FORCeS

Aerosol impacts on regional climate

This policy brief aims to bring together the latest advances in studies of regional aerosol climate impacts. The main focus is on exploring the following questions:

1. What role have natural and anthropogenic aerosol emissions played in regional climate change over the past decades?
2. What role will natural and anthropogenic aerosol emissions play in the upcoming decades?
3. What is needed to improve the understanding of atmospheric aerosols for a better representation of regional impacts of future changes?

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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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Key messages for policy makers:

- Aerosols have had, and are projected to have, a strong impact on climate in several regions of the world. Such is the case of the European continent where aerosols have contributed to a temperature increase of more than twice the global average over the past 30 years.
- Policies aiming at improving air quality leading to reduction in aerosols will translate into a climate penalty, exacerbating global warming and its regional impacts. This reinforces the need for stronger action to mitigate climate change by quickly reducing emissions of greenhouse gases.
- Future improvements are needed both in the scientific understanding of aerosols and their interaction with climate, as well as in the capacity of monitoring and modelling aerosols and their impact on climate. This will allow informing policymakers more accurately about regional changes in climate and climate change impacts, to better anticipate climate adaptation requirements.

Background information

Aerosols scatter, reflect and absorb sunlight, reducing the amount of solar radiation reaching the Earth's surface. Aerosols are also needed for clouds to form, acting as cloud condensation nuclei (CCN): when the air is saturated with respect to water vapour, water condenses on the surface of the aerosols to form droplets. Consequently, aerosols impact climate both directly by changing the radiative transfer in the atmosphere and indirectly by changing cloud properties (see Figure 1).

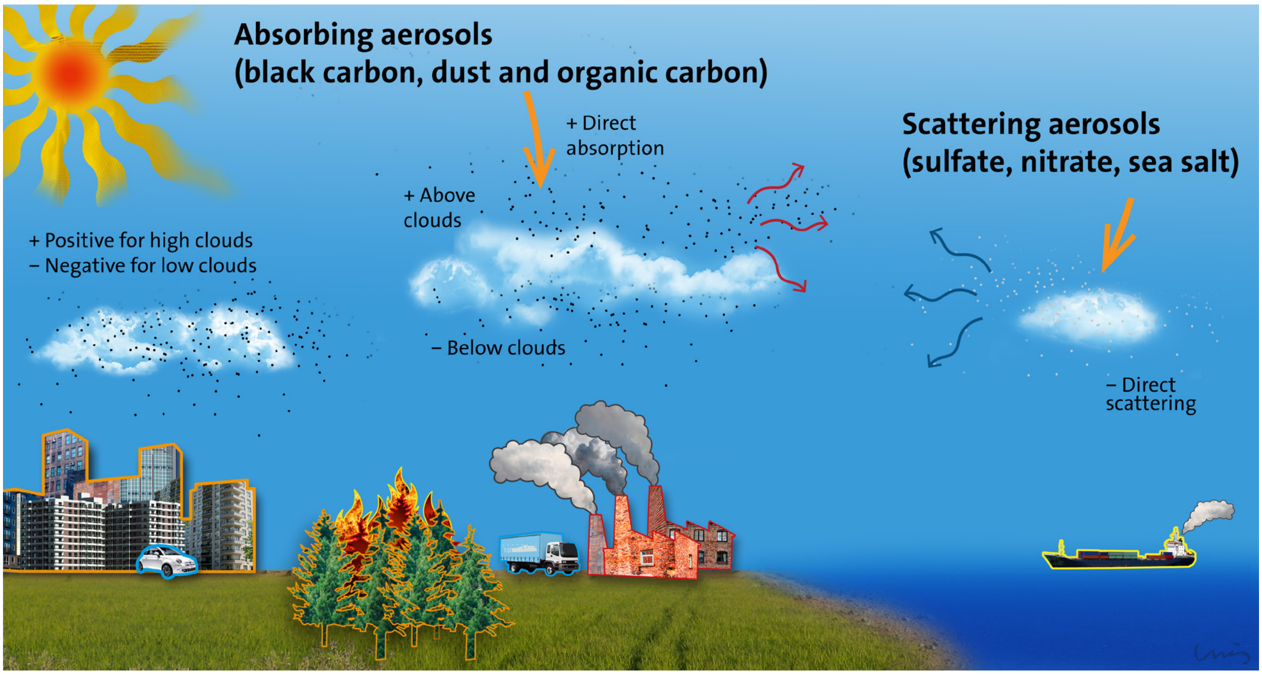

Figure 1. Aerosols emissions, impact on clouds, radiative forcing and climate (inspired by Li *et al.*, 2022). Different pollution sources emit different types of aerosols: those that absorb solar radiation (dark grey dots) and those that scatter (light grey dots). Scattering aerosols induce negative 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 (not shown in the figure) enhances the absorption and, thus, the warming effect. Orange arrows represent incident sunlight; red, the radiation re-emitted by absorbing aerosols; and dark blue, scattered sunlight. Illustration: Inês Jakobsson

What are aerosols? An aerosol is a suspension of a solid or liquid particle in the air. Aerosols are either emitted directly into the atmosphere or they are formed through gas-to-particle conversion from precursor gases emitted from various sources (natural or man-made).

Aerosols generally have a cooling effect if you look at the global average. However, their effective contribution to global cooling or warming due to changes in anthropogenic emissions is regionally varying, complex and its quantification is a matter of intense research.

Aerosols also have a strong impact on air quality, humans and ecosystem health. Policies aiming at reducing air pollution, including aerosols, therefore have direct consequences for the climate. Improvements in future air quality by reducing anthropogenic aerosols predominantly leads to a reduction in the aerosol cooling. This implies that when historic and current aerosol-induced cooling is reduced, it will exacerbate the foreseen continued greenhouse-gas-driven warming. For absorbing aerosols, such as soot, the situation is reversed as they act to warm the climate.

A fundamental difference between the impacts of aerosols and long-lived greenhouse gases on Earth's **radiative forcing** is tied to their atmospheric residence times (i.e., how long they stay in the atmosphere): greenhouse gases have residence times of decades to millennia, while the residence time of tropospheric aerosols is only up to several days. Therefore, climate responds to long-lived greenhouse gases such as CO_2 largely in terms of their cumulative emissions, but to aerosols in direct link to its current rate of emissions. The shorter residence time of aerosols leads to larger regional variations compared to greenhouse gases that are more evenly spread over the globe. Consequently natural and anthropogenic aerosols also have a strong impact on **regional climate** in the vicinity of their sources.

Greenhouse gas emissions will continue to warm the planet over the upcoming decades. The warming has strong regional impacts including: stronger warming over continents than over the oceans, stronger warming at high latitudes – especially the Arctic – than at lower latitudes and stronger warming in high altitude mountain areas. Also, it acts to strengthen the hydrological cycle with more evaporation from oceans, land and vegetation leading to increased global precipitation, where regional impacts vary and both floods and droughts tend to exacerbate. Acording to IPCC's AR6 report (Lee *et al.,* 2021), precipitation will very likely increase over high latitudes and the tropical oceans, and likely increase in large parts of the monsoon region, but likely decrease over large parts of the subtropics due to strongly increasing evaporation.

What is radiative forcing? Radiative forcing is the net change in the energy balance of the Earth system following an imposed perturbation (for instance in greenhouse gases, aerosols or solar irradiance) . It is usually expressed in watts per square meter averaged over a particular period of time. (IPCC, AR6, WG1, Chapter 7). *https://svs.gsfc.nasa.gov/20328*

What is regional climate? Although climate change is a global phenomenon, its manifestations and consequences are different in different regions. Regional climate change refers to a change in climate in a given region. Regional scales are defined by the IPCC (Doblas-Reyes *et al.*, 2021) as ranging from the size of sub-continental areas (e.g., the Mediterranean basin) to local scales (e.g., coastlines, mountain ranges and cities).

1. What role have natural and anthropogenic aerosol emissions played in regional climate over the past decades?

Changes in anthropogenic aerosol emissions are strongly related to regional socio-economic development and national mitigation policies. Such changes are heterogeneous in both space and time and have impacted the Earth's radiative energy budget. Recent research presents clear, robust, and consistent signals for net declining anthropogenic aerosol influence on climate during the period since 2000, with regions in which aerosol emissions declined (in particular over North America, Europe, and East Asia) dominating over regions with increasing trends (Quaas *et al.,* 2022). At the same time, uncertainty in future aerosol forcing remains one of the largest unknown factors when projecting future temperature and precipitation changes.

EMISSIONS	In Europe and North America aerosol emission show decreases after reaching a peak in the 1980s. In China emissions have increased until around 2010 and decreased thereafter. Over India and Africa aerosol emissions continued to rise throughout the period 2000–2019. Over remote oceanic regions, ship emissions played a substantial and increasing role until 2010, decreasing first in emission-controlled areas and since 2020 over much of the global oceans (Quaas *et al.*, 2022; Von Salzen *et al.*, 2022).
CONCENTRATTIONS	Trends in surface concentrations from local observations, ice-core analysis and remote sensing were found to be consistent with the emission trends and confirmed by modelling studies that attribute satellite-derived trends to emission changes (Quaas *et al.*, 2022; Moseid *et al.*, 2022).
CLOUDS	A review of trends in cloud quantities conducted by Quaas *et al.*, 2022 concluded cloud droplet number trends are spatially consistent with the expectation of declining anthropogenic aerosol emissions, strongly corroborating the conclusion based on satellites showing a declining trend in aerosols in regions of anthropogenic emissions.
RADIATION	The latest assessment report by the IPCC found the impact of aerosols on the Earth's energy balance, known as Effective Radiative Forcing (ERF), between 1750 and 2019 to be of –1.1Wm-2 (Forster *et al.*, 2021). However, this change has to be viewed in the light of different regional emission trends and changes in ERF over specific time periods as the timing at which the aerosol forcing became substantially less negative differs across regions. For instance, Quaas *et al.*, 2022 demonstrate that the aerosol ERF has been decreasing since 2000 over Europe and North America, and since 2010 over China.
CLIMATE	The IPCC (AR6, WGI) attributes a global warming of 1.07°C from 1850–1900 to 2010–2019 to human activities, with well-mixed greenhouse gases contributing with somewhere between 1.0°C and 2.0°C and aerosols being the largest contributor to a cooling of between 0.0°C and 0.8°C. This implies that without the cooling effect of aerosols, the world would likely already have reached the 1.5°C temperature threshold of "dangerous" climate change as set out by the Paris agreement (Forster *et al.*, 2021). In some regions, strongly declining trends in aerosols over the last decades have been followed by exacerbated warming. As an example of regional impacts, temperatures in Europe have increased at more than twice the global average over the past 30 years – more than in any other continent in the world, according to The State of the Climate in Europe report (WMO & Copernicus Climate Change Service, 2022). While the long-term warming in Europe is first and foremost a consequence of the human emissions of greenhouse gases, the decrease in aerosol emissions over the past four decades has strongly contributed to the temperature increase of over two degrees Celsius (Glantz *et al.*, 2022).

CLIMATE

As an example of impacts in precipitation, Wilcox *et al.*, 2020 have concluded that rapid reductions in anthropogenic aerosol and precursor emissions between the present day and the 2050s will lead to enhanced increases in global and Asian summer monsoon precipitation relative to scenarios with weak air quality policies. However, the effects of aerosol reductions do not persist to the end of the 21st century for precipitation, when instead the response to greenhouse gases dominates.

2. What role will natural and anthropogenic aerosol emissions play in the upcoming decades?

Future emissions of aerosols will have an impact on the regional climate. In areas with large future aerosol emissions part of the climate change signal induced by greenhouse gases can be attenuated. In areas of declining emissions previously "hidden warming" may become revealed in a similar way as has been seen for Europe over the last decades. New research indicates that the additional warming arising from air pollution mitigation can be delayed by two or three decades in heavily polluted locations. This implies that this cloud-mediated climate penalty will manifest markedly starting around 2025 in China and 2050 in India, after applying the strongest air quality policy (Jia & Quaas, 2023).

How large future impacts of changing aerosols we will see is a major source of uncertainty related to future climate change. A large part of it relates to future emissions, with scenarios spanning from small to moderate increases in global emissions, to dramatic reductions over the nearest decades (SSP scenarios as quoted by Persad *et al.,* 2022). As the residence time of aerosols in the atmosphere is short, and their impact on climate is regional in its nature, uncertainties in emissions have strong implications on regional scales. Our limited understanding of the actual impact of the aerosols on the climate system including their interaction with clouds is also one of the big unkowns in climate science.

The climate penalty from reducing aerosol emissions can be balanced by a reduction of methane and ozone forming components such as nitrous oxides and organic gases, as these drivers of a warming have lifetimes much shorter than CO_2. Consequently, strong reductions of methane and black carbon will not only give health and ecosystem benefits but will also significantly enhance climate change mitigation. Combined, these reductions can yeld a fully climate neutral air pollution emission reduction scheme and reduce warming with about 30% in 2050 (AMAP, 2021; von Salzen *et al.,* 2022). For long-term impact, these need to be accompanied by strong CO_2 emission reductions.

3. What is needed to improve the understanding of atmospheric aerosols for a better representation of regional impacts of future changes?

Climate research has improved our knowledge of aerosols and their impact on climate. Yet improvements are needed both in our scientific understanding of the aerosols and their interaction with climate and in our capacity of monitoring and modelling aerosols and their impact. This involves monitoring both emissions and aerosol concentrations and also to improve climate models that are used to produce scenarios for the future.

Global climate models with sophisticated treatment of aerosols and aerosol-cloud interaction are powerful tools for providing information about future regional climate change. In particular, these models can be used to understand how aerosols can impact the large-scale atmospheric circulation and thereby regional and local climate. As the global models are still too coarse to adequately address changes in extreme events, especially intense rainfall, high-resolution regional climate models are often used. High-resolution kilometre-scale climate models can be used to better understand the regional effects of aerosols. Such models do not include complex aerosol schemes but allow for a much more realistic representation of convection and cloud systems.

Although anthropogenic emissions of aerosols have been dramatically decreased in some regions, up to very recently, aerosol variations have hardly been considered in regional climate simulations. Different treatment of aerosols in global and regional climate models lead to differences in simulated climate change and its impacts.

Inclusion of time-varying aerosols in regions like Europe, that have seen strong changes in aerosols, improves consistency with observed trends in temperature. Models without time-varying aerosols, as is the case for many regional models currently used to provide information on future climate change, do not capture these trends.

In contribution to improving knowledge and tools, FORCeS has a focussed agenda aiming at investigating atmospheric processes involving aerosols and their interaction with clouds and how these may be improved in state-of-the-art climate models. The focus in FORCeS has primarily been on global climate models but as high-resolution regional climate models are often used for regional and local impact studies, a dialogue with regional climate modelers from CORDEX (the Coordinated Regional Downscaling Climate Experiment) has been initiated. During the international conference on regional climate – CORDEX 2023 – a dedicated session on atmospheric aerosols was jointly organized by FORCeS and CORDEX (*https://icrc-cordex2023.cordex.org/program/parallel-session-d-cordex-in-practice/session-d9-aerosol-impact-on-regional-climate-online-and-trieste*).

References

Li, J., Carlson, B.E., Yung, Y.L. et al. Scattering and absorbing aerosols in the climate system. Nat Rev Earth Environ: 3, 363–379, 2022. https://doi.org/10.1038/s43017-022-00296-7

AMAP, 2021. AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. x + 375pp

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D., Mauritsen, T., Palmer, M., Watanabe, M., Wild, M., and Zhang, H. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., chap. 7, Cambridge University Press, Cambridge, UK and New York, NY, USA, 923–1054, 2021. a, b, c, d, e, f, g, h, i

Glantz, P., Fawole, O. G., Ström, J., Wild, M., & Noone, K. J.m. Unmasking the effects of aerosols on greenhouse warming over Europe. Journal of Geophysical Research, Atmospheres: 127, e2021JD035889, 2022. https://doi.org/10.1029/2021JD035889

Jia, H., Quaas, J. Nonlinearity of the cloud response postpones climate penalty of mitigating air pollution in polluted regions. Nat. Clim. Chang. 13, 943–950 (2023). https://doi.org/10.1038/s41558-023-01775-5

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T. Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, 2021. doi: 10.1017/9781009157896.006.

Moseid, K.O., Schulz, M., Eichler, A., Schwikowski, M., McConnell, J. R., Olivié, D., et al. Using ice cores to evaluate CMIP6 aerosol concentrations over the historical era. Journal of Geophysical Research: Atmospheres: 127, e2021JD036105, 2022. https://doi.org/10.1029/2021JD036105

Persad, G.G., Samset, B.H., and Wilcox, L.J. Aerosols must be included in climate risk assessments, Nature: 611, 662–664, 2022. https://doi.org/10.1038/d41586-022-03763-9.

Quaas, J., Jia, H., Smith, C., Albright, A. L., Aas, W., Bellouin, N., Boucher, O., Doutriaux-Boucher, M., Forster, P. M., Grosvenor, D., Jenkins, S., Klimont, Z., Loeb, N. G., Ma, X., Naik, V., Paulot, F., Stier, P., Wild, M., Myhre, G., and Schulz, M. Robust evidence for reversal of the trend in aerosol effective climate forcing, Atmos. Chem. Phys.: 22, 12221–12239, 2022. https://doi.org/10.5194/acp-22-12221-2022.

von Salzen, K., Whaley, C.H., Anenberg, S.C. et al. Clean air policies are key for successfully mitigating Arctic warming. Commun Earth Environ: 3, 222, 2022. https://doi.org/10.1038/s43247-022-00555-x

Wilcox, L. J., Liu, Z., Samset, B. H., Hawkins, E., Lund, M. T., Nordling, K., Undorf, S., Bollasina, M., Ekman, A. M. L., Krishnan, S., Merikanto, J., and Turner, A. G. Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions. Atmos. Chem. Phys.: 20, 11955–11977, 2020. https://doi.org/10.5194/acp-20-11955-2020.

WMO & Copernicus Climate Change Service, 2022. State of the Climate in Europe 2022. WMO, 2023.

FORCeS contact information

Project manager Ana Cordeiro | *ana.cordeiro@su.se*
Office for Research, Engagement and Innovation Services (REIS)
Stockholm University, SE-106 91 Stockholm, Sweden