteriorate its material, harm vegetation, damage the aquatic ecosystem, cause breathing problems and increase mortality rate among humans (Seinfeld and Pandis, 2016) [22]. Atmospheric aerosols reduce visibility. Fine aerosols which have diameter between 0.3 to 1.0 µm cause visibility reduction (Eldering *et al.* 1993; Trijonis *et al.* 1991) [3, 26]. From 13th to 20th December 1952, high concentration of sulphur oxide and soot particles was responsible for 'London Smog', which led to over 4000 deaths (Noble and Prather, 1998) [18]. Moreover, the discovery of photochemical smog in the Los Angeles area in the mid-1940s have made high concentration of ozone and photochemical products and their impact on human health a major issue worldwide (Finlayson-Pitts and Pitts, 2000) [4].

In pollution studies, particulate matter has recently become an issue due to its noticeable effects on human health. Coarse particles (2.5 µm < dp 10 µm) are efficiently removed in the upper respiratory track while fine particles (dp < 2.5 µm) are deposited on the bronchi walls in the bronchi trees (Akeredolu, 1996). Particles (dp <0.1 µm) get deposited in the bronchi through Brownian motion while particles with diameter 0.1- 1µm get deposited in the lungs as they are too large for Brownian motion and too small to be trapped in the upper part of the trachea, thus increasing airways resistance (Akeredolu, 1996). Aerosols impacts on health consist of both long-term acute symptoms like asthma and bronchitis and short-term chronic irritation and inflammation of the respiratory track, which can potentially lead to cancer. Fine particles get deposited in the lungs and causes lung cancer and cardiopulmonary mortality (Dockery *et al.* 1993; Pope III *et al.* 2002) [1, 20] The major health effects of particulate matters are breathing and respiratory symptoms, the aggravation of existing respiratory and cardiovascular diseases, the alteration of body's defense against foreign materials, damage to lung tissue, carcinogenesis and premature mortality. These types of health effects are more noticeable in the elderly and children than other age groups. The specific air pollutants including the particulate matter and their associated health effects is shown in table 1 (source: (Stern *et al.* 1984) [25] while table 2 (source: (Kimani, 2007)) [16] shows the effects of heavy metal constituents of particulate matter on human health.

Table 1: Specific air pollutants and associated health effects

Pollutants	Effects
CO	Reduction in the ability of the circulatory system to transport O_2 Impairment of performance on tasks requiring vigilance Aggravation of cardiovascular diseases
NO_2	Increased susceptibility to respiratory pathogens
O_3	Decrement in pulmonary function Coughing; chest discomfort Increased asthma attacks
Peroxyacyl nitrates, Aldehyde	Eye irritation
SO_2/particulates	Increased prevalence of chronic respiratory disease Increased risk of acute respiratory disease

Source: Stern *et al.* (1984).

Table 2: Effects of heavy metal constituent of particulate matter on human health

Heavy metal	Environmental sources	Minimum risk level	Chronic exposure toxicity effects
Lead	Industrial and vehicular emissions, paints and burning of plastics, paper etc	Blood lead levels below 10 micrograms per deciliter of blood	Impairment of neurological development, Suppression of the hematological system (anemia), kidney failure, immunosuppression etc
Mercury	Electronic and Plastic wastes, pesticides, pharmaceutical and dental waste.	Below 10 microgram per deciliter of blood; oral Rfd 4 mg/kg/day	Gastrointestinal and respiratory tract irritation, renal failure, neurotoxic
Cadmium	Electronic, Plastic, batteries - diet and water.	Below 1 microgram per deciliter of blood	Local irritation of the lungs and gastrointestinal tract, kidney damage and abnormalities of skeletal system.
Arsenic	Herbicides and pesticides, electronics, burning of waste containing the element, contaminated water.	Oral exposure of 0.0003 mg/kg/day	Inflammation of the liver, peripheral nerve damage - neuropathy, cancer of the liver, skin and lungs, irritation of the upper respiratory system- pharyngitis, laryngitis, rhinitis, anemia, cardiovascular diseases.

Source: Kimani (2007)

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