

# Aerosols and Climate

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Our climate is strongly influenced by the manner in which solar radiation is absorbed and reflected in the atmosphere. Gases such as water vapour, carbon dioxide and methane allow most of the solar radiation to pass through but absorb most of infrared radiation emitted by the Earth. This increases the temperature of the Earth and is known as greenhouse effect. During the past 100 years the amount of carbon dioxide in the atmosphere has increased by about 25% on account of burning of coal and oil by human beings. This has caused the surface temperature of the Earth to increase by about one degree centigrade. The amount of carbon dioxide in the atmosphere is expected to increase exponentially in the next hundred years and this is expected to increase the global mean temperature by 2 to 5 degrees centigrade. The actual amount of increase will be difficult to predict on account of the influence of other factors such as clouds and aerosols. In this article the role of aerosols on climate is discussed.

## What is an Aerosol?

Atmospheric aerosols are particles of solid or liquid dispersed in the atmosphere. Aerosols are produced mainly by the mechanical disintegration processes occurring over land (e.g. lift up of dust) and ocean (e.g. sea-spray) and by chemical reactions occurring in the atmosphere (e.g. conversion of sulphur dioxide to sulphuric acid droplets). After production at one location, aerosols are often carried to locations far away from their sources, for example, the transport of dust from Sahara desert over the Atlantic Ocean by winds. Most of the aerosol sources are located near the Earth's surface and hence their concentration (mass per unit volume) is larger near the surface. Occasionally there may be layers aloft as well depending upon the atmospheric conditions. Aerosol size varies ranging from  $10^{-3}$  to  $10^2$   $\mu\text{m}$  depending

## Keywords

Global warming, greenhouse effect, aerosol.



**Box 1. Size Distribution**

Size distribution function describes how aerosol number (or area or volume) is distributed with respect to size. The size distribution mainly depends on the production mechanism (source). Aerosols formed by gas to particle conversion are in general smaller in size and those produced by mechanical disintegration are larger. The size distribution determines the lifetime of each species in the atmosphere.

upon their source and production mechanism. Depending on their size (*Box 1*), aerosols are broadly classified into three categories: (1) nucleation mode (radius  $\sim 0.001$  to  $0.1 \mu\text{m}$ ) (2) accumulation mode (radius  $\sim 0.1$  to  $1.0 \mu\text{m}$ ) and (3) coarse particle mode (radius  $> 1 \mu\text{m}$ ). The nucleation mode aerosols are produced mainly by the nucleation of volatile gases, a process known as gas-to-particle conversion, in the atmosphere. The accumulation mode aerosols are produced by coagulation (a process in which two or more aerosols combine together to form a single aerosol) and growth of nucleation mode aerosols by condensation of water vapour. Coarse mode aerosols are produced directly by mechanical processes (e.g., action of winds on aerosols). Aerosols of different size ranges are important for different atmospheric processes. Nucleation mode aerosols are important in atmospheric electricity, accumulation mode significantly influence the visible solar radiation and coarse mode aerosols can act as cloud condensation nuclei to form clouds. For particles in the size range from  $0.01$  to  $0.1 \mu\text{m}$  the average lifetime is typically a few days. Particles larger than  $10 \mu\text{m}$  cannot remain suspended in air for long because of gravity.

**How are Aerosols Produced?**

There are natural as well as anthropogenic (man-made) sources of aerosols. The aerosols of terrestrial origin are formed mainly by two mechanisms – (1) mechanical disintegration processes (primary sources) and (2) gas-to-particle conversion processes (secondary sources). On global scale natural sources are larger compared to anthropogenic sources, but on a regional scale anthropogenic sources can be larger especially near industrialized regions. Natural sources include production from sea-spray

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**Figure 1 (left).** The eruption of Mt. St. Helene's volcano in USA

(Credit: USGS/Cascades Volcano Observatory)

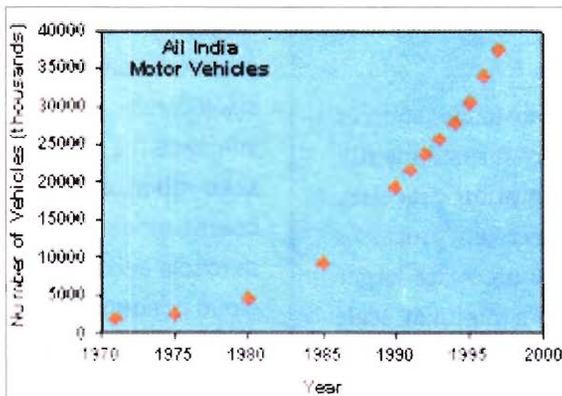
**Figure 2 (right).** The high levels of emissions from industries. The emitted smoke contains mainly sulphate and nitrates. (Credit: New Deal, Network, USA)

and volcanic eruptions (see *Figure 1*). Anthropogenic sources include industrial emissions (see *Figure 2*), transportation (see *Figure 3*) and biomass burning (see *Figure 4*).

**Figure 3 (left).** The increase in the number of vehicles from 1970 to 1998.

(Credit : Duli Chand, Physical Research Laboratory, Ahmedabad)

**Figure 4 (right).** Aerosols produced from biomass burning. The soot aerosol is produced in this way. (Credit to Forest Service Research, Washington, USA)



## Mechanical Disintegration

Fine soil and sand particles become airborne due to wind. Over a rough terrain, irregular soil and sand particles cause turbulent air motion, which picks up the particles at the surface and deposits them in the atmosphere. Wind speeds as low as  $0.5 \text{ ms}^{-1}$  are capable of picking up and keeping airborne soil particles as large as  $2 \text{ }\mu\text{m}$  in size. Another type of mechanical production of aerosols is from the ocean waves, which produce spray droplets at their crests during strong winds (wind speed  $> 10 \text{ ms}^{-1}$ ). At low wind speeds (wind speed  $> 3 \text{ ms}^{-1}$ ) bubbling occurs as a result of entrainment of air by breaking waves. The aerosols produced by the bursting of air bubbles form another kind of natural aerosols. Many types of organic particles like pollen, seeds, spores and leaf fragments released by the plants and distributed by various atmospheric circulation systems (winds) form another kind of primary aerosol source particularly over forest areas and regions containing thick vegetation.

## Gas-to-Particle Conversion

The particles in the atmosphere can be produced by the nucleation (condensation) of low volatile gases mainly produced as a result of industrial activities, forest fires, etc. This process is called gas-to-particle conversion. Gas-to-particle conversion may occur by heterogeneous or homogeneous nucleation. In homogeneous nucleation the precursor gases directly condense to form new particles whereas in heterogeneous nucleation the precursor gases condense on the surface of the existing particles. For homogeneous nucleation to occur, high super-saturations are required. Heterogeneous nucleation occurs with aerosols having sufficient surface area. Aerosols produced by homogeneous nucleation cover a wide range of sizes, but majority of them cover the nucleation particle range ( $r < 0.1 \text{ }\mu\text{m}$ ). Chemical reactions between various gases also result in the gas-to-particle conversion mostly catalysed by ultraviolet radiation from the Sun. Since the particles produced by gas-to-particle conversion are hygroscopic (water active), they can act as condensation

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nuclei for the formation of clouds. The major components involved in the process of gas-to-particle conversion are sulfur and nitrogen bearing gases.

### How Aerosols are Removed from the Atmosphere?

The major processes removing aerosols from the atmosphere are dry deposition or sedimentation (fall under gravity, see *Box 2*) and wet removal (by rain).

Sedimentation or fall out is the fall of aerosols under gravity.

#### Box 2.

The fall velocity and diffusion coefficient, are basic parameters which determine the removal rate. For particles much larger than air molecules, the fall velocity is given by,

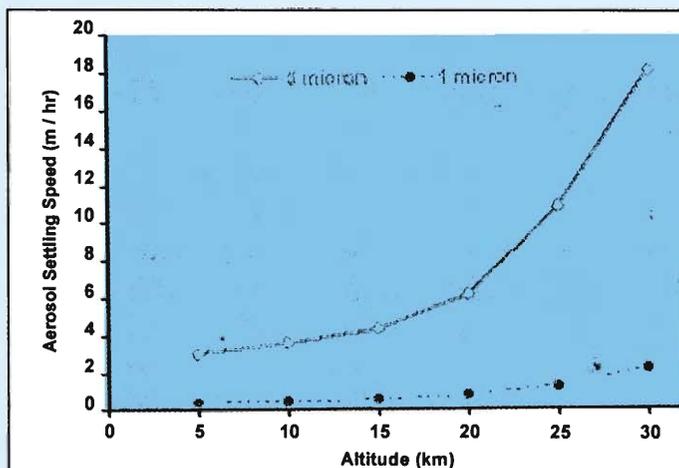
$$v = mgB,$$

where  $m$  is the particle mass,  $g$  is the acceleration due to gravity and  $B$  is the particle mobility defined as the velocity per unit driving force.

$$B = \frac{D}{kT},$$

where  $D$  is the diffusion coefficient,  $k$  is the Boltzmann's constant, and  $T$  is the temperature. The particle mobility decreases as the air molecule density increases. Thus at lower atmosphere, since the molecular density is more, the mobility is less and at upper atmosphere since the molecular density is less the mobility is more. Since the fall velocity is directly proportional to the particle mobility, at lower

levels, the fall velocity is less compared to that at upper levels. In addition to particle mobility, the only parameter determining the fall velocity is the particle mass. As such heavy particles have larger fall velocity compared to lighter ones. The fall velocity of different sized particles at different levels is shown in *Figure 5*.



**Figure 5.** The fall velocity (under gravity) of aerosols at different altitudes for two aerosol sizes  $5 \mu\text{m}$  and  $1 \mu\text{m}$ .

The falling particles are disturbed by the atmospheric circulation systems. In calm atmospheric conditions, the falling particles attain a terminal velocity when gravitational force is balanced by the opposing force due to viscous drag by air.

The removal of aerosols from the atmosphere by the falling raindrops is called 'rain out'. Since some of the particles (especially small aerosols) are probably pushed away by the air stream of the falling rain drops that are larger than them, all the particles in the air path of a raindrop are not removed from the atmosphere. The efficiency of collection depends on the sizes of both the raindrops and particles. Many particles merge with the falling drops and are removed from the atmosphere. The overall removal rate depends on size distribution of both raindrops and aerosols.

In the presence of water vapour the aerosol particles are capable of acting as condensation nuclei for the formation of clouds. In this process of cloud formation, the aerosol particles are removed from the atmosphere. This process is called wash out by clouds. Very small particles are not capable of acting as condensation nuclei but will remain inside the cloud and are called 'interstitial particles'. The minimum size of the aerosol, which can act as cloud condensation nuclei, depends on the degree of super saturation of air.

### What Constitutes an Aerosol?

Aerosols produced from different natural and anthropogenic activities are mixed together and hence each aerosol particle is a composite of different chemical constituents. Chemical composition of aerosols determines their complex (contain real and imaginary parts) refractive index. Particle refractive index is an important parameter while determining the radiative effects. The real part determines the scattering properties and imaginary part, the absorption characteristics. The chemical composition and hence refractive index depends on the source of particles. The real part of particle refractive index usually lies in

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Aerosols, in general, consist of sulfates, nitrates, sea-salt, mineral dust, organics, carbonaceous components (often called soot), etc.

the range 1.3 to 1.6 and imaginary part varies over several orders of magnitude from about  $5 \times 10^{-9}$  to  $5 \times 10^{-1}$ . Particles originating from combustion (burning) processes usually have high absorption properties and hence high imaginary part of refractive index.

Thus each aerosol species is formed in the atmosphere separately by different processes and are mixed together to form particles of mixed composition. Aerosols, in general, consist of sulfates, nitrates, sea-salt, mineral dust, organics, carbonaceous components (often called soot), etc.

### Sea-Salt Aerosols

Sea-salt particles are produced over the sea mainly by the processes associated with the bursting of bubbles. When there are very strong winds with speeds,  $U > 10 \text{ ms}^{-1}$  direct sea-spray production takes place by the breaking of wave crests. At moderate wind speeds of  $\sim 3\text{-}5 \text{ ms}^{-1}$  white capping occurs as the ocean surface waves overturn. The air trapped by these waves produces a large number of air bubbles in the near sea surface. Bubbles of air reaching the air-sea interface burst and eject liquid droplets into the marine atmosphere. These are called jet droplets. During bursting of bubbles the break-up of the bubble film produces a shower of very small particles called film droplets.

After production the seawater droplet starts evaporating in order to maintain equilibrium with the ambient relative humidity (RH). Depending on the RH, the particle can exist either as solution droplet or crystalline matter. Extensive measurements of sea-salt aerosols revealed that the bubble production at the sea surface and hence the concentration of sea-salt particles depends strongly on wind speed at the sea surface.

### Non-Sea Salt Aerosols

The main source of non-sea-salt (nss) aerosol is from the gas-to-particle conversion of sulfur bearing gases. The sulfur compounds present over the remote oceans can be of marine or



continental origin. Almost all species of marine phytoplankton release dimethyl sulphide (DMS), which get oxidized by different radicals to form  $\text{SO}_2$ . The non-sea-salt sulfate particles present in the marine boundary layer are hygroscopic (water active) in nature and play an important role as cloud condensation nuclei. An increase in the marine DMS emission increases the number density of sulfate aerosol over the marine atmosphere and consequently the number density of cloud droplets, which result in an increase in cloud albedo (reflectance). This enhancement in cloud albedo reduces global temperature and lower temperature in turn reduces productivity and emission of marine DMS. Thus a negative feedback mechanism exists which control the production of non-sea-salt aerosols.

### Sulfates and Nitrates

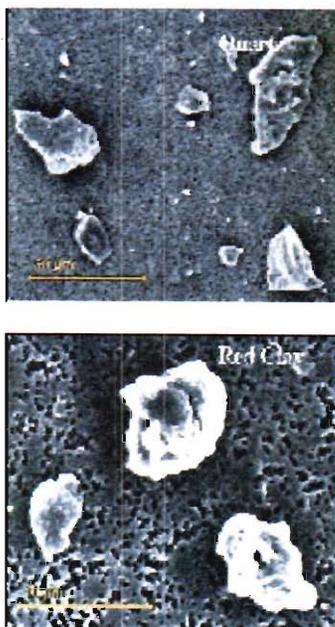
The major source of sulfates and nitrates is industrial activities (see *Figure 2*). In addition, volcanic eruptions inject large amounts of dust and gaseous materials such as sulfur dioxide into the stratosphere, where it is gradually converted into sulfuric acid aerosols. Since the removal mechanisms such as rain do not affect stratosphere, these aerosols remain there for several years.

The sulfur bearing precursor gases in the atmosphere are of both natural and anthropogenic origin. The sulfur compounds of natural origin include those originating from the biosphere (e.g., DMS) and those injected by volcanoes. The man-made sources are those caused by industrial activities. The major sulfur compounds in the atmosphere are sulfur dioxide, hydrogen sulfide, carbon disulphide, carbonyl sulfide and dimethyl sulfide. The oxidation of these sulfur compounds are photochemically induced and depends on the amount of ultraviolet radiation. Since UV radiation is amply available in the stratosphere, these compounds are mainly photo-oxidised whereas in the troposphere they are mainly oxidized by OH radical.

Anthropogenic activities produce nitrogen-bearing gases. The major nitrogen compound in the atmosphere is nitrous oxide ( $\text{N}_2\text{O}$ ), which decomposes into nitrogen and nitric oxide (NO).

#### Box 3. Optical Depth

Optical depth is a measure of transmittance of a vertical atmospheric column of unit cross-sectional area. A large optical depth implies less atmospheric transmittance. The optical depth is a result of the combined effect of scattering and absorption in a vertical column. Major contributors of this extinction (a measure of attenuation) in the atmosphere are aerosols and air molecules. The optical depth due to aerosol only (aerosol optical depth) is obtained by subtracting the contribution due to air molecules from the total atmospheric optical depth, which is known with reasonable accuracy.



**Figure 6.** The electron microscope picture of different types of aerosols.

(Photos obtained from <http://www.nat.vu.nl/vakgroepen/ster/english/research/res1.html>)

<sup>1</sup> Single Scattering Albedo: SSA describes the contribution of scattering to extinction. SSA is defined as the ratio of scattering to extinction. SSA depends on the chemical composition. It varies from ~0.2 for soot to about unity for sea-salt. For dust it is ~0.8. Observations over the oceanic regions adjacent to the Indian subcontinent show a SSA of ~0.9. It simply means 90% scattering and 10% absorption.

Nitric oxide quickly oxidized to nitrogen dioxide ( $\text{NO}_2$ ) by reacting with ozone.  $\text{NO}_2$  reacts with OH and forms  $\text{HNO}_3$ .

### Mineral Dust

They are produced over arid and semi-arid (dry) regions by the action of surface winds. Dust is a mixture of quartz and clay minerals (see *Figure 6*). The long-range transport of mineral dust by the combined action of convection currents and general circulation systems make these particles a significant constituent even at locations far from their sources. For example, several investigators have observed Saharan dust even at remote locations of the Atlantic Ocean (thousands of kilometres away from source). Since these particles are generated at the earth's surface, they are mainly confined within the troposphere. As the composition of the soil varies locally, the mineral aerosols derived from soil exhibit high variability in their radiative effects.

### Organic Aerosols

Organic aerosols are produced mainly by gas to particle conversion processes. Organic aerosols, unlike the other species, are a collective term, which refers to a large number of individual compounds. Each individual compound has a different characteristic in terms of their radiative effect. Since they are volatile, its sampling is difficult compared to other species. This type of aerosols is one of the less understood aerosol species.

### Carbonaceous Aerosols (Soot)

These are among the most complex aerosol types. They are produced mainly from burning and transportation. Their radiative effects vary depending on the production mechanism. Soot has a significant role in climate modification because of its absorption characteristics. Its absorption properties depends on the amount of graphite present which varies depending on whether the aerosol is produced after being completely burned or not. The single scattering albedo<sup>1</sup> can vary from 0.02 (almost completely absorbing) to 0.7 (partly absorbing) depending on

the amount of graphitic carbon.

On a global scale the natural aerosol (mainly sea-salt, non-sea-salt sulphates from ocean, and dust) amount is several times larger than that of anthropogenic aerosols (mainly sulphates, nitrates, soot, etc). But downwind of major cities where man-made sources are present, the anthropogenic aerosol amount can be much higher than that of natural aerosols. The measurements of aerosols over oceanic regions adjacent to the Indian sub-continent have shown that anthropogenic aerosols contribute to as much as 70% to the total aerosol optical depth<sup>2</sup> (Box 3, page 55). If we consider sulphate aerosol only, the latest estimates show that anthropogenic contribution is larger than the natural.

### How do Aerosols Influence Climate?

Although making up only one part in a billion of the mass of the atmosphere, aerosols have the potential to significantly influence the climate. The global impact of aerosol is assessed as the change imposed on planetary radiation measured in  $Wm^{-2}$ , which alters the global temperature.

Effect of aerosols on the solar radiation (also called radiative forcing) can be broadly classified into two: (i) direct influence and (ii) indirect influence.

#### Direct Radiative Influence

*In Visible Region:* Aerosols scatter and absorb radiations. The scattering and absorption of visible radiation by aerosols produces climate-forcing by changing the planetary albedo (reflectance of the planet). Absorption and re-radiation of infrared radiation enhances the atmospheric greenhouse warming. These two effects are called direct-forcing of aerosols on radiation and climate. The presence of aerosol in the atmosphere decreases (due to scattering and absorption) the surface reaching solar radiation and generally increases the outgoing radiation (due to back scattering).

<sup>2</sup> Contribution of Aerosol Species to Optical Depth: Investigations over Indian Ocean show that sulphates and nitrates contribute 29%, sea-salt 17%, soot 11%, organics 20%, ash 8% and dust 15% to the optical depth.

#### Box 4. Aerosol Climate Effect

Recent investigations over the Indian Ocean have revealed that the soot aerosols due to their high absorption effects are the single largest contributor to the reduction of solar flux at the surface whereas sulphate and nitrate aerosols due to their scattering effects constitute the single largest contributor to the solar radiation reflected back to space.

Aerosols can act as cloud condensation nuclei for the formation of clouds.

An increase in the concentration of aerosols can result in an increased concentration of cloud droplets, which in turn can increase the albedo (or the reflectance) of clouds.

***In Infrared Region:*** The presence of aerosol increases the surface reaching infrared radiation and decreases the outgoing infrared radiation. A fraction of the reduction in visible solar radiation at the surface (due to aerosols) is offset by the increase in infrared solar radiation. A net reduction in the surface reaching solar radiation may reduce evaporation. Since most of the aerosols are concentrated near the surface (within 3 km), absorbing aerosol component heats the lower atmosphere.

### Indirect Radiative Influence

Aerosols can act as cloud condensation nuclei for the formation of clouds. An increase in the concentration of aerosols can result in an increased concentration of cloud droplets, which in turn can increase the albedo (or the reflectance) of clouds. This causes a decrease in the visible solar radiation reaching the Earth's surface. Thus cloud albedo has a significant role in determining the global energy balance. An increase in aerosols increases the cloud droplet concentration and reduces the mean droplet size. This is because the water vapour availability per aerosol is less when aerosol number is more. This increases the cloud lifetime and thus inhibits precipitation (rain).

Mean temperature of the Earth is given by

$$H = S_0/4 (1-\alpha) - \sigma T_e^4 = 0, \quad (1)$$

In the steady state, when the amount of solar energy absorbed equals the emitted energy, we have

$$S_0(1-\alpha)(\pi r^2) = (4\pi r^2) \sigma T_e^4 \text{ or } S_0/4 (1-\alpha) - \sigma T_e^4 = 0, \quad (2)$$

where  $r$  is the radius of the Earth,  $\sigma$  is the Stefan-Boltzmann constant,  $T_e$  the global temperature and  $S_0$  is the solar power per unit area intercepted at the mean Sun-Earth distance (1365 to 1372  $\text{Wm}^{-2}$ ). The quantity  $\alpha$  is the albedo (reflectance) of the planet, which is the fraction of the solar radiation reflected by the Earth's surface and atmosphere. The mean solar radiation incident at the top of the atmosphere is  $\sim 343 \text{ Wm}^{-2}$  out of which  $\sim 103 \text{ Wm}^{-2}$  is reflected back to space by Earth's surface and

## Suggested Reading

atmosphere. Thus the value of  $\alpha$  is  $\sim 0.3$ . The energy balance equation implies that a change of 0.005 in the value of  $\alpha$  results in a 0.7% change in the global temperature. Aerosols have a significant influence in determining the value of albedo ( $\alpha$ ), and have consequent impact on the climate system.

## Warming or Cooling?

The question of whether aerosols increases or decreases the value of  $\alpha$  depends on its chemical composition. A completely scattering aerosol increases the value of  $\alpha$  (which means a decrease in temperature as is evident from the equation (2) for energy balance). If the absorbing aerosol (for e.g., soot) amount is significant, the net effect of aerosol can be a decrease in the values of  $\alpha$  because of absorption. This means the warming or cooling effect can change from region to region depending on many factors such as the relative strengths of various sources and sinks. The aerosols, which have a net cooling effect partly, offset the warming due to greenhouse gases and those, which has a net warming effect complement to the greenhouse warming. Experiments over the oceanic regions adjacent to Indian sub-continent have shown that the presence of aerosols increases the value of  $\alpha$  by about 10%. That is an increase of albedo by 0.03. More quantitatively aerosols increase the solar radiation reflected back to space by  $\sim 10 \text{ Wm}^{-2}$  and reduce the surface reaching solar flux by  $\sim 29 \text{ Wm}^{-2}$ . The balance of  $\sim 19 \text{ Wm}^{-2}$  is absorbed in the lower atmosphere (where most of the aerosols are present). This absorbed energy results in the warming of lower atmosphere. Thus the net effect is a cooling at the surface simultaneous with a warming of lower atmosphere. This may have implications on the climate. In addition, the reduced solar radiation at the surface reduces the evaporation rate and which in turn may affect water cycle of the planet. A number of observational programmes are going on to study aerosols and their effect on climate all over the globe. However, there are many questions to be answered about the net effect on climate of these small particles suspended in the atmosphere.

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