AEROSOLS AND CLOUDS

Climate refers to long-term atmospheric patterns, while weather describes short-term conditions. Satellites have improved weather forecasts by collecting data over time, and studying climate requires analysing clouds and aerosols, which play crucial roles in Earth's climate system.

Clouds regulate Earth's temperature by either reflecting solar energy, causing cooling, or trapping emitted energy, leading to warming.

Aerosols, tiny particles suspended in the atmosphere, influence sunlight's reflection and absorption, affecting cloud brightness, coverage, and climate in complex, not fully understood ways.

AEROSOLS

Even if the air appears clear, it contains millions of tiny solid particles and liquid droplets called aerosols, which are present across all ecosystems. These particles, which can be found everywhere from deserts to oceans, range in size from tiny nanometres to the width of a human hair. Despite their small size, aerosols significantly impact both our climate and health.

Aerosols are categorized by specialists based on their size, shape, and chemical composition. Terms like PM2.5 or PM10 (particulate matter) are used to describe their size, while everyday names like smoke, ash, and soot hint at their sources.

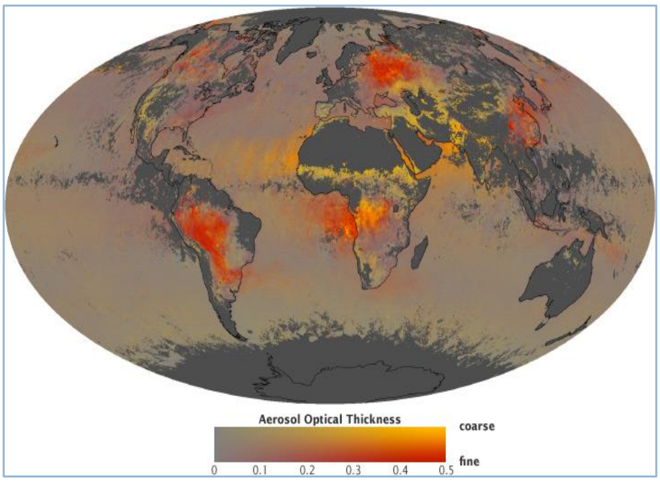
Climatologists classify aerosols into groups such as sulphates, organic carbon, black carbon, nitrates, mineral dust, and sea salt. These particles often mix together, forming complex combinations like soot coated with sulphates or dust.

About 90% of aerosols come from natural sources, like volcanic ash, forest fire smoke, sea salt from ocean spray, and dust from deserts. Even plants and ocean algae contribute to aerosol production through chemical reactions.

The other 10% are human-made, mostly from industrial activities like fossil fuel combustion, deforestation, and agriculture. These anthropogenic aerosols are common in urban and industrial areas, with vehicles, factories, and even indoor activities like cooking and smoking adding to the mix.

PATTERNS

From space, Earth's aerosols show distinct patterns driven by both natural and human activities. Natural aerosols, like sea salt and dust, form large detectable swaths over oceans and deserts. For instance, the winds near Antarctica generate a heavy band of airborne salt, while dust plumes rise from deserts around the world.



This map shows the global distribution of aerosols and the proportion of those aerosols that are large or small. Intense colours indicate a thick layer of aerosols. Yellow areas are predominantly coarse particles, like dust, and red areas are mainly fine aerosols, like smoke or pollution. Gray indicates areas with no data.

Human-made aerosols are concentrated in urban and industrial areas, particularly in the eastern U.S., Europe, and rapidly growing cities in Asia. Cities like New York, London, and Berlin produce significant industrial aerosols, mainly sulphates from power plants and carbon from vehicles.

In the western U.S., places like Los Angeles suffer from a mix of industrial pollution, dust, and wildfire smoke. Meanwhile, Asia, especially regions like the Indo-Gangetic Plain and eastern China, has some of the most aerosol-laden air, driven by dust and pollution, especially during pre-Monsoon season.

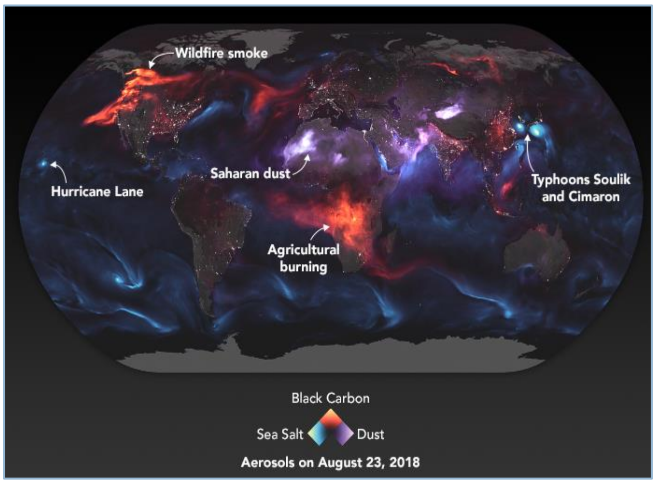
Although, most aerosols have short life span (4 days to a week), they can travel long distances, crossing oceans and continents. Dust from the Sahara reaches the Caribbean, and aerosols from Asia cross the

Pacific. Wildfire smoke from places like Siberia and Canada can even reach the Arctic.

Over time, aerosol emissions have changed. While industrialization in Asia has increased emissions, aerosols have decreased in North America and Europe due to stricter clean air regulations.

AEROSOL ON EARTH

Aerosols come from various sources such as wildfires, volcanic eruptions, and dust storms. Satellites like Terra, Aqua, Aura, and Suomi NPP, along with NASA's GEOS FP model, offer a comprehensive view of these particles from space.



A visualization of GEOS FP model output on August 23, 2018, shows significant aerosol activity: smoke plumes over North America and Africa, three tropical cyclones in the Pacific, and dust clouds over African and Asian deserts. Sea salt aerosols (blue) were lifted by winds over the ocean, black carbon (red) came from fires and industrial emissions, and dust (purple) swirled through deserts. Nightlight data from VIIRS on Suomi NPP shows the location of cities.

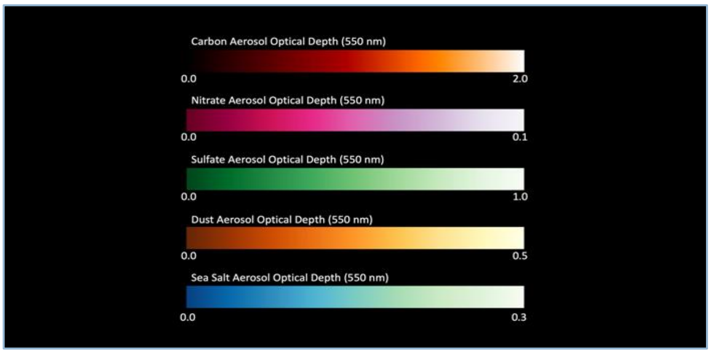
The model, which incorporates satellite data and ground measurements, simulates atmospheric conditions using inputs like temperature, moisture, and aerosols. MODIS data from Aqua and Terra helped track fire locations and intensities to model black carbon behaviour. On this day, Hurricane Lane threatened Hawaii with floods, and twin tropical cyclones Soulik and Cimaron neared South Korea and Japan. Smoke over North America came from large wildfires, while smoke over Africa was from seasonal agricultural fires.

GLOBAL TRANSPORT OF SMOKE FROM AUSTRILIAN BUSHWIRES

This visualization, based on NASA's GEOS-FP data assimilation system, shows the global distribution of aerosols from August 1, 2019, to January 14, 2020, released by Australia's extreme bushfires and transported over the South Pacific Ocean. Different aerosol types are color-coded: dust (orange), sea-salt (blue), nitrates (pink), sulphates (green), and carbon (red), with brighter regions indicating higher aerosol concentrations.

NASA's MODIS observations captured biomass burning regions and aerosol optical depths, highlighting the Australian bushfires and downstream aerosol transport. It also shows weather events like Hurricane Dorian and major fire outbreaks in South America and Indonesia during the same period.

The Australian bushfires caused devastating local impacts and extreme air quality issues, with smoke plumes transported globally due to deep vertical movement into the upper troposphere and lower stratosphere , eventually circumnavigating the globe over the Southern Ocean and returning to Australia, with pronounced effects across the southern Pacific Ocean and South America.

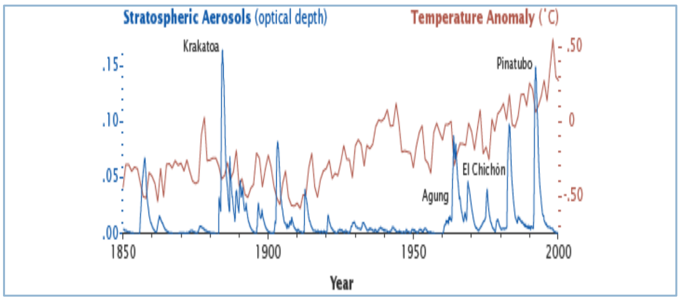


AEROSOLS & SUNLIGHT

The Sun drives Earth's climate, but not all of its energy reaches the surface due to aerosols and clouds that reflect about 25% of solar energy back into space. These aerosols vary in their ability to scatter or absorb sunlight based on their physical properties, creating a complex "direct effect" on Earth's radiation field.

Most aerosols reflect sunlight, but some, like black carbon, absorb it. Bright or translucent aerosols typically scatter light, while darker particles tend to absorb it. Pure sulphates and nitrates reflect nearly all radiation, cooling the atmosphere, whereas black carbon warms it by absorbing radiation. Organic carbon's (brown carbon or organic matter) impact on warming depends on the brightness of the surface beneath it. Dust's effects vary based on its mineral composition and whether it's coated with black or brown carbon.

A significant example of aerosols affecting climate occurred in 1991, when the eruption of Mount Pinatubo released over 20 million tons of sulphur dioxide, creating sulphate aerosols high in the atmosphere. This resulted in a temporary global temperature drop of about 0.6°C for two years. Such large eruptions that can alter temperatures happen approximately once a decade.



Large volcanic eruptions may lift sulphate aerosols into the stratosphere, which usually cools the global climate for the following year or two.

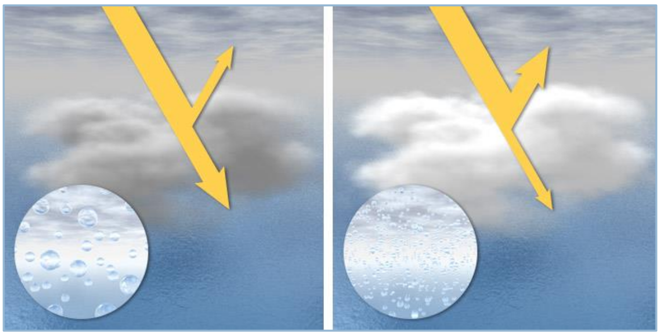
Aerosols also influence the planet's reflectivity, or albedo. Bright surfaces like sea ice reflect more radiation and cool the climate, while darker surfaces like oceans absorb more and warm the climate. Aerosols, particularly black carbon, can darken ice and other bright surfaces, contributing to accelerated melting, especially in the Arctic.

Overall, scientists believe that the cooling effect of reflective aerosols, such as sulphates, has counteracted about half of the warming caused by greenhouse gases since the 1880s. However, aerosols are not evenly distributed, leading to more significant regional impacts. Despite advancements in research, accurately estimating the direct climate effects of aerosols remains a developing field, with many climate models still primarily focused on sulphates.

AEROSOLS & CLOUDS

Aerosols influence climate not only by scattering light and changing Earth's reflectivity but also through their effects on clouds. These "indirect effects" generally lead to cooling, contrasting with the warming caused by greenhouse gases. While greenhouse gases are evenly dispersed, aerosol effects vary based on their interaction with clouds.

Clouds form when water vapor condenses around tiny particles known as cloud condensation nuclei, with natural aerosols like sulphates and sea salt acting as these seeds. In polluted air, higher concentrations of water-soluble particles lead to smaller cloud droplets, making polluted clouds brighter and more reflective. This brightness reflects more sunlight, cooling the planet through what's called the "cloud albedo effect."



Clouds in clean air are composed of a relatively small number of large droplets (left). As a consequence, the clouds are somewhat dark and translucent. In air with high concentrations of aerosols, water can easily condense on the particles, creating a large number of small droplets (right). These clouds are dense, very reflective, and bright white. This influence of aerosols on clouds is called the "indirect effect," and is a large source of uncertainty in projections of climate change.

The impact of aerosols on cloud brightness can be seen in ship tracks, where exhaust from ships creates bright streaks in marine clouds. Clouds already shade about 60% of Earth's surface, and a 5% increase in their reflectivity could offset the warming effects of greenhouse gases from the industrial era. However, aerosols are unevenly distributed, so their effects do not simply counteract those of greenhouse gases.

Aerosols can also affect precipitation. Generally, they suppress rainfall by reducing droplet size, but in certain conditions, they can create taller clouds that lead to more thunderstorms. The type of aerosol is crucial; while reflective aerosols enhance cloud brightness, black carbon from soot can warm the atmosphere and cause cloud droplets to evaporate, resulting in haze and reduced rainfall.

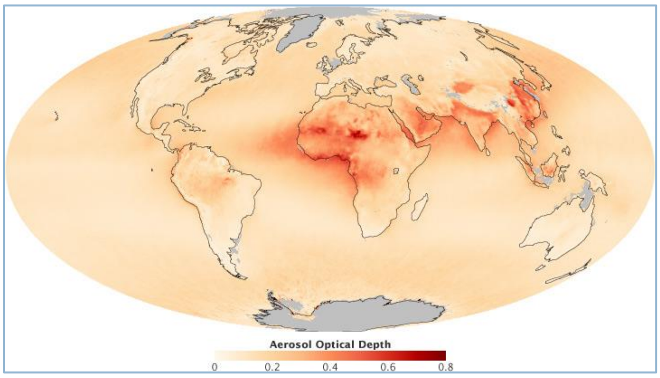
Current estimates suggest that aerosol indirect effects cool the climate by less than half the warming caused by greenhouse gases, but these effects vary greatly over space and time. Understanding these indirect effects is challenging, as instruments struggle to measure aerosols within clouds.

Consequently, the role of clouds remains one of the largest uncertainties in climate prediction, with less than a third of climate models in the Fourth Intergovernmental Panel on Climate Change (IPCC) accounting for aerosol effects, mainly focusing on sulphates.

MEASURING AEROSOLS

About 40 years ago, scientists recognized that aerosols could influence climate, but the measurements necessary to quantify their effects were insufficient. Fortunately, advancements have been made. Today, scientists utilize a variety of satellite, aircraft, and ground-based instruments to monitor aerosols, with radiometers being among the most vital tools.

They measure aerosol optical depth (AOD), which indicates the amount of light that aerosols scatter and absorb. An AOD of less than 0.05 signifies a clear sky, while a value of 1 indicates hazy conditions, and values above 2 or 3 represent very high aerosol concentrations.



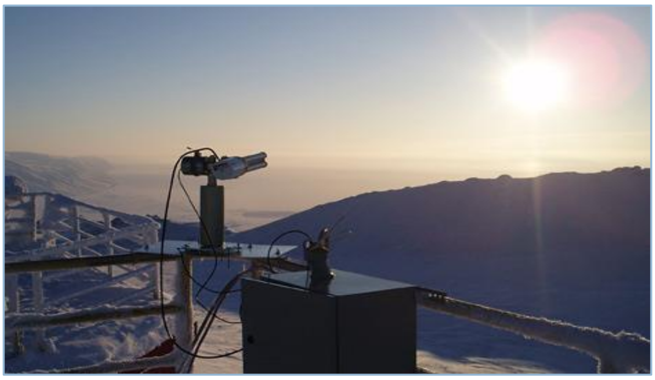
This map shows the average distribution of aerosols from June 2000 through May 2010, measured by the Multi-angle Imaging Spectroradiometer (MISR). Red indicates high concentrations of aerosols, beige indicates low concentrations.

They also measure single scattering albedo (SSA), the fraction of light that is scattered compared to he total. SSA values ranges from around 0.7 for highly absorbing aerosols to 1 for aerosols that only scatter.

The Advanced Very High Resolution Radiometer (AVHRR) was the first satellite instrument capable of monitoring aerosol optical depth from space, starting in the late 1970s. Since then, instruments like the Multi-angle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) have improved capabilities, allowing for more accurate assessments of aerosols over land and sea.

Additional instruments, such as the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observer (CALIPSO) and the Aerosol Polarimeter Sensor (APS), provide detailed insights into aerosol properties, including vertical profiles and particle types.

While satellites offer a global perspective on aerosol impacts, ground-based sensors are essential for validating satellite data. NASA's Aerosols Robotic Network (AERONET), which includes over 200 sun photometers, measures aerosol optical depth worldwide. In situ instruments aboard aircraft and ground stations provide accurate measurements of specific aerosol properties, albeit less frequently.



Land-based and airborne instruments complement NASA's satellites. AERONET is a global network of sun photometers that measures aerosols from the ground, such as this station in the Canadian Arctic (top).

Despite these advancements, significant questions remain regarding aerosols' competing impacts. Measuring particles within clouds is particularly challenging, as different aerosol types can form complex hybrids. Additionally, variations in humidity and temperature can significantly alter aerosol behaviour and interactions with cloud droplets.

To address these uncertainties, it is crucial to enhance the precision of aerosol measurements and properties. Improved data collection and sophisticated computer modelling are essential for fully integrating aerosol effects into climate models, thereby reducing uncertainties about future climate change.