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Atmospheric Aerosols: Air Quality and Climate Change Perspectives

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ABSTRACT

Recently, air quality has become a matter of concern of everyone. According to the reports, atmospheric aerosols play very crucial role in air quality. PM_{10} and $PM_{2.5}$ aerosols are integral parts of total suspended particulate matter which affect our health. Often air quality has been reported very poor due to violation of National Ambient Air Quality Standard (NAAQS) limits. PM_{10} and $PM_{2.5}$ limits are crossed for both residential as well as sensitive sites. This is one of the major reasons of increasing cases of respiratory diseases in urban areas. However, aerosol loadings alone are not the factor for deciding or predicting toxic and harmful effects of aerosols. Chemical composition and size ranges do matter. Aerosol loadings can be due to three major source categories viz. marine, crustal and anthropogenic. Since, marine and crustal content of aerosols are generally non-toxic and hence, degree of toxicity of air needs to be decided on the basis of anthropogenic fraction having metals, PAHs and other harmful content. Apart from air quality and health, atmospheric aerosols play vital role in other atmospheric processes such as cloud formation, radiative transfer and monsoon etc. Though there are several studies reported on different aspects of atmospheric aerosols, but most of the findings are sort of data reporting based on short term observations. Hence, there is need to investigate the atmospheric aerosols in order to demonstrate local and regional phenomenon on the basis of long term datasets.

Key words: Atmospheric aerosols, Air quality, PM_{10} aerosols, $PM_{2.5}$ aerosols, Aerosol effects.

INTRODUCTION

Solid or liquid particles suspended in the air are termed as aerosols. These particles generally range from 1nm to 10 µm size diameter[1]. Atmospheric aerosols are contributed by several natural and anthropogenic sources such as earth crust, volcanic eruption, ocean and sea spray, industries, biomass burning and vehicular traffic etc. During recent past, aerosol production from anthropogenic sources has increased significantly. Studies have reported that atmospheric aerosols have very high impact on air-quality, visibility, cloud formation and atmospheric chemistry, radiation budget etc. Besides, they have significant impact on human health too. Deposition of aerosols affects surface albedo and water bodies etc[2]. In particular, deposition of dust and carbonaceous aerosols on ice significantly impacts the surface albedo[3,4]. However, in spite of huge research findings about various aspects of atmospheric aerosols, global annual budget of aerosols still has large uncertainties[5,6,7] which can be estimated by attempting the gap areas. In this paper we review about atmospheric aerosols, their sources, effects and role in various atmospheric processes including air quality.

Air quality and aerosols

Continuous and rapid increase of urbanisation and industrialisation has resulted in extremely poor air quality in mega cities. According to various international reports, air quality of Indian cities, in particular Delhi air is found to be the worst. Average SPM (suspended particulate matter) levels are noticed above 500 µg/m^3 (Table 1). Very high SPM levels have been reported two decades ago at Agra near Taj Mahal[8]. The levels of PM_{10} aerosols which represent respirable particles have also been

recorded above 200 µg/m^3 at most of the sites in Delhi. Even $PM_{2.5}$ levels reach 400 µg/m^3 during winter months in Delhi. However, it is important to note that these surveys primarily consider high particulate matter levels as major reason for poor air quality of Delhi. In general, gases such as SO_2, NOx are found within the permissible limits.

Based on Air Quality Monitoring data of National Air Quality Monitoring Programme (NAMP), the trends of respirable suspended particulate matter (RSPM) for Delhi have been given in Table 2. As mentioned earlier the air of Delhi mostly exceeds the NAAQS value PM_{10} (60 µg/m^3**)** through out the year. The major sources of the particulate matter are their emissions from soil-dust, road dust, construction activities, generator sets, small scale industries, biomass burning and vehicular emissions etc. Delhi has 25.8 million population. In 2010, total number of vehicles was around 4.7 million which is expected to grow upto 26 million by 2030. As compared to 2001, energy consumption of the city has increased 57% in 2011. Such huge number of vehicles, energy consumption and growing construction activities will further deteriorate the air quality of the city.

Criteria limits

The Central Pollution Control Board (CPCB) has developed permissible limits for criteria pollutants known as National Ambient Air Quality Standards (NAAQS). The NAAQS limits for PM_{10} and $PM_{2.5}$ have been given in Table 3. Table gives the NAAQS annual and 24 hour average values for industrial as well as ecological sensitive areas.

Pollution level classification for industrial, residential, rural and ecological sensitive areas on the basis of PM_{10} concentrations as defined by CPCB has been given in Table 4. There are four categories viz low, moderate, high and critical have been defined. PM_{10} level exceeding 90 µg/m^3 is considered as critical pollution. According to the measurement data, PM_{10} concentrations are recored above 90 µg/m^3 at most of the sites of Delhi indicating poor air quality.

It is important to mention that while considering $PM_{2.5}$ and PM_{10} as the basis of air quality, one should not forget that background levels of $PM_{2.5}$ and PM_{10} atmospheric aerosols at both rural as well as urban sites are naturally high due to their contribution from wind blown dust. Generally, such natural aerosols are not toxic in nature as compared to anthropogenic aerosols. Because of these natural aerosols, the ambient SO_2 levels are controlled in Indian region as the SO_2 gets oxidized onto the dust particles forming calcium sulphate[9,10]. Hence, in order to judge the air quality of a particular location, apart from their concentrations, size ranges and chemical compositions need to be evaluated[11]. This will help in deciding the quality of air, its health and climate related consequences in appropriate manner.

Formation of aerosols

Formation of atmospheric aerosols takes place via two mechanisms - i) disintegration as primary aerosols and ii) gas to particle conversion as secondary aerosols. Sea salt, mineral dust, black carbon etc. are emitted into the atmosphere as primary particles which are generally coarser in size. Sulphate, nitrate and ammonium aerosols are generally contributed via secondary aerosol formation process and exist as fine aerosols. Major fraction of atmospheric aerosols is composed of inorganic species such as ammonium, nitrate, sulphate, black carbon (BC), sea salts, mineral species, bioaerosols and organic species etc. The organic aerosols have both significant primary and secondary sources.

Types of aerosols

According to size, atmospheric aerosols are classified into two groups-

i) Fine mode aerosols (d < 2.5 µm)

•Aitken nuclei mode: (0.005 µm < d < 0.1 µm)

•Accumulation mode: (0.1µm < d < 2.5 µm)

ii) Coarse mode aerosols : (d > 2.5 µm)

In general, the aerosol mass size distribution of aerosols shows both fine and coarse mode aerosols resulting in bimodal distribution[12,13,14,15,16,17]. Several workers consider d< 1 µm for fine mode aerosols. In the areas where natural sources are the major contributors, mass size distribution shows coarse mode dominance whereas fine mode dominance is observed in the areas having anthropogenic source dominance. The origin of fine and coarse mode particles is generally different

so their transformations and removal mechanisms from the atmosphere are also different. Since, their origin is different, the chemical composition of fine and coarse mode aerosols is also different so their radiative properties are different too.

Aitken mode particles are formed via gas-to-particle conversion process. These are also formed during condensation of hot vapours. Aitken particles are short lived particles and act as condensation nuclei for low- vapour pressure gases which further grow to fall into accumulation range. Generally, ammonium, nitrate and sulphate species represent accumulation mode particles. The term accumulation is named because these particles are least affected by normal particles scavenging mechanism and hence, are accumulated in the atmosphere until their removal by precipitation.

Sources of atmospheric aerosols

Both natural as well as anthropogenic sources contribute atmospheric aerosols. Natural sources of aerosols include earth crust, volcanic eruption, sea spray etc. whereas anthropogenic sources of aerosols include vehicular traffic, industries, biomass burning etc. Table 5 gives the major sources of different aerosol species. From the table it is clear that the sea spray is a huge source of atmospheric aerosols which contributes 3-30 Pg aerosols every year[18]. Bubble rupturing during breaking waves is the major source of sea spray. Dimethylsulphide emitted by oceans contributes a significant fraction of global sulphate aerosols[19,20,21]. Wind blown dust is produced by disintegration of larger particles over arid surface in desert areas e.g.[22,23].

Table 1: Annual average of SPM (µg/m^3)at selected sites in Delhi during 2010. (Source: CPCB, Delhi)

Location	SPM (µg/m^3)
Mayapuri Industrial Area	576
Shahzada Bagh	527
Shahadra	501
N.Y.School, Sarojini Nagar	426
Townhall, Ayurvedic Dispensary,Chandni Chowk	560
Nizamuddin	456
Pritampura	444
Siri Fort	448
Janakpuri	511

The range of global emission budget of aerosols along with their precursors have been summarized in Table 6. The dust aerosols have a wide range of concentration depending on the location on the globe. Mineral dust aerosols have their relatively higher concentrations in Central Asia, Middle East, north India and some parts of China. Generally, SO_4^{2-} aerosols accounts about 10-30% of aerosol mass while NO_3^- and NH_4^+ aerosols account for about 6% depending upon the location of the site. EC normally accounts for less than 5% of aerosol mass. However, OC contributes a significant fraction up to 20% in the regions like North America and South America. OC contribution has been reported as very high in Indian region too due to biomass burning.

Global and regional anthropogenic emissions of black carbon aerosols as well as biomass burning aerosols are given in Table 7.

Impacts of atmospheric aerosols

Visibility Reduction

Atmospheric aerosols play very critical role in visibility. Fine aerosols mainly those having dia between 0.3 and 1.0 µm cause visibility reduction[24,25,26,27] because of the fact that their diameter is similar to that of wavelength of light which interferes with visible radiation[1,28]. It has been observed that in north India during winter season, road traffic, air traffic as well as rail traffic are hampered due to extreme foggy conditions during low visibility.

Table 2: Ambient Air Quality Trend in Delhi City. (Source: CPCB, Delhi)

Years	2008	2009	2010	2011	2012	2013
PM_{10} levels(µg/m^3)	214	252	261	222	237	221

Radiative Forcing

Radiative forcing can be defined as the change in irradiance at the tropopause due to an applied perturbation fixing all other variables constant[29,30,31]. Atmospheric aerosols affect in two different manners i) Directly and ii) Indirectly. Direct effect of aerosols involves scattering and absorption of solar as well as thermal infrared radiation which alter the radiative balance of the Earth-atmosphere through altering the planetary albedo. Indirect effect of aerosols modifies the microphysical as well as the radiative properties of clouds[32]. Monsoon is

Table 3: Limits of National Ambient Air Quality Standards (NAAQS) for ambient aerosols (CPCB, 2009)

Types of aerosols	Time perid	Concentration in ambient air (µg/m^3)	
		Industrial, Residential, Rural and other area	Ecologically sensitive area
PM_{10}	Annual/24 hours	60/100	60/100
$PM_{2.5}$	Annual/24 hours	40/60	40/60

Table 4: Pollution Level Classification on the basis of PM_{10} levels (CPCB, 2011)

Pollution level	Annual Mean Concentration Range (µg/m^3)	
	Industrial, Residential, Rural & others areas	Ecologically Sensitive Area
Low (L)	0-30	0-30
Moderate (M)	31-60	31-60
High (H)	61-90	61-90
Critical (C)	>90	>90

Table 5: Major sources of the Aerosol Species. (Source: AR5 of IPCC)

Aerosol Species	Main Sources
Sulphate	Primary sulphate: marine and volcanic emissions. Secondary sulphate: formed by the oxidation of oxides of S
Nitrate	Oxidation of NOx
Black carbon	Emitted from fossil fuel combustion, biomass and biofuel burning
Organic aerosols	Fossil fuel combustion, biomass and biofuel burning, Continental and marine ecosystems. Non-combustion sources including biogenic origin
Brown carbon	Biofuel and biomass burning. Humic-like materials of biosphere origin
Terrestrial primary biological aerosol Particles	Terrestrial ecosystems
Mineral dust	Wind erosion and resuspension of soil. Selected agricultural activities and industrial units
Sea spray	Bubble rupturing and wind erosion.
Marine primary organic aerosol	Aerosols injected with sea spray in the biologically active regions of the oceans

also affected by such implications of atmospheric aerosols. Table 8 gives the radiative forcing contributed by different types of aerosols.

It is found that the accumulation mode is the critical size range for radiative forcing because of their interaction with solar radiation. Moreover, accumulation mode particles have longest lifetime which also help in contributing extra radiative forcing. Accumulation aerosols scatter the light which is called Mie scattering as their size is of the order of the wave-length of the incidental light. Hence accumulation mode sulphate aerosols cool the atmosphere. Absorbing aerosols e.g. BC are responsible for warming the atmosphere. Absorbing aerosols have been reported heat convection reducer[33] contributing towards cloud re evaporation which affects the oceans for reduced evaporation and disturb the complete hydrological cycle over the oceans[34]. Very recently, apart from carbon aerosols, polymeric organic compounds have also been identified as absorbing aerosols[35,36].

Table 6: Emissions of atmospheric aerosols and their aerosol precursors from natural sources (Tg yr^{-1}) (Source: AR5 of IPCC)

Natural sources of aerosols	Global Natural Emissions
Marine primary organic aerosols(POA)	2-20
Dimethyl sulphide (DMS)*	10-40
Spores	28
Monoterpenes**	30-120
SOA production BVOCs	20-380
Isoprene**	410-600
Terrestrial bioaerosols	50-1000
Mineral dust	1000-4000
Sea spray	1400-6800

*(TgS yr^{-1}), **(TgC yr^{-1}).

Indirect radiative forcing of the aerosols

Cloud microphysical and radiative properties are significantly affected by atmospheric aerosols. Increasing aerosol concentration increases CCN for a given liquid water content. This scatters the light backwardly causing a cloud albedo. Also, recently increase in cloud lifetime is reported due to indirect effect of aerosols[37]. The cloud droplets need a threshold radius of 14 μm for the formation of rain. But the increased concentration of CCN averts the droplets from reaching the threshold radius increasing cloud lifetime and suppressing the rainfall[32].

Table 7: Global and regional anthropogenic emissions of black carbon and biomass burning aerosols. Unit is Tg yr^{-1}. (Source: AR5 of IPCC)

Year 2000 Emissions (Tgyr^{-1})	Anthropogenic Black Carbon	Biomass Burning Aerosols
Western Europe	0.4	0.4
Central Europe	0.1	0.3
Former Soviet Union	0.3	5.4
Middle East	0.1	0.3
North America	0.4	2.0
South America	0.3	5.9
Central America	0.1	1.44
Africa	0.5	23.9
China	1.2	1.1
India	0.7	0.5
Rest of Asia	0.6	2.0
Oceania	0.03	5.8
International Shipping	0.1	-
Total	4.8	49.1

Damage to materials

Corrosion of material is caused due to highly acidic or alkaline aerosols. Deterioration of artwork and historic monument has been reported due to acidity of aerosols[38,39]. Similarly, alkaline nature of atmospheric dust causes damage to walls, doors, furniture and automobiles etc. It has been found that reduction in aerosols can give economic benefits[40].

Acidification and Eutrophication

Oxides of S and N are found to contribute acid rain[41]. The phenomenon of acid rain has caused severe damage to ecosystems in USA, Canada, Europe, China and Japan. Acid rain has severe adverse effects on soil fertility and water bodies. Eutrophication is another adverse effect which is caused by high concentration of nutrients, especially phosphates and nitrates in a water body which promotes excessive algal growth. High amount of organic matter is built up due to decomposition of the organisms. This further depletes the oxygen of water resulting in the death of other organisms, such as fish. Generally, eutrophication is seen as a serious threat on coastal environments. If the rate of deposition of nutrients increases with the present rates it could become a global problem very soon. Water enriched with nutrients leads to greater production of organic matter which further results in oxygen deficiency killing marine biota[42,43,44].

Table 8: Global mean of RF (W m^{-2}) during 1750-2011 due to aerosol–radiation interaction of different aerosols used in AR5. (Source: AR5 of IPCC)

	Global Mean Radiative Forcing (W m^{-2})
Sulphate aerosols	–0.40 (–0.60 to –0.20)
Black carbon aerosols from fossil fuels and biofuels	+0.40 (+0.05 to +0.80)
Primary organic aerosols from fossil fuels and biofuels	–0.09 (–0.16 to –0.03)
Biomass burning	–0.0 (–0.20 to +0.20)
Secondary organic aerosols	–0.03 (–0.27 to +0.20)
Nitrate	–0.11 (–0.30 to –0.03)
Dust	–0.10 (–0.30 to +0.10)
Total	–0.35 (–0.85 to +0.15)

Effects on human health

Most important effect of atmospheric aerosols is human health effect which is caused by inhalation of air. Coarse particles (2.5 µm< dp< 10 µm) are mainly removed in the upper respiratory track whereas fine particles (dp< 2.5µm) are deposited on the different parts of respiratory track up to the bronchi walls[45]. Particles smaller than 0.1µm get collected in the bronchi through Brownian Motion. But the particles between 0.1 -1 µm 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. Deposition of such particles in the lungs causes airway resistance[46]. Accumulation of fine aerosols in the lungs results in various diseases depending up on the chemical characters[47].

Vegetation and animals

Different air pollutants enter the plant systems through direct and indirect pathways. Direct entry of particulate matter into leaves takes place through stomata by diffusing into and out of leaves while indirect pathway occurs through the root system. Gupta et al., [48] have demonstrated that the deposition of dust SO_4^{2-} on plant foliar causes changes in biochemical process of foliar. Atmospheric dust also clogs stomata. Aerosol deposition on the soils, vegetation and surface water can alter the nutrient content levels[49]. Sometimes the deposition of aerosols can harm to the palisade or spongy cells resulting in necrosis[50]. In addition, aerosols significantly affect the crop yield and so the economy.

Deposition of metal aerosols on vegetation and water bodies can be toxic to animals including fish[41]. Gaseous and particulate phase fluoride can cause harm and damage to various animals (domestic, wild and fish). Similarly, high intake of arsenic results in severe diarrhoea, colic and liver cirrhosis[41]. Mercury in fish has been found in the water of developed countries which is generally present as methyl mercury in aquatic systems.

CONCLUSION

Air quality is seriously affected by the atmospheric aerosols. Air quality of cities is deteriorating drastically in urban areas. PM_{10} and $PM_{2.5}$ aerosols have been recorded higher than their NAAQS prescribed limits at most of the sites in Delhi. In general, apart from anthropogenic emissions, the particulate matter levels are very high in Indian region partly due to natural contributions from wind blown dust. Hence, the assessment of air quality needs segregation of natural fraction vs toxic metal and organics from the total particulate content in order to evaluate the real health consequences of atmospheric aerosols. Global scenario of atmospheric aerosols is quite clear but still it needs corrections based on regional and local measurements. There is great need to reduce uncertainties in atmospheric aerosol budget in Indian region for which we need to strengthen aerosol measurement networks through out the country especially by increasing the number of sites appropriately so as to represent all type of topography, land use, activities etc.

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