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Atmospheric Aerosols: From Ocean Spray to Human Health – Sources, Properties and Environmental Impacts

ORIGINAL ARTICLE

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Abstract

Atmospheric aerosols are ubiquitous suspensions of solid and liquid particles that profoundly influence Earth's climate, air quality, and public health. Originating from diverse natural sources including sea spray, volcanic eruptions, mineral dust storms, and biological emissions as well as anthropogenic activities such as fossil fuel combustion and industrial processes, these particles exhibit remarkable diversity in size, shape, composition, and optical properties. This article provides a comprehensive overview of aerosol sources, classification based on physical characteristics (size, shape, density, refractive index), meteorological influences, and their dual environmental and health impacts. Sea salt aerosols generated from wave breaking and non-sea-salt sulfates derived from phytoplankton-produced dimethyl sulphide dominate marine atmospheres, while mineral dust from arid regions and volcanic emissions significantly impact regional and global climate. Anthropogenic sulfates, nitrates, and black carbon from incomplete combustion contribute substantially to radiative forcing and air pollution. Aerosol size governs atmospheric lifetime and deposition patterns: nucleation mode particles (<0.1 ìm) form via gas-to-particle conversion, accumulation mode particles (0.1-1.0 ìm) persist for days to weeks and efficiently scatter solar radiation, while coarse mode particles (>1.0 ìm) settle within hours. Health impacts are most severe for PM, .… , which penetrates deep into alveolar regions, causing approximately 0.8 million premature deaths annually worldwide from respiratory and cardiovascular diseases. Understanding aerosol characteristics is essential for developing effective mitigation strategies and reducing uncertainties in climate models.

Key Words

Sea Salt Aerosols, Mineral Dust, Black Carbon, Aerosol Classification, Radiative Forcing.

Introduction

Atmospheric aerosols are suspensions of solid or liquid particles in air, originating from both natural and anthropogenic sources. They play a critical role in Earth's climate system through direct and indirect radiative forcing, affect visibility, and have significant implications for human health[1]. Aerosol particles range from a few nanometers to hundreds of micrometers, with physical and chemical properties determined by source characteristics and atmospheric processing.[2]

This article provides a comprehensive overview of aerosol sources, classification schemes based on physical properties, and the environmental and health impacts of atmospheric particulate matter.

Sources of Atmospheric Aerosols

Natural Sources

1. **Sea Salt Aerosols:** Sea salt aerosols are produced by the tearing of wave crusts during whitecap formation and bubble bursting at the ocean surface. These particles are primarily composed of sodium chloride and other marine salts, with sizes ranging from 0.05 to 10 ìm diameter. Sea salt aerosols are highly hygroscopic, efficiently scatter solar radiation, and serve as effective cloud condensation nuclei (CCN)[3]. Global emission estimates range from 1000 to 10,000 Mt yr{ ^{1}, making them one of the most abundant natural aerosol types.
2. **Non-Sea-Salt (Oceanic) Sulfate Aerosol:** The primary non-sea-salt sulfate (NSS) aerosol source is gas-to-particle conversion of sulfur-bearing gases[4]. Marine phytoplankton discharge dimethyl sulphide (DMS), which oxidizes via OH radicals under solar UV radiation to form SO, and subsequently sulfate aerosols. The CLAW hypothesis proposes a negative feedback mechanism: increased DMS emissions enhance cloud albedo, reducing global temperature, which decreases phytoplankton productivity and DMS emission[5]. These NSS particles are hygroscopic and act as CCN, significantly influencing marine cloud properties.
3. **Mineral Dust:** Mineral dust is a major contributor to aerosol loading and optical thickness, particularly in subtropical and tropical regions. Dust particles are formed in arid and semi-arid areas by surface wind action, combining quartz and clay minerals[6]. The Sahara Desert (largest global source) and Thar Desert in India emit an estimated 1000-3000 Mt yr{ ^{1}, with particles transported thousands of kilometers affecting downwind regions across the Atlantic and Indian Oceans[7]. Dust aerosols influence radiative forcing, ocean fertilization, and cloud microphysics.
4. **Volcanic Aerosols:** Volcanic emissions contribute both primary dust and gaseous sulfur. Large-magnitude eruptions (e.g., Mount Pinatubo 1991) can impact global climate by reducing solar radiation reaching the surface by 2-5%, lowering tropospheric temperatures by 0.5°C, and altering atmospheric circulation patterns for 2-3 years. Sulfuric gases convert to sub-micron sulfate droplets containing approximately 75% sulfuric acid, which scatter incoming solar radiation and absorb terrestrial radiation.[8]
5. **Extra-Terrestrial Aerosols:** Interplanetary dust consists of solid particles ranging from tenths of micrometers to few millimeters in diameter, primarily originating from cometary debris. Approximately 40,000 tons of cosmic dust enters Earth's atmosphere annually, contributing to the positive ion concentration in the upper atmosphere and representing the most fundamental natural background aerosol level.[9]
6. **Biological Aerosols:** Biological aerosols include plant debris (cuticular waxes, leaf fragments), humic matter, and microbial particles (bacteria, fungi, viruses, algae, pollen, spores). Concentrations range from 10t to 10v particles m{ ^{3} in forested areas. Humic-like substances make this aerosol light-absorbing, especially in the UV-B region, and biogenic particles can act as both cloud droplet and ice nuclei, influencing supercooled cloud processes.[10]
7. **Biomass Aerosols:** Forest and bush fires produce large quantities of sub-micrometer particles, with global emissions of 50-190 Mt yr{ ^{1}. The mean particle diameter is approximately 0.3 ìm, with few particles exceeding 10 ìm. Biomass burning significantly contributes to atmospheric aerosol loading, particularly in tropical regions during dry seasons, and is a major source of organic carbon and black carbon.

Anthropogenic Sources

1. **Sulfates:** Most global SO, emissions (120-180 Mt yr{ ^{1}) result from fossil fuel burning, industrial sources like oil refineries, and power plants. SO, oxidizes to sulfate via gas-phase or aqueous-phase reactions within cloud droplets. Both pathways produce submicron sulfate aerosols that are efficient light scatterers, contributing approximately -0.4 W m{ ^{2} to global radiative forcing.[11]
2. **Nitrates:** Nitrates are secondary particles formed through chemical reactions involving NO“ and NHƒ . Primary anthropogenic sources include vehicles, factories, and agricultural emissions. In regions with high NO“ and NHƒ emissions (Europe, India, North America), NH„ NOƒ aerosol concentrations (20-50 Mt yr{ ^{1}) may exceed those of sulfate, contributing to regional haze and nutrient deposition.[12]
3. **Black Carbon Aerosols:** Black carbon (BC) is formed as a by-product of incomplete combustion of fossil fuels and biomass (10-30 Mt yr{ ^{1}), consisting of graphite and light-absorbing particles in the fine mode. BC is uniquely absorbing (mass absorption cross-section 5-20 m^2 g{ ^{1}) and contributes positive radiative forcing of approximately +0.4 W m{ ^{2}. Sink mechanisms include wet and dry deposition, with atmospheric lifetime of 4-12 days depending on particle size and altitude.[13]

Classification of Aerosols

1. **Aerosol Shape:** Aerosols exhibit diverse morphologies[14]:

- **Isometric particles:** All three dimensions approximately equal (typical spherical particles, volcanic ash).
- **Platelets:** Two dimensions large, one dimension smaller (leaf fragments, mineral dust platelets).
- **Fibers:** One dimension much larger than the other two (asbestos, mineral fibers, pollen tubes).

2. **Aerosol Size**

Table 1: Classification of aerosols based on size

Particle Size Range (µm)	Classification	Chief Source	Lifetime	Number Concentration	Mass Contribution
0.001-0.1	Nucleation mode	Gas-to-particle conversion	< 1 day	104 -105 cm? ^{3}	<5%
0.1-1.0	Accumulation mode	Coagulation, condensation	Days to week	10^2-104 cm? ^{3}	30-60%
1.0-100	Coarse mode	Mechanical disintegration	Hours	1-10 cm? ^{3}	40-70%

Nucleation mode particles form via gas-to-particle conversion (GPC), primarily consisting of sulfuric acid compounds from oxidation of sulfur-containing gases. Accumulation mode particles result from coagulation of smaller particles and heterogeneous condensation, possessing the longest atmospheric residence time and greatest light scattering efficiency. Coarse mode particles originate from mechanical processes including wind erosion and sea spray.

3. **Aerosol Density**

Table 2: Densities of different aerosol species[15]

Aerosol Species	Density (g cm? ^{3})
Water-insoluble (organic)	2.0
Water-soluble (inorganic)	1.8
Sea-salt	2.2
Mineral dust	2.6
Soot (Black carbon)	1.0
Sulfate droplets	1.7
Volcanic dust	2.8

Mean bulk density of aerosols ranges between 1.0 and 3.0 g cm{ ^{3}, influencing settling velocities and atmospheric lifetimes.

4. **Refractive Index:** The complex refractive index (m = n - ik) determines aerosol radiative properties. The real part (n) typically ranges from 1.3 to 1.6, governing scattering efficiency. The imaginary part (k) varies over orders of magnitude (5 × 10{ y to 5 × 10{ ^{1}), with higher values indicating stronger absorption. Particles from combustion processes (soot, brown carbon) exhibit high k values (0.1-0.8), while sulfate and sea salt have negligible absorption (k < 10{ ^{3}).[16]

Meteorological Influences on Aerosols

- **Temperature:** Higher temperatures lower air density, increasing boundary layer height (up to 2-3 km) and aerosol dispersion; lower temperatures reduce boundary layer (100-500 m), trapping aerosols near surface and increasing concentrations by 3-5 times.
- **Solar radiation:** Drives photochemical reactions, secondary aerosol formation, and heat/moisture exchange influencing deposition processes.
- **Wind:** Controls transport (100-1000 km day{ ^{1}), dispersion, and re-suspension of deposited particles; threshold wind speeds of 5-8 m s{ ^{1} initiate dust emissions.
- **Relative humidity:** Determines water uptake by hygroscopic aerosols; at 90% RH, sulfate and sea salt particles increase in diameter by 2-3 times, enhancing light scattering by factor of 5-8.

Effects of Atmospheric Aerosols

1. **Environmental Effects**

- **Direct Radiative Forcing:** Aerosols scatter and absorb incoming solar radiation. Scattering aerosols (sulfates, sea salt, nitrates) produce cooling (-0.3 to -1.0 W m{ ^{2} globally), while absorbing aerosols (black carbon, dust) produce warming (+0.2 to +0.8 W m{ ^{2}). The net effect (-0.9 to +0.1 W m{ ^{2}) represents the largest uncertainty in anthropogenic climate forcing [17].
- **Indirect Radiative Forcing:** Aerosols act as cloud condensation nuclei, modifying cloud albedo, lifetime, and precipitation efficiency. Increased aerosol concentrations (from 100 to 1000 cm{ ^{3}) lead to more numerous but smaller cloud droplets (15 to 10 ìm diameter), increasing cloud reflectivity by 5-10% (Twomey effect) and potentially suppressing precipitation, extending cloud lifetime by hours [18].

  Chemical composition includes water-soluble ions (Naz , NH„ z , Kz , Mg^{2}z , Ca^{2}z , Cl{ , SO„ ^{2}{ , NOƒ {), organic carbon (20-60% of fine mass), and elemental carbon (5-15%), serving as source markers.[19]

2. **Human Health Effects:** PM‚ …. (particles <2.5 ìm aerodynamic diameter) penetrates deep into nonciliated and alveolar regions of the lungs, depositing with 30-50% efficiency. Health impacts include:

- Allergies and asthma exacerbation (10-20% increase during high pollution episodes).
- Cardiovascular disease (8-18% increased mortality per 10 ìg m{ ^{3} PM‚ ….).

- Respiratory infections (15-30% increase in children).
- Lung cancer (8-14% increased risk per 10 ìg m{ ^{3}).
- Premature mortality.

Globally, ambient PM,.... air pollution is responsible for approximately 0.8 million premature deaths and 6.4 million years of life lost annually. The World Health Organization estimates that 91% of the world's population lives in areas exceeding PM,.... guidelines (10 ìg m{ ^{3} annual mean).

Conclusions

Atmospheric aerosols originate from diverse natural and anthropogenic sources, each with distinct physical and chemical characteristics. Natural sources dominate global emissions (3500-5500 Mt yr{ ^{1}) and include sea salt (1000-10,000 Mt yr{ ^{1}), mineral dust (1000-3000 Mt yr{ ^{1}), non-sea-salt sulfates from DMS oxidation (60-110 Mt S yr{ ^{1}), volcanic emissions (4-10,000 Mt yr{ ^{1}), biological particles, and biomass burning (50-190 Mt yr{ ^{1}). Anthropogenic sources contribute 1000-1300 Mt yr{ ^{1}, encompassing sulfates (120-180 Mt yr{ ^{1}), nitrates (20-50 Mt yr{ ^{1}), and black carbon (10-30 Mt yr{ ^{1}).

Aerosol classification based on shape (isometric, platelets, fibers), size (nucleation: <0.1 ìm, accumulation: 0.1-1.0 ìm, coarse: >1.0 ìm), density (1.0-3.0 g cm{ ^{3}), and refractive index is essential for understanding optical and radiative properties. Accumulation mode particles (0.1-1.0 ìm) possess the longest atmospheric lifetime (days to weeks) and greatest light scattering efficiency, making them most significant for climate forcing.

Meteorological parameters significantly influence aerosol behavior: temperature controls boundary layer dynamics, solar radiation drives photochemistry, wind governs transport and re-suspension, and relative humidity determines water uptake by hygroscopic species, enhancing scattering by factors of 5-8 at high humidity.

Environmental impacts include direct radiative forcing through scattering and absorption (-0.9 to +0.1 W m{ ^{2} globally), and indirect forcing via cloud modification (reflectivity increase of 5-10%, lifetime extension). Health impacts are predominantly associated with PM,...., which penetrates deep into alveolar regions causing allergies, asthma, cardiovascular disease (8-18% increased mortality per 10 ìg m{ ^{3}), and premature mortality (0.8 million annual deaths globally).

Understanding aerosol sources, properties, and effects is crucial for developing effective mitigation strategies, improving air quality management, and reducing uncertainties in climate models (currently ±50% of total forcing). Future research priorities include size-segregated chemical characterization, real-time source apportionment, and assessment of aerosol-cloud-precipitation interactions.

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