FORCeS

Is there a conflict between the clean air goals of the European Green Deal and climate neutrality?

This policy brief will answer:

- Why is there a potential conflict between the climate and clean air goals?
- What is known about the cooling and warming effects of aerosol particles?
- What is the relevance for policy?

The ultimate aim of the FORCeS project is to understand and reduce the long-standing uncertainty in anthropogenic aerosol radiative forcing. This is crucial if we are to increase confidence in climate projections.

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Executive summary

- Reducing atmospheric aerosol particle concentrations is urgent in many parts of the world to improve air quality and public health.
- At the same time, aerosol particles affect temperature as well as regional patterns of winds and precipitation and hence the livelihoods of millions of people.
- Aerosol particles cool the climate. Therefore, concentration reductions may imply a "climate penalty" in terms of an unveiling of the anthropogenic greenhouse warming.
- The magnitude of the climate penalty from reducing aerosol particles is highly uncertain, but it does not undermine the fact that the most important policy measure for climate action is reduced carbon dioxide emissions.
- It is likely that most of the climate penalty due to aerosol particle reductions has already been taken.
- Recent research suggests that future aerosol particle reductions will result in a relatively small climate penalty (less than 0.5°C). However, any climate effect may still have drastic consequences for predicting the near-term climate evolution and the success of the European Green Deal and the Paris Agreement.

Why is there a potential conflict?

Science plays a pivotal role in supporting the societal transformation towards a sustainable future. The United Nations (UN) has agreed on 17 Sustainable Development Goals (SDG) and intends to reach them by 2030[1]. As a part of the European contribution in reaching the UN SDGs, the European Commission has launched the European Green Deal for reaching a carbon neutral and environmentally sustainable, yet prosperous economy. The Green Deal calls for coherent policies on climate, environment and energy with the overarching goal of climate neutrality by 2050. **Anthropogenic emissions of aerosol particles[2] sit at the crossroads of these policies, as they have adverse effects on human health and ecosystems while they at the same time dampen the warming effects of increasing greenhouse gas emissions (Fig. 1).**

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[1] UN General Assembly, Transforming our world: the 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1, available at: *https://www.refworld.org/docid/57b6e3e44.html*.

[2] We here refer to a suspension of a solid or liquid particle in the air as "an aerosol particle". Aerosol particles are either emitted directly into the atmosphere or they are formed through gas-to-particle conversion from precursor gases emitted from various sources.

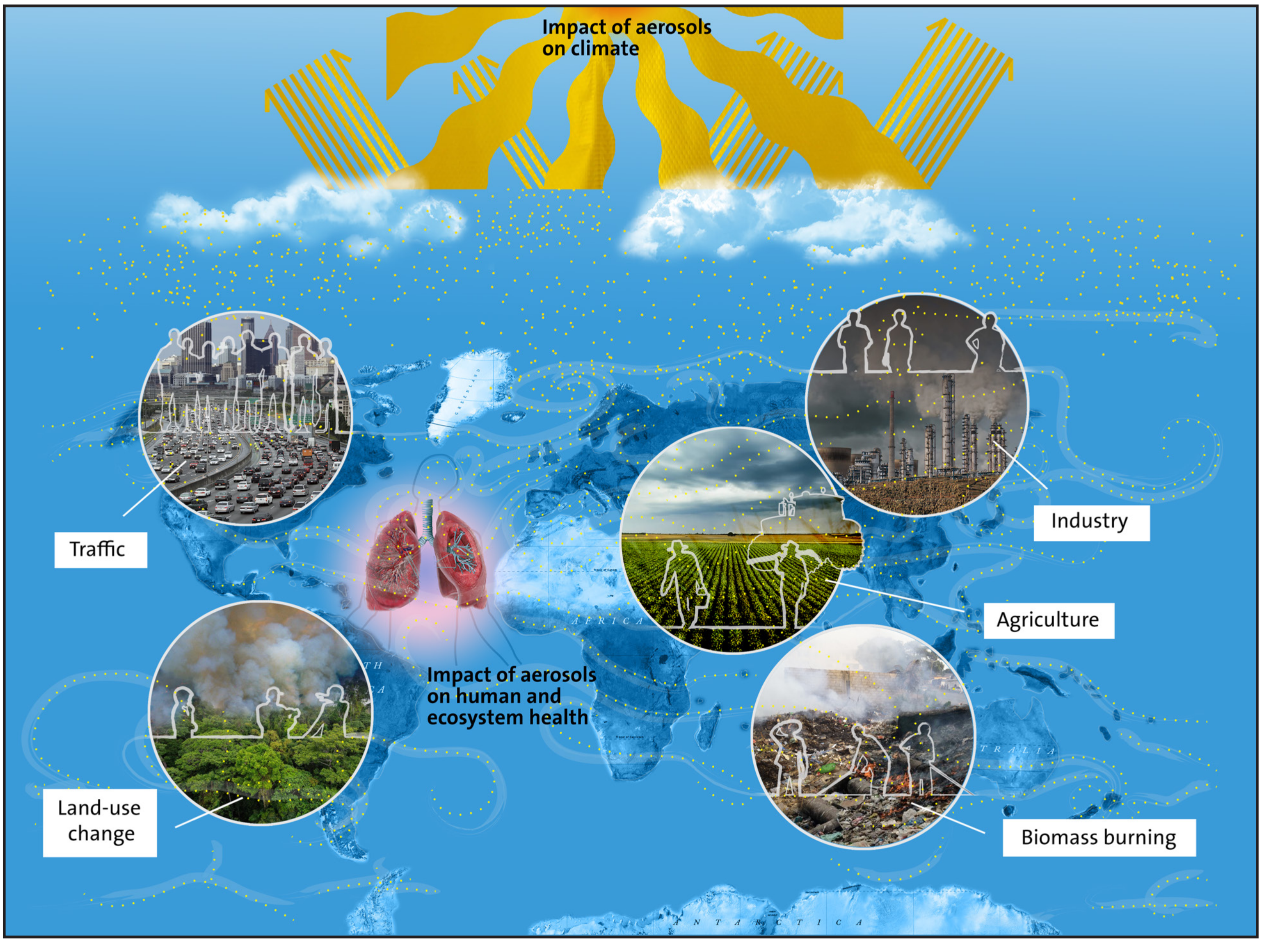

Figure 1. A schematic illustration on the global and regional sources and impacts of anthropogenic aerosol particles. Illustration by Ines Jakobsson

The major source of anthropogenic aerosol particles is the combustion of different fuels (transport, energy and heat production, or industrial processes). As fuel burns, nano- to micrometer-sized aerosol particles of different chemical composition (e.g. sulfur or carbon) are emitted or formed in the atmosphere. These particles contribute to many environmental issues, such as acid rain, impaired visibility, damage to plants and crops and corrosion of materials. Furthermore, the World Health Organization has listed air pollution as the foremost environmental threat to human health causing for example respiratory symptoms and cardiovascular diseases. They report that worldwide, ambient air pollution contributes to over 4 million deaths every year[3].

Aerosol particles affect climate directly by scattering and absorbing sunlight as well as indirectly by modifying clouds. The net effect of anthropogenic aerosol particles on the Earth's radiative balance is a cooling. These aerosol particles have therefore counteracted some of the warming produced by the increase in greenhouse gases since the beginning of the industrial period. However, the climate effect of anthropogenic aerosol particles varies a lot in time since the particles only stay in the atmosphere for a short period after emission (~days to weeks).

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[3] https://www.thelancet.com/gbd.

The global cooling effect was most likely largest during the 1960s to 1980s when sulfur emissions from industry and traffic over Europe and North America were at their highest.

As the emissions started to decrease in the 1980s due to environmental policies targeting the reduction of acid rain and air pollution (the Convention on Long-Range Transboundary Air Pollution CLRTAP) and the disintegration of the Soviet Union, the cooling effect was quickly reduced. The rapid reductions in aerosol particle emissions over Europe and North America might explain about half of the Arctic warming during the past three decades. At the same time, the fast economic growth over Asia has resulted in an increase in aerosol particle concentrations bringing back some of the global cooling. However, aerosol particle emissions over parts of Asia, in particular China, are now starting to decrease due to environmental policies meaning that more of the anthropogenic greenhouse gas warming may be unveiled.

Different types of aerosols have different climate effects. Soot particles (consisting of black carbon) warm the climate while particles containing sulfur, nitrate or organic carbon have a net cooling effect.

The short time that aerosol particles stay in the air also results in large spatial variations in particle concentrations, which impacts precipitation and atmospheric circulation patterns (such as the monsoon). For example, the band of heavy precipitation in the tropics (the intertropical convergence zone) has most likely shifted southward due to the large emissions of anthropogenic aerosol particles in the northern hemisphere, affecting precipitation patterns over sensitive regions such as the Amazon, the Sahel and the Himalayas.

Within the EU, about 400 000 premature deaths occur every year due to the effects of anthropogenic aerosol particles on health. Under the umbrella of the Green Deal, the 'Zero Pollution Action Plan', aimed to be adopted by the commission in 2021, intends to achieve no pollution from "all sources", cleaning the air, water and soils by 2050.

It is challenging to determine and predict the magnitude and time-evolution of aerosol particle climate effects due to the complex physical and chemical processes involved. The Intergovernmental Panel on Climate Change (IPCC) recognizes the aerosol climate effect as the single largest source of uncertainty in past and near-term future climate projections. Air quality improvements are urgently needed in many parts of the world. The anticipated reductions in aerosol particles may result in an enhanced warming, which is currently poorly quantified. Our inability to robustly estimate the climate effects of anthropogenic aerosol increases the uncertainty regarding the exact magnitude and timing of the greenhouse gas reductions needed to achieve the target of the Paris Agreement[4,5]. At the same time, the prediction of regional impacts of climate change, for example in terms of precipitation changes, is also affected.

What is known about the cooling and warming effects of aerosol particles?

Despite the many challenges in understanding and determining the climate effects of anthropogenic aerosol particles, many things are known. The average composition of anthropogenic aerosol particles has varied (and will continue to vary) as emissions have varied in time and by region (Fig. 2). The aerosol particles that dominated the global anthropogenic burden until the 1980s came mainly from Europe and North America and consisted predominantly of sulfur. As the particle pollution over Europe and North America decreased, particles instead steadily increased over large parts of Asia, at least until about 2010 when the emissions started to decrease over East Asia. These particles also contain sulfur, but also a relatively large fraction of soot and organic carbon, meaning less average cooling. Nitrate particles, on the other hand, do not clearly follow the regional trends of the other anthropogenic aerosol particles. Nitrate concentrations have increased steadily during the 20th century and nitrate is today the second most important anthropogenic aerosol component globally after sulfate, with particularly high prevalence over Europe, Asia and Midwest US. The formation pathways of nitrates are complex and they require the presence of other pollutants (for example ammonia) to form. The relative importance of nitrates will become even larger in the future as ammonia emissions from agriculture are expected to increase while anthropogenic sulfur emissions are projected to decrease.

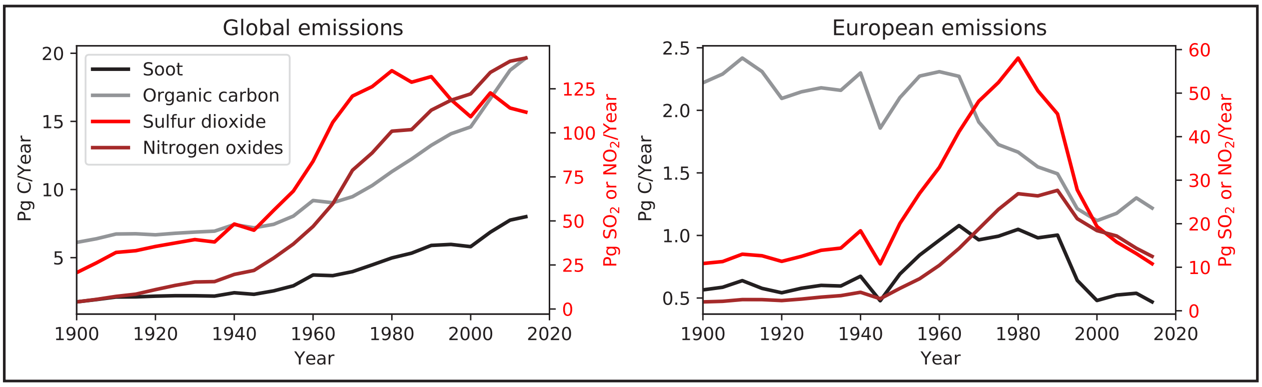

Figure 2. Historical emission trends of soot, organic carbon, sulfur dioxide (SO_2, a precursor of sulfur particles) and nitrogen oxides (NO_x, a precursor of nitrate particles). Please note the different axes for carbonaceous aerosol particles (soot and organic, left) and inorganic aerosol particle precursors (SO_2 and NO_2, right).

Even if all anthropogenic particles would cease to exist, natural aerosol particles will still be formed and emitted. Examples of these types of particles are dust and sea spray. In terms of global emissions of aerosol particles, dust and sea spray actually dominate the mass burden. So why do anthropogenic aerosol particles have such a large climate effect?

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[4] Acosta Navarro J. A. C. et al., Journal of Climate, 2017, *http://dx.doi.org/10.1175/JCLI-D-16-0466.s1*.

[5] Shindell, D. and Smith, C. J., Nature, 2019, *https://doi.org/10.1038/s41586-019-1554-z*.

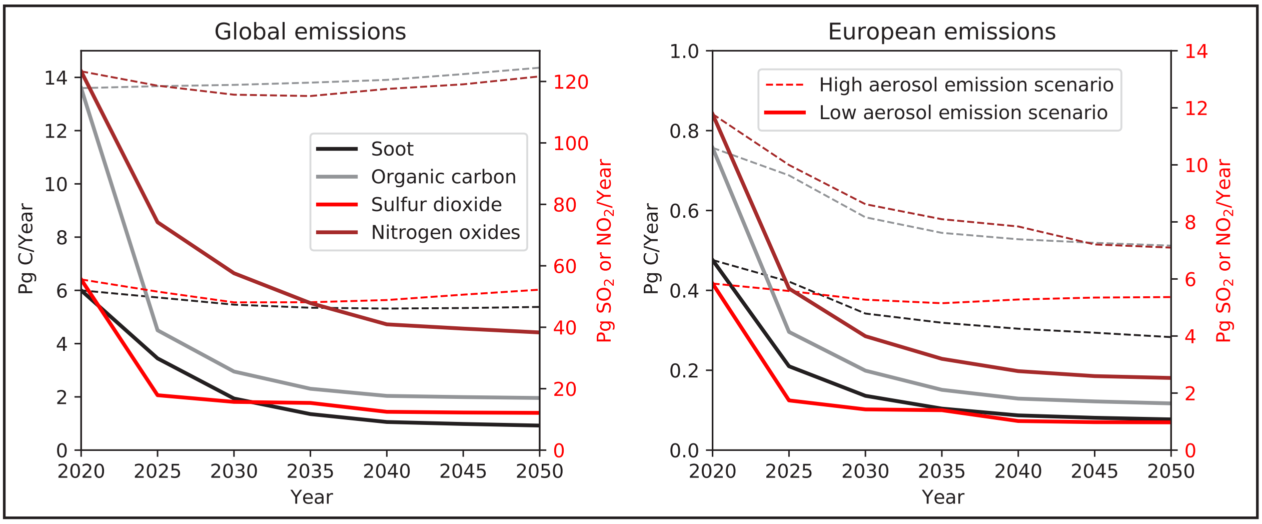

Figure 3. Future emission scenarios of soot, organic carbon, sulfur dioxide (SO_2, a precursor of sulfur particles) and nitrogen oxides (NO_x, a precursor of nitrate particles). Emissions following a "low aerosol emission scenario" (Maximum Feasible Reduction) are marked with full lines while emissions following a "high aerosol emission scenario" (Current Legislation) are marked with dashed lines.

The main reason is that they are numerous and relatively small, often less than one micrometer in size. The size and the number are particularly important when considering the climate effects of aerosol particles. As future anthropogenic aerosol particles are projected to decrease, natural aerosol particle sources will, however, become increasingly important. Sources and changes of natural aerosols are dependent on different climate parameters that are difficult to predict. For example, ocean winds may change in a warmer climate and forest fires may become more frequent, which will affect the emissions of sea spray, organic carbon and soot.

Taken all together, anthropogenic aerosol particles cool the climate today, but the magnitude of the global average cooling is smaller than during most of the 20th century. The cooling is likely to decrease even more in the future as most types of anthropogenic aerosol particles are projected to decrease, in particular over Asia. A range of plausible aerosol particle emission scenarios have currently been estimated to result in a global average "climate penalty" of 0 to 0.3°C by 2050[4].

The concentrations and impacts of anthropogenic aerosol particles on solar radiation are highest close to the emission regions, but many of the climate effects are *global*. The particle reductions over Europe and North America have contributed significantly to the rapid global temperature increase at the end of the 20th century. However, the climate effect is largest in the northern hemisphere and the Arctic region has warmed the most. The reason is that winds transport some of the excess heat from the mid-latitudes to the poles. This transport then triggers Arctic climate feedback processes such as enhanced sea ice melt, which induces further warming. Local heating of the Arctic from anthropogenic aerosol particles, for example due to the deposition of soot on snow, is of much less importance. The hemispheric warming imbalance has likely caused spatial shifts in the band of heavy rain that encircles the tropics, the so-called intertropical convergence zone.

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4 Acosta Navarro J. A. C. et al., Journal of Climate, 2017, *http://dx.doi.org/10.1175/JCLI-D-16-0466.s1*.

Furthermore, regional impacts of aerosol particles on cloud droplet and ice crystal formation, radiation and the exchange of heat and water at the Earth's surface may have affected other important weather events and precipitation patterns such as tropical cyclones, the Indian monsoon and the severity of thunderstorms. The exact magnitude of such types of climate effects are currently poorly known.

What is the relevance for policy?

Future reductions in aerosol particles from all anthropogenic sources as a consequence of clean air policies will result in a climate penalty as the aerosol particles currently cool the climate on a global scale. In addition to temperature, regional wind and precipitation patterns will be affected. We do not know the exact magnitude of this penalty, which has implications for the likelihood of reaching the targets of the Paris Agreement and reducing the risks of anthropogenic climate change for various forms of life on Earth. **It is however clear that from a policy perspective, the uncertainty in the aerosol climate effects does not undermine the fact that the most important policy measure for climate action is the reduction in carbon dioxide emissions.** It is also important to note that some air quality measures related to e.g. traffic, energy, industry or agricultural emissions can have a simultaneous impact on emissions and concentrations of greenhouse gases, in particular ozone and carbon dioxide, which can reduce the overall climate penalty. Future reductions in methane emissions will also remain as an important policy instrument to reduce global warming rates and minimize the risks associated with global warming.

In general, emission reductions of anthropogenic sulfur and organic carbon will unveil greenhouse gas warming while emission reductions in soot will dampen global warming. Therefore, a reduction in soot emissions presents a win-win situation in terms of air quality and climate effects. However, soot emissions are often difficult to reduce without simultaneously reducing emissions of organic carbon, and the overall outcome for e.g. the indirect aerosol effects is at present difficult to quantify. The climate benefit when targeting soot emissions may therefore be smaller than one immediately expects..

Fortunately, looking at past and future projections of aerosol particles, it is likely that most of the climate penalty on a global scale due to aerosol particle reductions has actually already been taken[4,5]. Sulfur emissions, which dominate the global anthropogenic aerosol particle burden, have decreased by approximately 60% since 1980 until 2020 and may only decrease by an additional maximum 30% until 2050. At the same time, in the same scenario, soot emissions are projected to decrease (reduced warming) which will compensate some of the decrease in sulfur emissions (reduced cooling). A major question mark in terms of future aerosol particle trends is nitrate, where further focused research efforts are warranted. It is likely that nitrates will decrease much less in the future than the other aerosol particle types due to relatively high emissions of ammonia, but our knowledge on the formation paths and concentration levels of nitrates is generally very poor.

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[4] Acosta Navarro J. A. C. et al., Journal of Climate, 2017, *http://dx.doi.org/10.1175/JCLI-D-16-0466.s1*.

[5] Shindell, D. and Smith, C. J., Nature, 2019, *https://doi.org/10.1038/s41586-019-1554-z*.

The newly established research project **FORCeS**, funded by the European Union's Horizon 2020 Research and Innovation Programme, will **improve the description of key processes governing aerosol particle radiative forcing and feedbacks in climate models.** The project brings together 22 leading climate research groups from twelve European countries with the aim to understand and reduce climate uncertainty associated with aerosols and clouds.

The FORCeS consortium plans to publish a series of policy briefs to provide European policy makers with related information, including new results from the project. Potential topics for future briefs include: links between aerosols and the Arctic amplification, role of aerosols for regional climate change impacts in the Mediterranean, the role of aerosols in geoengineering as a way to combat climate change. Input on other topics are most welcome!

For more information and points of contact, please go to *www.forces-project.eu* or follow us on Twitter *@FORCeS_H2020*.

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Further reading

If you would like more information about aerosol particles and their climate effects, we recommend reading chapter 7 from working group 1 in the most recent assessment report from the Intergovernmental Panel on Climate Change (IPCC): *www.ipcc.ch/report/ar5/wg1/clouds-and-aerosols*. Keep your eyes open also for the next IPCC assessment report with a planned release in 2021 (*www.ipcc.ch/assessment-report/ar6*).