INSIGHTS

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PERSPECTIVES

CLIMATE

How cleaner air changes the climate

Air quality improvements affect regional climate in complex ways

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Aerosols have a strong influence on the present climate, but this influence will likely be reduced over the coming decades as air pollution measures are implemented around the world. At a global level, aerosols have helped to reduce the warming effect from greenhouse gas emissions, and necessary reductions in air pollution may thus make it harder to achieve ambitious global climate and environmental aims, such as the Paris Agreement's 2°C target. Furthermore, the local nature of air pollution means that the impacts of changes to aerosol emissions—on temperature, precipitation, extreme events, and health—are likely to differ widely from one place to another. Model and observational studies are beginning to assess these impacts, particularly the link between aerosols and precipitation, to elucidate the climate effects of cleaning up our air.

Human influence on the climate is a tug-of-war, with greenhouse gas–induced warming being held partly in check by cooling from aerosol emissions. In a Faustian bargain, humans have effectively dampened global climate change through air pollution. Increased greenhouse gas concentrations from fossil fuel use are heating the planet by trapping heat radiation. At the same time,

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Smog covers Lujiazui, Shanghai, China. Cleaning up air pollution affects regional air temperature and precipitation.

emissions of aerosols—particles that make up a substantial fraction of air pollution—have an overall cooling effect by reflecting incoming sunlight (*1*). The net effect of greenhouse gases and aerosols is the ~1°C of global warming observed since 1880 CE. The individual contributions of greenhouse gases and aerosols are, however, much more uncertain. Recent climate model simulations indicate that without anthropogenic aerosols, global mean surface warming would be at least 0.5°C higher, and that in their absence there would also be a much greater precipitation change (*2*, *3*) (see the figure).

Many climate effects from aerosols are, however, regional rather than global. Whereas the major greenhouse gases, carbon dioxide and methane, get distributed globally, aerosols are removed from the atmosphere in a matter of days, leading to quite different patterns of impact. A reduction in aerosol emissions—as has already occurred in the United States and Europe and is assumed to continue in most climate scenarios—can be expected to have disproportionately strong impacts near emission regions, where most of the world's population lives. The effects of global warming on society are therefore different if the warming is due to loss of aerosol cooling, rather than from greenhouse gas-induced warming. Simply put, it matters not only that we limit global warming to 2°C, but also how we do it.

Since 1990, there has been little change in the global volume of anthropogenic aerosol emissions. Regionally, however, there are large differences, with reductions in Europe and the United States balanced by increases in Africa and Asia (see the photo) (*4*). Recent simulations of the industrial era suggest that aerosols have prevented most surface warming from greenhouse gases in East Asia and, at the same time, changed what would have been a precipitation increase into a marked drying (see the figure). Although there are large differences between models, these results are broadly consistent with observations (*5*).

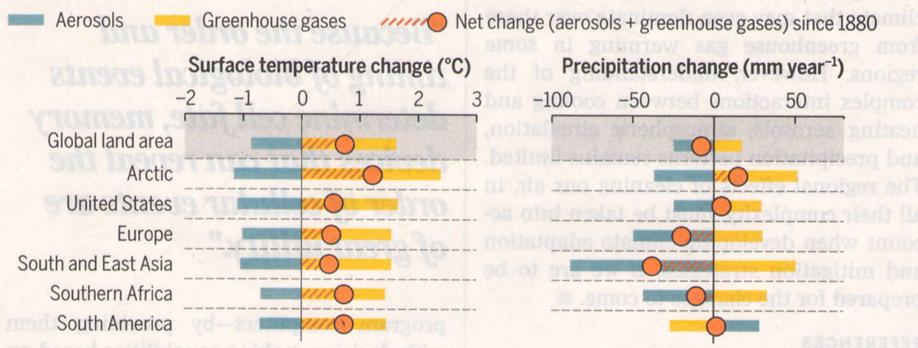
Regional cooling has likely also strongly influenced the rates of occurrence of extreme events (*3*) and the hydrological cycle (*6*). Modeling cannot, however, give definitive answers regarding these effects, because the model resolution is too coarse and it remains difficult to accurately reproduce the relevant cloud processes. It therefore remains unclear how an Asian aerosol cleanup would affect local precipitation and extreme weather events such as storms and droughts. The topic is urgent because Asian emissions levels are changing rapidly. According to one recent study, Chinese emissions of SO_2, a main precursor of cooling sulfate aerosols, have declined by 75% since 2007, whereas those from India increased by 50% over the same period (*7*).

Aerosols also affect region-specific climate and weather phenomena, such as the South Asian monsoon. Indian summer monsoon rainfall has steadily declined since the 1950s, and model simulations indicate that aerosol forcing is critical to explaining this trend (*8*). Aerosol-induced surface cooling is thought to lead to anomalous circulation patterns over much of the region, weakening moisture transport from the Indian Ocean and thereby reducing monsoon rainfall (*9*).

Furthermore, aerosols are mainly emitted over Northern Hemisphere land masses, resulting in a hemispheric asymmetry that may have driven a shift in the position of the Intertropical Convergence Zone over the past century (*10*). Overall, today's precipitation patterns in the Northern Hemisphere are likely markedly influenced by aerosols, both near and far from emission sources.

Tug-of-war between aerosol cooling and greenhouse gas warming

Surface temperature and precipitation have, since preindustrial times, been affected by both greenhouse gases and aerosols. Model simulations comparing the periods 1985 to 2005 and 1880 to 1900 show that across the global land area, aerosols have limited the impacts of greenhouse gas warming. The regional patterns are more complex for precipitation. Data from (*14*).



To add to the complexity, not all aerosols cool the climate. Carbonaceous aerosols, byproducts of incomplete combustion, absorb sunlight and can therefore heat the atmosphere. The global warming effects of black carbon, the main absorbing aerosol type, are likely to be moderate, but black carbon can have substantial regional climate impacts (*11*). Absorbing aerosols change the temperature profile of the atmosphere and therefore also alter circulation, cloud formation, and precipitation. These processes may have contributed to the observed drying trend in Southern Africa since the 1950s (*12*). Also, the deposition of dark aerosols on white snow has likely contributed to the strong Arctic warming since the 1980s (*13*).

Currently, most anthropogenic aerosol emissions are related to fossil fuel use. The massive emission reductions necessitated

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by the Paris Agreement will therefore also reduce aerosol-induced cooling. Health and air quality considerations provide further, strong motivations for rapid reductions in particle emissions. Legislation targeting air pollution, such as the U.S. Clean Air Act and the European Union's Ambient Air Quality Directive, has proven that such mitigation is possible. Despite limited regulation, aerosol concentrations are currently falling in parts of Asia, although the driving factors are incompletely understood. Health concerns may drive local and regional aerosol reductions faster than foreseen in the climate scenarios used, e.g., in the IPCC (Intergovernmental Panel on Climate Change) assessments. This, in turn, implies that reductions in greenhouse gas emission may need to be even more rapid than has been assumed, in order to meet the goals of the Paris Agreement. Policy measures may also target cooling sulfate aerosols and heating carbonaceous aerosols differently, making it even more challenging to predict the outcomes of specific mitigation strategies.

Aerosol emissions are an important component of human influence on the climate today. Fossil fuel use reductions and air quality measures make it likely that this influence will be greatly reduced over the coming decades, with consequences for the climate that may even dominate over those from greenhouse gas warming in some regions. However, understanding of the complex interactions between cooling and heating aerosols, atmospheric circulation, and precipitation patterns remains limited. The regional effects of cleaning our air, in all their complexity, must be taken into account when developing climate adaptation and mitigation strategies, if we are to be prepared for the changes to come. ■

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