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Aerosols: Are They Beneficial or Harmful?

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Fine particles and gases are constantly injected into the atmosphere. Particles can be formed via chemical reactions with the gases injected into the atmosphere. Their source can be natural or man-made. The particle sizes range from a few hundredths of a millimeter to a few nanometers (millionths of a millimeter). Depending on their size and the atmospheric conditions, they remain in the atmosphere typically between a few hours up to a few years for those injected into the stratosphere (above 10 km altitude). Particle suspensions in the atmosphere other than clouds[1], are called aerosols.

Natural aerosol emissions

The natural sources of aerosols are numerous and diverse. The aerosols emitted may be mineral or organic.

- Volcanoes are powerful ash emitters, along with various gases that can be injected all the way up to the stratosphere. Some of these gases react with the atmosphere and form particles. The reaction of Sulfurous oxide (SO2), for example, produces sulfate aerosol.
- Forest or savanna wildfires, naturally ignited by lightning, generate smoke and soot particles (organic compounds and carbon).
- Wind erosion, particularly active in deserts, sends soil particles into the atmosphere. This is the origin of the "Sahara sand" clouds that the wind occasionally brings to Europe.
- Ocean spray is a source of salt aerosols. The oceans also emit sulfur compounds (dimethyl sulfide) which are generated by phytoplankton and oxidized to produce sulfate aerosols.
- Forests also are a source of volatile organic compounds, which react with the atmosphere to form aerosols.

Man-made aerosol emissions

Human activities generate many aerosols

- The primary man-made source of aerosols is the combustion of carbon compounds. The use of fossil fuels (coal, oil, natural gas) produces numerous aerosols: carbonaceous aerosols, sulfate aerosols due to the presence of sulfur in these fuels; biomass combustion, to produce heat; burning forest, agricultural or savannah land for slash-and-burn agriculture. As with natural fires, those caused by man obviously generate aerosols.
- Standard intensive agriculture also is a source of aerosols. Pesticide and fertilizer spreading induces aerosol emissions. Aerosols are also formed by the chemical transformation of sprayed products. Bare soil can also be the cause of dust aerosol emissions through wind erosion, as was observed in the United States in the 1930s with the catastrophic dust bowl.
- Aerosols are emitted in mechanical friction: wear and tear on vehicle brakes during mechanical braking, wear and tear on tires as they travel over the road, clutch wear, etc.

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[1] Clouds behave very differently from aerosols, because of the thermodynamic properties of water.

- Work in quarries and other earth-moving activities emit dust.
- Industrial and domestic sprays ("aerosol" cans) are obviously sources of aerosols.

What do aerosols become once they are in the atmosphere

The particles injected in the atmosphere are subject to transformations.

Two examples:

- The oxidation of sulfur compounds to form sulfates as mentioned above.
- Hygroscopic particles act as nuclei for the condensation of water vapor, and thereby constitute the basis of cloud formation.

Aerosols do not stay where they are formed. They are borne by winds that can transport them over thousands of kilometers, as in the case of Sahara sands as mentioned above.

Aerosols remain in the atmosphere for a limited duration. Their residence time depends on several parameters.

- The atmospheric conditions: the main driver of aerosol loss is precipitation (rain, snow).
- In the absence of precipitation, they drop naturally under the effect of gravity, more or less rapidly depending on the geometry of the particles, which determines the air resistance to their fall.

Aerosols and climate

The physical and chemical properties of aerosols make them key players in the climate machine. Aerosol particles can act directly on the radiation balance[2]. They can also affect the environment in ways that have an indirect impact on the climate.

Direct effects of aerosols on the climate

The particles form a screen that scatters and/or absorbs part of the sun's radiation, preventing it from reaching the earth's surface. Depending on their type, particles predominantly absorb or scatter the solar radiation. Their effect on the climate will be very different.

- Aerosols that predominantly absorb solar radiation

Soot particles, formed by the combustion of carbon compounds, strongly absorb solar radiation, reducing the amount that reaches the surface. They thus have a cooling effect on the climate. But the surplus heat resulting from the radiation absorbed is communicated to the surrounding atmosphere, locally altering its balance.

- Aerosols that predominantly scatter solar radiation

Scattering occurs when the incident radiation is reflected in more or less all directions, like with frosted glass. Part of the radiation is sent back to space, and does not contribute to heating the earth's surface. In this way, scattering aerosols have a direct cooling effect on the climate.

Indirect effects of aerosols on the climate

Water vapor contained in the atmosphere can condense only in the presence of impurities. Hygroscopic particles act as a condensation nucleus for atmospheric water vapor, producing water droplets or small ice crystals depending on the local temperature. These eventually form clouds. Thus, the presence of aerosols facilitates cloud formation.

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[2] The radiation balance is the difference between the energy supplied by the sun's rays and the energy radiated back to space by reflected solar radiation and infrared radiation emitted by the Earth.

Water droplet clouds reflect a fraction of the sun's rays back to space, reducing the amount of heat brought to the earth's surface. They have a cooling effect on the climate.

- The impact of aerosols on clouds
    - For an equal amount of liquid water, a cloud composed of many small droplets reflects more solar radiation. The presence of aerosols increases droplet formation, which in turn increases the cloud's reflectivity and therefore its cooling effect.
    - For the same initial quantity of water vapor, the number of water droplets increases with the number of aerosol particles, so their size decreases. A water cloud disappears by precipitation when the water droplets it contains are heavy enough to overcome the air's resistance to their fall. Droplets formed on condensation nuclei must coalesce (agglomerate) before they can fall. The smaller the initial droplets, the longer this process takes. The aerosols thus increase the longevity of the cloud. This increases the cloud's cooling effect.
- Terrigenous aerosols (desert sands and others) can be transported thousands of kilometers. They contribute minerals which play an important role in some carbon sinks.
    - For example, the sand from the Sahara that reaches the Amazon rain forest, provides the phosphates it needs to grow. In this way, the aerosols contribute to the carbon sink that this vast forest represents.
    - Deposits of terrigenous aerosols on the oceans are a valuable source of iron which is essential for phytoplankton. Phytoplankton consume dissolved carbon dioxide. They reduce the partial pressure of dissolved carbon dioxide, which increases the ocean's CO_2 uptake, thus playing an essential role in the ocean's capture of the CO_2 injected into the atmosphere by human activities.
- According to some authors, aerosols also play a role in hurricane formation. As we have seen, in the presence of aerosols, the earth's surface is heated less by the sun. Aerosols can thus moderate ocean surface temperatures. A high surface water temperature (above 27°C) is a prerequisite for the transformation of tropical storms into hurricanes, and for an increase in hurricane power. Aerosols would then have a limiting effect on the formation and power of hurricanes.
- Soot aerosol deposits on snow or ice reduce the surface's reflectivity, making it more absorbent to solar radiation. This has a warming effect.

Summing up the impact of aerosols on global warming.

Aerosols are emitted sporadically, and their spatial and temporal distributions fluctuate widely. It is not possible to measure them continuously over the entire globe, and it is impossible to predict future emissions. In order to determine the effects of aerosols on the climate on a global scale, aerosol input to models cannot rest on observations alone but has to be complemented with realistic assumptions on their emissions. Under such conditions, model results are obviously fraught with uncertainty. By using a set of models with different assumptions, we can estimate the global effects of aerosols and quantify the associated uncertainties.

Overall, the cooling effects of tropospheric aerosols far outweigh the warming effects.

Stratospheric aerosols act as a cooling screen, as illustrated by the eruption of Pinatubo in 1991. This volcano ejected its cloud of gas and ash up to a 34 km altitude, into the stratosphere. The large quantities of ejected sulfur dioxide were transformed into sulfates. The absence of precipitation and the stratification of the air in the stratosphere mean that the aerosol remains there for a long time (over 2 years) before falling back to earth under gravity. This is more than enough time for the aerosol to spread across the globe in terms of longitude and latitude thus affecting the entire globe. The shielding effect of the aerosol significantly limited the flow of solar radiation reaching the lower layers of the atmosphere, resulting in a 0.6°C drop in global surface temperature for 2 years. Some suggest that such a process could be used to temporarily limit global warming by injecting sulfate particles into the stratosphere[3], an action that falls under geoengineering...

Year	Aerosol-radiation Interactions	Cloud-aerosol Interactions	Soot carbon on snow	Total Human-made forcing	Total Natural Forcing	Total Forcing
1920	-0,10	-0,43	0,03	0,23	0,20	0,43
1930	-0,11	-0,46	0,03	0,26	0,21	0,48
1940	-0,15	-0,52	0,03	0,29	0,23	0,52
1950	-0,15	-0,55	0,03	0,35	0,24	0,59
1960	-0,25	-0,73	0,04	0,26	0,27	0,54
1970	-0,38	-0,92	0,052	0,29	0,13	0,42
1980	-0,41	-1,04	0,06	0,66	0,19	0,86
1990	-0,38	-1,05	0,07	1,17	0,24	1,42
2000	-0,30	-0,92	0,07	1,74	0,29	2,02
2010	-0,27	-0,99	0,08	2,10	0,13	2,23
2015	-0,23	-0,89	0,08	2,47	0,14	2,61
2019	-0,22	-0,84	0,08	2,72	0,12	2,84

Table 1 – Radiative[4] forcing between 1920 and 2019 in W/m^2. Direct and indirect (via interactions with clouds) aerosol forcings are compared. The table also shows total forcing (including greenhouse effect...), natural and human-made forcing.

Over decades, the impact of aerosols on the climate was poorly quantified. It was only in the mid 1990s that aerosols were included in the global climate models. Their cooling effect explains why global warming turned out to be lower than expected given the increase of greenhouse gases alone (see Table 1). According to some experts, the high temperatures observed in 2023 and 2024 could be partly due to the fact that the regulation limiting the amount of sulfur contained in maritime transport fuels was implemented.

According to the 2021 IPCC report, aerosols could have limited the earth surface temperature increase by 0.4°C from the early years of the industrial era to 2020.

Globally, aerosols have contributed to mitigating global warming. Without them, it would be about 40% higher.

Unfortunately, aerosols also have very harmful effects. Some particulate deposits on vegetation disrupt its functions. More importantly, aerosols are a major factor in important health issues.

[3] Injecting sulfates into the stratosphere would require scrupulous upkeep of the stratospheric stockpile of these particles, or else the global surface temperature would rise sharply. In addition, there is a risk of harmful side-effects that are difficult to estimate with sufficient precision.

[4] When a change in the environment upsets the balance between radiation incident on the Earth and radiation leaving the Earth, the difference induced between incoming and outgoing flux is called radiative forcing. Positive forcing leads to warming.

Impact of aerosols on health

Aerosols enter the body by inhalation. While the larger particles are stopped in the superior respiratory tract, finer particles reach the lungs. Particles smaller than 10 microns can penetrate various organs and the blood stream to be propagated in the entire organism, including the brain.

These particles can undergo chemical transformations. This is the case, in particular, of oxidizing particles the majority of which are man-made. Inflammatory reactions ensue. These can have a minor effect in the short term: eye irritation, respiratory tract irritation with coughing, sneezing, runny nose, shortness of breath. The long term effects are much more serious, such as: asthma, coughing and chronic bronchitis, cardiovascular disease, stroke, even cancer.

The aerosol particles that we inhale can carry toxic chemical compounds or viruses. Indeed, aerosols have contributed significantly to the propagation of COVID.

According to official bodies (WHO, Paul Scherrer intsitute) aerosols cause 7 million premature deaths worldwide each year, including over 4 million in urban and rural areas alone. In France, 40 000 persons aged 30 or more die each year because of aerosols.

The benefits of emissions reductions

Global warming must be limited. It is just as essential to improve air quality. For the climate, greenhouse gas emissions must be reduced. For the air quality, the emissions of aerosols and some gases must be reduced. This is sketched in Figure 1, based mainly on a schematic from the IPCC AR6 report. This figure clearly shows the severity of the dilemma: the reduction of emissions required to protect human health has multiple effects, some beneficial, some harmful for climate warming mitigation.

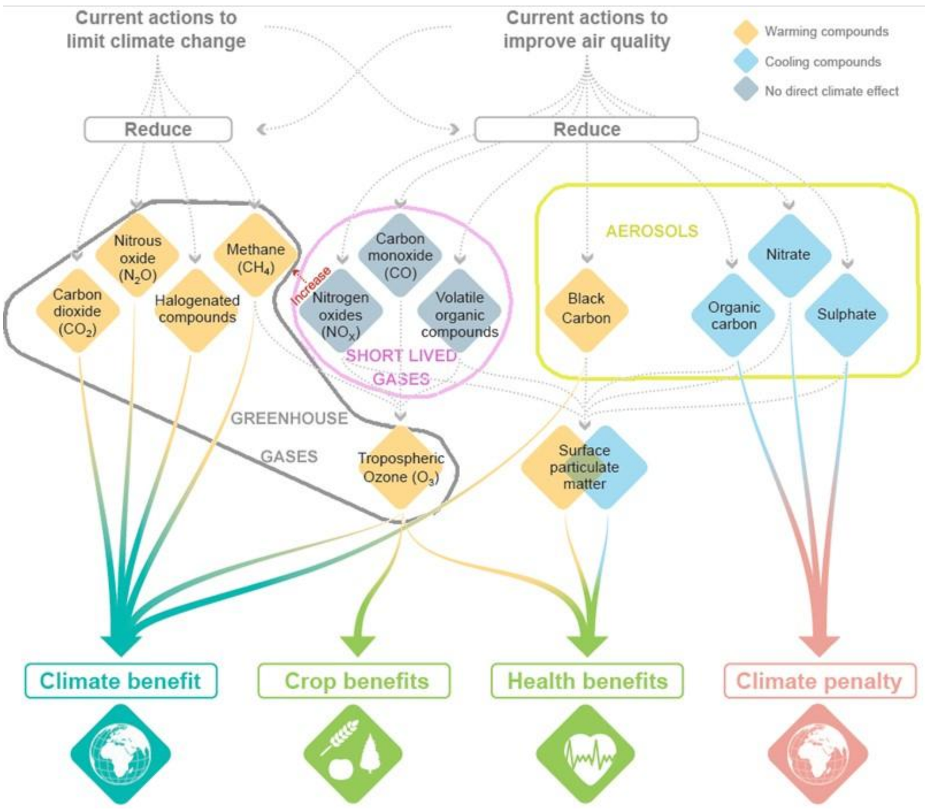

Figure 1: In the fight against climate warming and atmospheric pollution, an emissions reduction that benefits one of the issues can be harmful for the other.

Carbon dioxide and pollutant emissions cannot be systematically considered separately.

In some cases, reducing CO2 emissions results in increased pollutant emissions. This is the case, for example, with heating based on biomass grown and exploited in such a way that the CO2 emissions balance is zero: the carbon emitted in combustion is that which has been fixed by the plant during its growth. If the plant has been specially planted to be burned, the carbon balance over the period covering plant growth and combustion is indeed zero. But the combustion of biomass emits numerous pollutants in gaseous or aerosol form, with health effects that can be highly detrimental.

Another case was mentioned above, it relates to maritime transport. In order to reduce pollution, the sulfur content of maritime fuels has been capped so as to reduce their sulfate emissions. This has no direct effect on CO2 emissions but results in a reduction of the screening effect of solar radiation, doing away with a cooling effect which mitigates the greenhouse effect.

Favorable situations also occur, where the two reductions go hand in hand. A combustion engine vehicle emits both. The combustion of fossil fuels as well emits both CO2 and aerosols. In such cases, the thing to do is substitute to that system a different one that renders the same services but does not emit greenhouse gases or aerosols. Using electricity for transportation and heating is thus a good choice provided the electricity is produced with no carbon dioxide of aerosol emissions.

So then, what is to be done?

The health effects of aerosols are particularly harmful. The presence of toxic aerosols in the atmosphere must be drastically suppressed. However, as we know, doing so removes an efficient means to reduce climate warming. Yet, the cooling effect of aerosols cannot serve as a pretext to expose millions of people to premature death every year. To move in the right direction, the two battles must be undertaken in parallel: limit any emissions that can generate aerosols, while limiting greenhouse gas emissions.