Climate Change Science

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Lecture 43
Impact of Aerosols on Climate

In this course, we have already examined how greenhouse gases and changes in surface albedo due to ice, snow, and clouds affect the Earth's climate. Now, we turn to a third key factor: the role of aerosols. Aerosols are tiny particles suspended in the atmosphere that are invisible to the naked eye, yet they can alter the Earth's energy balance by changing its albedo, thereby influencing the amount of solar radiation reflected or absorbed.

However, the influence of aerosols is far more complex than that of greenhouse gases like carbon dioxide. Unlike CO_2, which is a single, chemically stable molecule that is well-mixed across the globe and relatively uniform with altitude, aerosols vary significantly in space and time. Their concentration depends on seasonal factors, geographic location, and proximity to sources such as urban areas, deserts, forests, or volcanic regions.

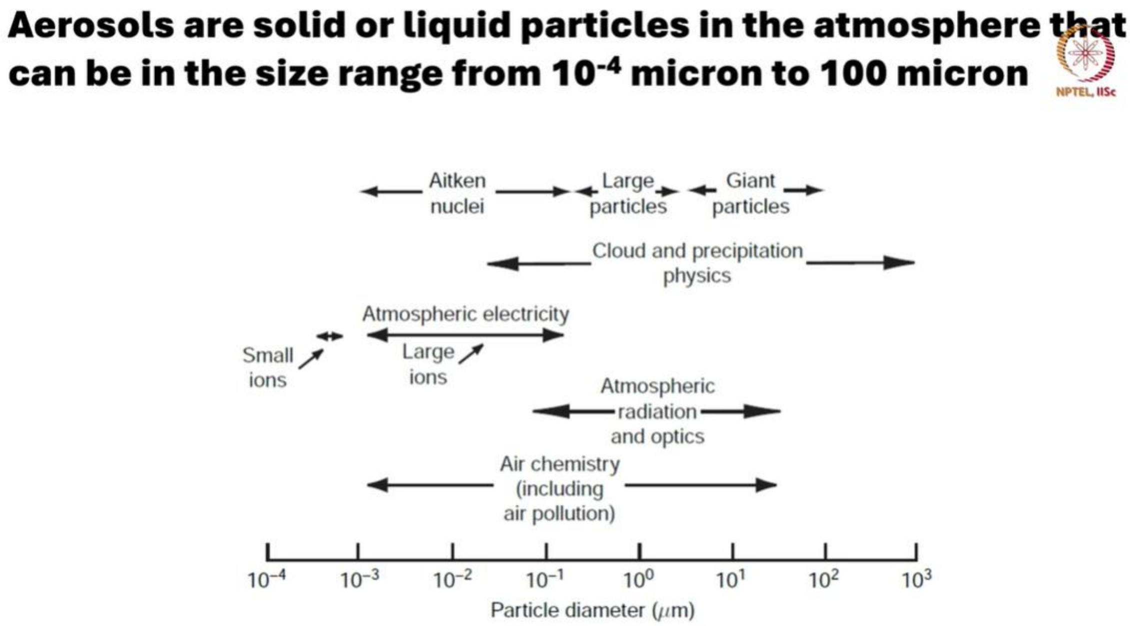
Another layer of complexity arises from their diverse chemical composition. Aerosols are not a single substance but a heterogeneous mixture that includes dust, sea salt, black carbon, sulphates, and organic compounds, each with distinct radiative and chemical properties. Some aerosols scatter sunlight and increase albedo, leading to cooling, while others, such as black carbon, absorb radiation, contributing to warming.

Because of these variabilities and their short atmospheric lifetimes, it is challenging to obtain sufficient observational data to accurately model aerosols and their climatic effects. This makes them one of the least certain factors in climate prediction models. The scientific study of aerosols and their climatic implications has significantly advanced only in the last three decades, but uncertainties remain.

This lecture will explore the varied nature of aerosols, their sources, types, and interactions with radiation and clouds, and will highlight the challenges they pose in predicting future climate change.

Aerosols encompass a broad range of particle sizes, each with unique origins, properties, and impacts. At the smallest end of the spectrum are Aitken nuclei, extremely fine particles, while at the larger end are coarse particles and giant aerosols, such as mineral dust. The size range of aerosols spans approximately from 10^{-4} microns (0.0001 μm) to 100 microns, covering an enormous variety of particle types.

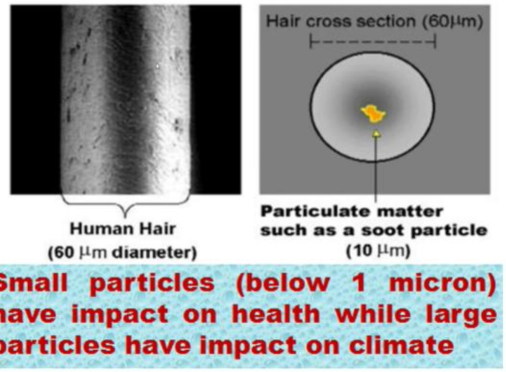
Some of these include dust particles (from deserts), soot (black carbon from combustion), sulphate aerosols (from volcanic eruptions or fossil fuel burning), organic aerosols (from vegetation or biomass burning), cloud droplets and ice crystals, which also fall under the category of atmospheric aerosols.



Aerosols are not only important for climate, but also play major roles in:

- Radiation scattering and absorption, directly influencing Earth's energy balance,
- Atmospheric chemistry, especially as surfaces for heterogeneous reactions,
- Cloud formation and lightning generation, by acting as cloud condensation nuclei (CCN) or ice nuclei (IN),
- Air pollution and human health, particularly the ultrafine particles which, when inhaled, can penetrate deep into the lungs and bloodstream, causing respiratory and cardiovascular issues.

However, the focus here is on their climatic effects. For this, the most climatically relevant aerosol size range is between 0.2 to 1 micron. These particles are efficient in interacting with solar radiation, especially in the visible spectrum, thus altering the Earth's albedo.



To put this in perspective, a human hair is about 60 microns thick. While, a typical soot particle is about 10 microns, already much smaller. Even smaller are sulphate aerosols and diesel exhaust particles, which are of concern both for climate (due to radiative forcing) and health (due to toxicity and respiratory impacts).

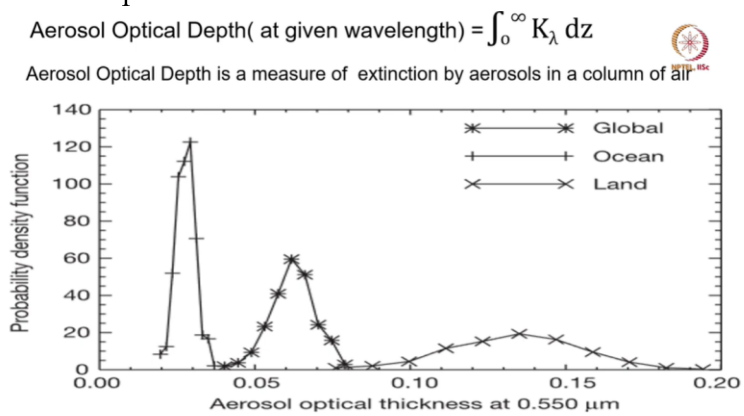
In this lecture, the emphasis remains on how these fine to coarse particles influence the Earth's climate, particularly through direct interactions with radiation and indirect effects via cloud formation.

Aerosols play a significant role in Earth’s climate system by modifying the global radiation budget through both direct and indirect effects. The direct effect involves aerosols scattering incoming solar radiation, either upward back to space or downward to the surface, as well as absorbing radiation and converting it into heat, thereby altering atmospheric temperature profiles. In contrast, the indirect effect stems from the role aerosols play in cloud formation. Aerosols act as cloud condensation nuclei (CCN), upon which water vapor condenses to form cloud droplets. Therefore, an increase in aerosol concentration can influence the number and size of cloud droplets, ultimately affecting cloud reflectivity, lifetime, and precipitation processes.

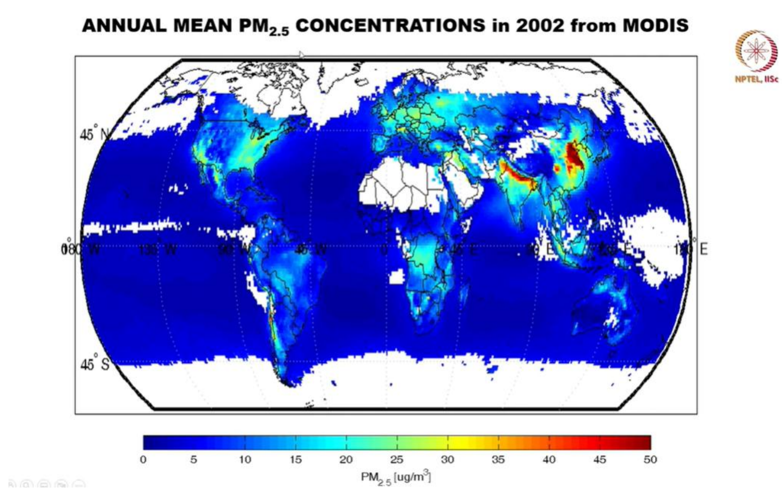
While our understanding of the direct aerosol effects under clear-sky conditions is relatively robust, the indirect effects are far more complex and uncertain. This is partly because climate models struggle to accurately represent clouds, due to limitations in model grid resolution. Since aerosols impact clouds whose behaviour is already not well captured in models, this interaction becomes a major source of uncertainty in climate projections.

To quantify aerosol influence, we often use Aerosol Optical Depth (AOD), which represents the integrated extinction coefficient (the sum of scattering and absorption) from the surface to the top of the atmosphere. Satellite observations provide estimates of AOD globally. On average, the global mean AOD is about 0.06, indicating a relatively small overall impact. However, this value varies significantly by region:

- Over land, the AOD is higher (~0.14) due to larger and more abundant particles, as land is a major source of dust, soot, and anthropogenic aerosols.
- Over oceans, AOD is lower (~0.03) since the dominant aerosols are sea salt particles and sulphate aerosols from natural emissions like dimethyl sulfide (DMS). These oceanic aerosols are smaller in size and less abundant than their terrestrial counterparts.



Thus, aerosol sizes range broadly from larger particles over land to smaller ones over the ocean, with the global average AOD settling around 0.06. This spatial variability further complicates efforts to model their climate impact accurately.



Aerosols vary widely in concentration, size, composition, and spatial distribution, making their impact on climate highly complex. Satellite observations like the one shown above have provided data on the concentration of fine particulate matter (PM2.5) - particles with diameters less than 2.5 microns - expressed in micrograms per cubic meter. Annual mean values for 2002 show the highest concentrations over the Indo-Gangetic Plain and eastern China, with values reaching around 40 $\mu g/m^3$. In contrast, oceanic regions exhibit much lower concentrations, typically in the 5–10 $\mu g/m^3$ range. Even within land regions, there is considerable variation due to local emissions and geography. Sparse data over regions like the Sahara and polar areas adds further uncertainty.

Aerosols also exist in a diverse range of chemical forms:

- Sulphates, formed from sulfur dioxide emissions by industries,
- Nitrates, originating from fertilizers,
- Sea salt, produced by ocean spray and evaporation,
- Black carbon (soot), primarily from incomplete combustion processes.

Most aerosols, such as sulphates and sea salt, scatter incoming solar radiation, especially in the shortwave part of the spectrum, leading to surface cooling by increasing the Earth's albedo. However, black carbon aerosols are an exception; they absorb solar radiation, leading to atmospheric warming while still cooling the surface by reducing the incoming solar flux.

The vertical location of these aerosols is crucial. Black carbon above clouds or snow/ice surfaces enhances absorption and contributes more significantly to atmospheric heating, while black carbon below clouds has much less climatic effect. This vertical positioning complicates the estimation of net radiative forcing due to aerosols.

Beyond climate, aerosols have important implications for human health. Fine particles, when inhaled, penetrate deep into the lungs and are linked to various respiratory and cardiovascular issues. Aerosols also affect agriculture by settling on leaves, obstructing pores (stomata), and reducing photosynthesis. Additionally, aerosols influence the monsoon system, both by modulating the solar radiation reaching the surface and by modifying cloud properties, which in turn affects rainfall patterns. These diverse and interconnected effects make aerosols a critical but challenging component in climate science.

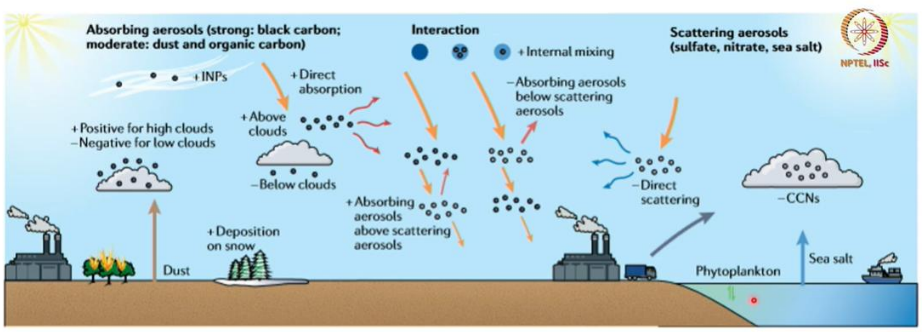


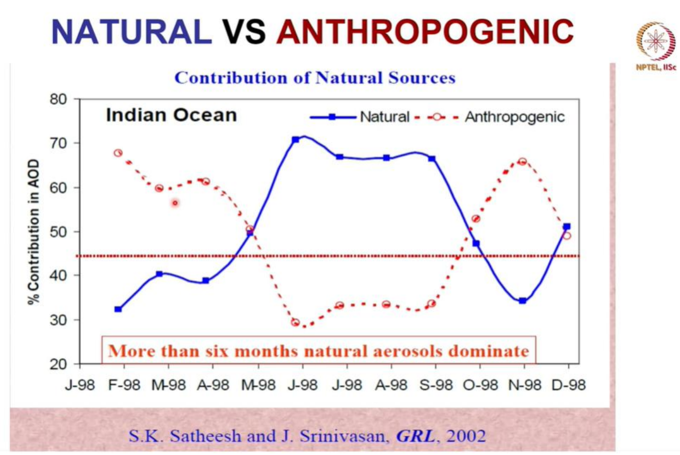
Fig. 2 | **The radiative effects of aerosols.** Schematic of radiative effects of absorbing (dark grey dots) and scattering aerosols (light grey dots), as well as their interactive effects. Scattering aerosols induce negative forcing (−) by directly reflecting sunlight and interacting with clouds; absorbing aerosols, in general, have a warming effect (+), although their interaction with clouds might produce slight cooling. The interaction between scattering and absorbing aerosols enhances the absorption and, thus, the warming effect. Light orange arrows represent incident sunlight; dark orange, scattered radiation by scattering aerosols; red, the radiation re-emitted by absorbing aerosols; and dark blue, scattered sunlight. CCN, cloud condensation nuclei; INPs, ice-nucleating particles.

Aerosols interact with the climate system through a complex network of processes involving the atmosphere, clouds, and the surface. These processes are illustrated through in the above schematic that highlights the multiple pathways of aerosol influence. Aerosols directly affect the atmosphere by scattering incoming solar radiation, thereby increasing planetary albedo and leading to cooling. Some aerosols, such as black carbon, absorb radiation, causing atmospheric warming while simultaneously reducing the energy reaching the surface, thus cooling it.

In addition to direct radiative effects, aerosols exert indirect effects by acting as CCN. When aerosol concentrations increase, they lead to a higher number of cloud droplets that are smaller in size, affecting cloud albedo (Twomey effect), lifetime, and precipitation efficiency. This modifies both cloud reflectivity and climate feedbacks.

Aerosols also influence the biosphere and cryosphere. When dust aerosols settle over oceans, they can supply nutrients like iron, stimulating phytoplankton growth and affecting the carbon cycle. Deposition of black carbon on snow and ice reduces surface albedo, accelerating melting and potentially altering surface energy budgets and hydrological cycles. Unlike long-lived, well-mixed greenhouse gases like carbon dioxide, aerosols are short-lived and spatially heterogeneous. Their concentrations and effects vary dramatically by location and time. This makes their climate impact highly variable and more regionally focused.

Aerosols originate from both natural and anthropogenic sources. Natural sources include dust from barren land, sea salt from evaporating ocean spray, and volcanic eruptions, which occasionally inject large quantities of aerosols into the stratosphere. However, over the last century, human activities have become dominant sources. These include sulphates from industrial emissions of sulfur dioxide, nitrates from agricultural fertilizers, organic carbon from biomass and vegetation processes, and black carbon from fossil fuel and biomass combustion. The growing anthropogenic contribution has made aerosols a central focus in climate science, particularly in understanding regional climate changes and uncertainties in climate modeling.



Aerosol concentrations show distinct seasonal variations, and the relative contributions of natural and anthropogenic sources vary throughout the year. Data over India reveals that natural aerosols (shown in blue) and anthropogenic aerosols (shown in red dotted lines) are generally out of phase with each other.

During the monsoon season, high wind speeds increase the presence of natural aerosols, such as dust and sea salt, which become dominant due to enhanced mobilization and transport by strong winds. In this period, human-induced aerosols decrease significantly, dropping to around 30% of total aerosol load.

In contrast, during the pre-monsoon and post-monsoon periods, particularly in winter, anthropogenic aerosols dominate. This is largely due to increased emissions from activities such as combustion for heating and cooking. Additionally, thermal inversions, a situation where temperature increases with height near the ground contrary to the normal lapse rate, trap aerosols near the surface. These inversions are common during winter and lead to a build-up of pollutants, especially in regions like North India, resulting in high aerosol concentrations.

Aerosols also differ significantly from carbon dioxide in terms of their residence time in the atmosphere. The lifetime of aerosols depends on their size:

- Large aerosols (e.g., dust particles): around 10 days
- Smaller aerosols: can remain up to 23 days
- Rain droplets (~1000 µm): only last for a few minutes

In contrast, carbon dioxide is a long-lived greenhouse gas, persisting in the atmosphere for hundreds of years. This difference is crucial: aerosol impacts are short-lived and localized, while CO_2 effects are long-term and global.

	AEROSOLS	**CO_2**
Lifetime	**~Weeks**	**~100 years**
Chemistry	**Complex**	**Known**
Spatial	**Non-uniform**	**Uniform**
Temporal	**Highly variable**	**Seasonal**
Impact	**Warming/Cooling**	**Warming**

The key distinctions and uncertainties associated with aerosols and carbon dioxide can be summarised as below:

- Lifetime: Aerosols have a short atmospheric lifetime, typically lasting from a few days to about three weeks, depending on particle size and meteorological conditions. In contrast, carbon dioxide (CO_2) is a long-lived greenhouse gas, persisting in the atmosphere for hundreds of years. This makes aerosol effects transient and regional, whereas CO_2 impacts are long-term and global.

- Chemical Complexity: Aerosols exhibit complex chemistry, with constituents such as sulphates, black carbon, organic matter, and various mixtures. Their interactions, particularly with clouds and radiation, are composition-dependent. CO_2, on the other hand, has stable and well-understood chemistry, with no variability in its molecular form.

- Spatial Distribution: Aerosols are spatially heterogeneous. Their concentrations vary significantly across regions, especially between urban and rural areas, and between land and ocean. In contrast, CO_2 is well-mixed globally, showing relatively uniform concentrations across the atmosphere.

- Temporal Variability: Aerosol concentrations show high temporal variability, especially in regions like India, where levels change dramatically between the monsoon and winter seasons due to meteorological factors and emission patterns. CO_2 also exhibits seasonal variation, primarily due to biospheric uptake and release, but this cycle is highly regular and predictable.

- Radiative Forcing: Aerosols have dual climate effects. They can cool the climate by scattering sunlight or warm the atmosphere through absorption (e.g., black carbon). CO_2, however, can only cause warming by trapping outgoing longwave radiation.

	Evidence	Agreement	Confidence Level
Well-mixed greenhouse gases	Robust	High	*Very high*
Tropospheric ozone	Robust	Medium	*High*
Stratospheric ozone	Robust	Medium	*High*
Stratospheric water vapour from CH_4	Robust	Low	*Medium*
Aerosol–radiation interactions	Robust	Medium	*High*
Aerosol–cloud interactions	Medium	Low	*Low*

The Intergovernmental Panel on Climate Change (IPCC) categorizes the level of scientific confidence and model agreement across various climate-forcing agents.

- Well-mixed greenhouse gases like CO_2, CH_4, N_2O are very well understood, with high confidence and high agreement among models and observations.

- Ozone in the troposphere and stratosphere is also relatively well understood, although with slightly lower confidence due to fewer measurements in some regions.

- Water vapor feedback from stratospheric methane oxidation is less certain, with lower confidence and limited agreement across datasets.

- For aerosol–radiation interactions (direct effects like scattering and absorption), understanding is fairly robust, but due to the diversity of aerosol types, inter-model agreement is moderate, and confidence is high but not as strong as for CO_2.

- The largest uncertainty lies in aerosol-cloud interactions (indirect effects), which remain poorly understood. This area suffers from limited observational data, low model agreement, and low confidence. These interactions significantly influence cloud formation, cloud lifetime, and precipitation, and are thus a critical area of ongoing research.

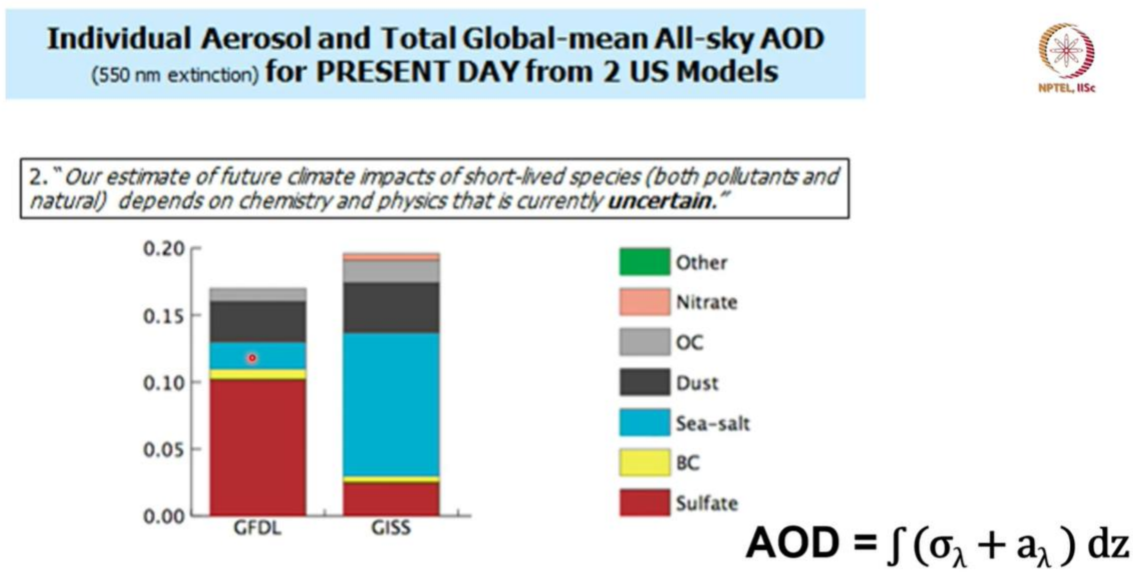
In summary, while greenhouse gases like CO_2 are well-characterized in terms of distribution, radiative impact, and longevity, aerosols present a far more complex and uncertain challenge, particularly in how they influence cloud processes. This continues to be a major focus of current climate research.

Aerosols influence the Earth's radiation budget primarily through their scattering and absorption properties. The fundamental radiative transfer equation governing this interaction indicates that the intensity of radiation traveling in a given direction (say, along the x-axis) diminishes due to two key processes: absorption, in which photons are converted into heat energy, and scattering, in which photons are redirected away from the original path. In both cases, the net result is a reduction of radiant energy in the direction of interest, affecting the amount of solar radiation reaching the Earth's surface or being reflected back to space.

To quantify the total columnar amount of aerosol in the atmosphere, scientists use a parameter known as Aerosol Optical Depth (AOD). AOD measures the integrated extinction (scattering + absorption) of solar radiation by aerosols along the vertical path through the atmosphere. It is a key indicator of aerosol loading and plays an important role in climate modeling and satellite remote sensing.

However, estimates of AOD and aerosol burden can vary significantly across different climate models, reflecting the complexity and uncertainties associated with aerosol processes. For example, comparisons between two major U.S. climate models, the Goddard Institute for Space Studies (GISS) model and the Geophysical Fluid Dynamics Laboratory (GFDL) model reveal notable discrepancies:

- Sea Salt Aerosols: GISS predicts a higher concentration of sea salt aerosols compared to GFDL, likely due to differences in wind speed parameterizations over oceans.
- Sulphate Aerosols: GFDL shows higher sulphate levels than GISS, possibly reflecting differences in SO_2 emissions, oxidation schemes, or wet removal processes.
- Dust and Organic Carbon: Both models exhibit comparable estimates for dust and organic carbon aerosols.
- Nitrate Aerosols: The GISS model includes nitrate aerosols, while the GFDL model does not, further contributing to the divergence.



These inter-model differences stem from varying assumptions regarding emission sources, aerosol composition, removal mechanisms, and process representation (e.g., cloud interactions, deposition). Consequently, aerosols remain a significant source of uncertainty in climate projections, particularly in estimating their net radiative forcing and regional impacts.

Single Scattering Albedo (SSA) is a key parameter that characterizes the radiative behaviour of aerosols. It quantifies the fraction of incident radiation that is scattered (rather than absorbed) by aerosol particles and is defined as:

$$SSA = \frac{\sigma_\lambda}{\sigma_\lambda + a_\lambda}$$

The value of SSA ranges from 0 to 1. While SSA = 1 corresponds to completely scattering aerosol (e.g., sea salt, sulphates), an SSA = 0 corresponds to completely absorbing aerosol (e.g., soot/black carbon)

The single-scattering albedo (SSA) is defined as the ratio of scattering to extinction coefficient

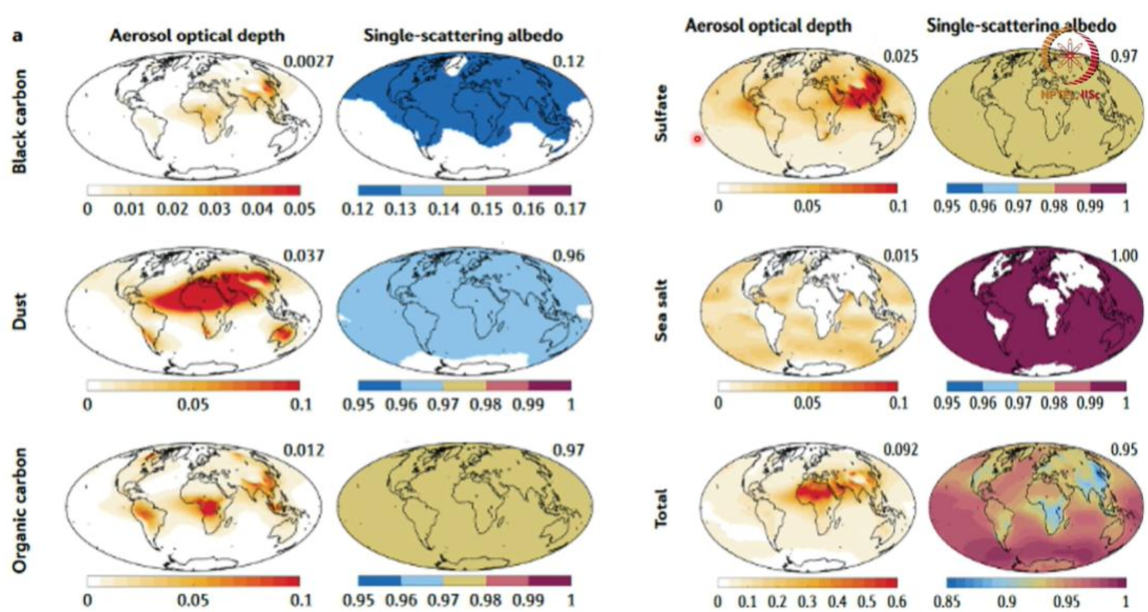
$$\mathrm{SSA} = \sigma_\lambda/\{\sigma_\lambda + a_\lambda\}$$

where σ_λ and a_λ are scattering and absorption coefficients and their sum is the extinction coefficient

Table 1 | Regional boxes used in the anthropogenic DRF estimation

	Boundaries	Anthropogenic fraction over land	AERONET site	SSA at 0.55 μm
North America	90° N-30° N 180° N-30° W	0.56 ± 0.21	GSFC (USA)	0.98 ± 0.02
Eurasia	90° N-30° N 30° W-180° E	0.54 ± 0.16	Creteil (France)	0.94 ± 0.03
Central America	30° N-0° 120° W-60° W	0.43 ± 0.11	Mexico City (Mexico)	0.90 ± 0.02
South America	30° N-90° S 180° W-30° W	0.35 ± 0.09	Brazil	0.91 ± 0.03
Africa, Oceania	30° N-90° S 30° W-180° E	0.43 ± 0.17	Mongu (Zambia)	0.86 ± 0.015
Indian Ocean	30° E-120° E 30° N-10° S	0.51 ± 0.15	Maldives	0.91 ± 0.03

The above table shows satellite observations of SSA over different regions. North America has an SSA of 0.98 indicating that aerosols there are dominated by sulphate aerosols, which scatter sunlight efficiently with little absorption. Over Africa and South America, the SSA are 0.86 and 0.91 respectively indicating higher presence of black carbon and dust aerosols which can absorb solar radiation.



The above figure provides a good overview of how AOD and SSA varies spatially as obtained from satellite. We see that black carbon aerosols have a very low optical depth and a low single scattering albedo (as they absorb a lot). Sulphate has nearly 10 times more optical depth than black carbon implying a higher fraction of sulfate aerosol in the total aerosol load. When it comes to dust, its optical depth is comparable to sulphate and its single scattering albedo is similar to sulphate. When it comes to sea salt, its amount - optical depth is little less than sulphate and is totally scattering (SSA=1). The organic carbon produced during combustion has optical depth larger than black carbon (5 times) and the single scattering albedo is 0.97, similar to sulphate. The total global AOD sums to around 0.1 and SSA of 0.95. But we see that there is lot of spatial variation in the aerosol amount.

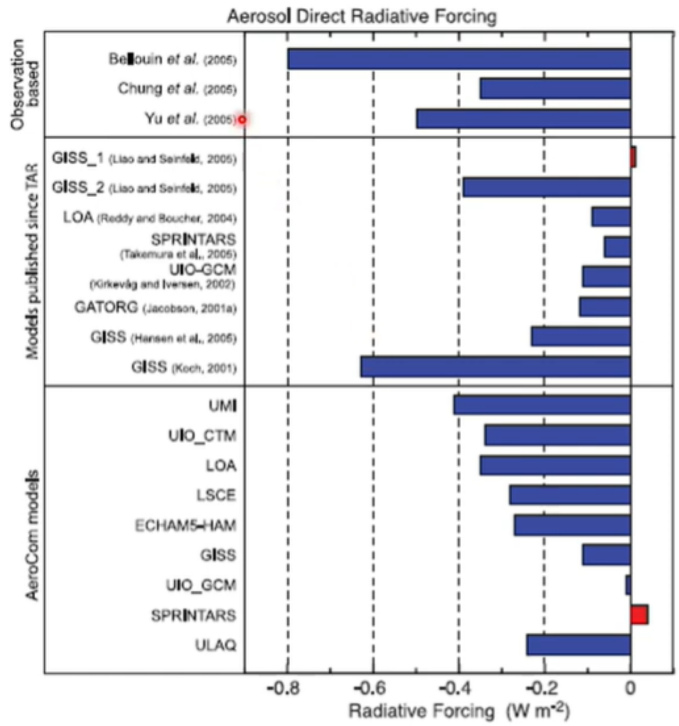
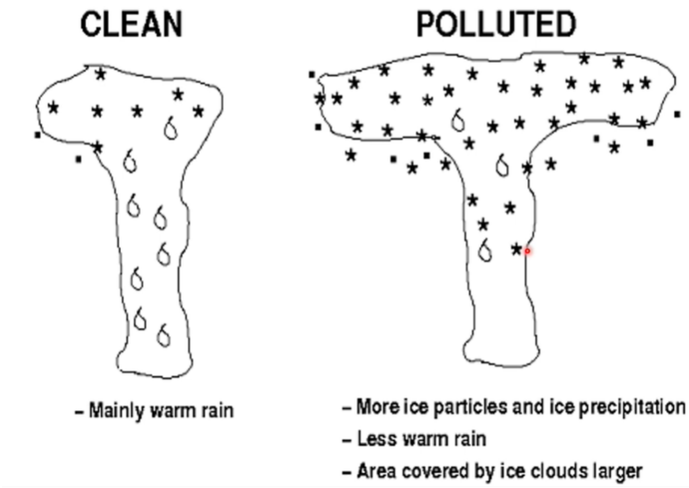


Figure 2.13. *Estimates of the direct aerosol RF from observationally based studies, independent modelling studies, and AeroCom results with identical aerosol and aerosol precursor emissions. GISS_1 refers to a study employing an internal mixture of aerosol, and GISS_2 to a study employing an external mixture. See Table 2.4, Note (a) for descriptions of models.*

Aerosols exert a direct radiative forcing (DRF) under clear-sky conditions by altering the Earth's radiation budget. This is quantified as the difference in the amount of solar radiation reflected by the atmosphere with and without aerosols. Most models estimate this forcing to be negative, indicating a net cooling effect due to increased reflection of sunlight back to space. Model estimates of DRF vary significantly, typically ranging from −0.1 to −0.4 W/m², while the Goddard Institute for Space Studies (GISS) model produces values as low as −0.6 W/m². Satellite-based observations show a broader range from −0.8 to −0.3 W/m², highlighting a notable disagreement among models and observations, which contributes to uncertainty in quantifying aerosol effects.

Aerosols influence climate both directly and indirectly. The direct effects include scattering incoming solar radiation, thereby cooling the surface, and absorbing radiation, which warms the atmosphere. The indirect effects arise through aerosol-cloud interactions, where aerosols alter cloud properties and lifetimes. These indirect effects are more complex to quantify, as they depend on whether aerosols are located above or below clouds, and on their hygroscopicity i.e., their tendency to attract or repel moisture.



For example, in a clean atmosphere with few aerosols, cloud droplets are typically larger, resulting in fewer but coarser droplets. In contrast, a polluted atmosphere with more aerosols leads to the formation of numerous smaller droplets, which may later convert to ice particles at high altitudes. This change increases the area covered by ice clouds, modifying cloud albedo and radiative properties. The extent of this transformation is governed by the hydrophilic or hydrophobic nature of the aerosols, making the indirect effects highly variable and uncertain.

The impact of aerosols on clouds is multifaceted, and due to the variety of processes involved, these are categorized under distinct effect names. The indirect effect primarily refers to the influence of aerosols on cloud microphysical properties. The first indirect effect, also known as the Twomey effect, occurs through a reduction in cloud droplet radius due to an increase in cloud condensation nuclei (CCN). The second indirect effect relates to an increase in the number of cloud droplets, which enhances cloud reflectivity and prolongs cloud lifetime.

The semi-direct effect arises when aerosols absorb solar radiation, warming the surrounding air and affecting the liquid water content in clouds, often resulting in cloud evaporation. Another mechanism is the dispersion effect, where aerosols modify the spatial distribution of cloud droplets without necessarily altering their number or size directly. The glaciation indirect effect refers to the conversion of supercooled liquid water droplets into ice crystals, altering cloud phase and radiative characteristics.

These various interactions illustrate the complex influence of aerosols on cloud structure, composition, and radiative properties. For instance, aerosols can suppress drizzle, increase cloud height, and extend cloud lifetime. Such modifications are shown schematically in the below illustration.

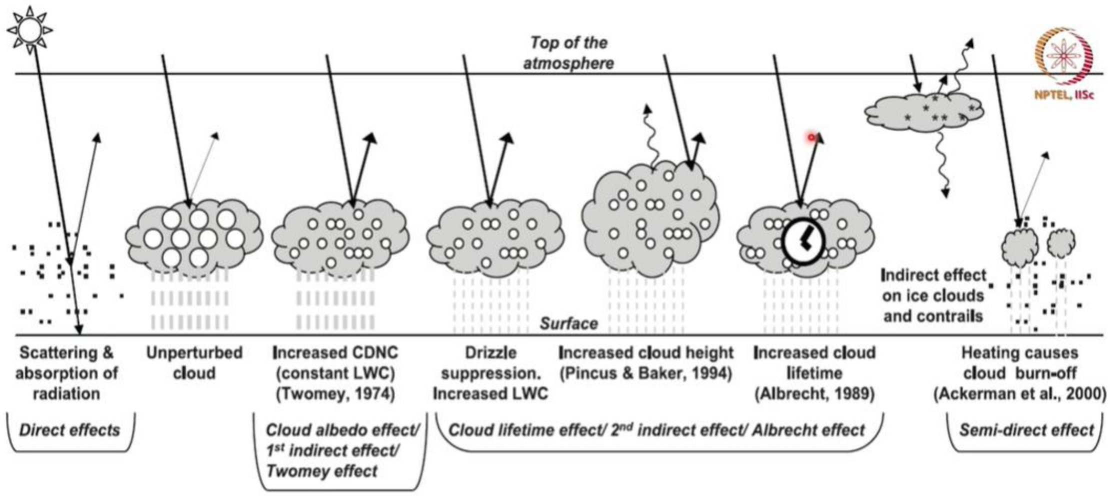
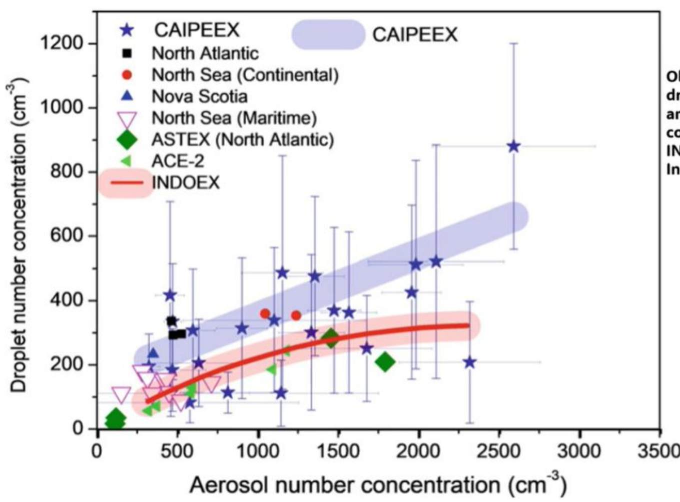


Figure 2.10. *Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols (modified from Haywood and Boucher, 2000). The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.*



Observations of cloud droplet number concentrations and associated aerosol number concentrations with data from INDOEX and CAIPEEX over the Indian continental region

This complexity is further reflected in observational data. Field experiments across different oceanic regions, such as the Atlantic and Indian Oceans, show that cloud droplet number concentration generally increases with increasing aerosol particle concentration. However, the magnitude of the response differs across regions, underscoring spatial variability and the challenges models face in capturing aerosol-cloud interactions accurately. These complexities contribute to significant variability among climate model simulations of aerosol impacts on clouds and climate.