Unraveling the interconnections between air pollutants and climate change

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The eruption of Mt. Pinatubo in 1991 temporarily cooled the planet by half a degree Celsius, showing the power of tiny particles called aerosols. Credit: Dave Harlow, USGS

In June 1991, Mount Pinatubo in the Philippines erupted for nine hours, ejecting volcanic ash, water vapor, and at least 15 to 20 million tons of noxious sulfur dioxide gas into the stratosphere. Within two hours, the gas transformed into tiny sulfate mists or aerosols that formed bright clouds. Those clouds spread across the entire Earth and persisted for a year, effectively reducing global temperatures by 0.4 to 0.5 degrees Celsius between 1992 and 1993. Once these cooling aerosols fell out of the stratosphere two years later, global temperatures rose again.

Although microscopically tiny, aerosol particles can have mighty impacts on the atmosphere and climate. Major volcanic eruptions and their resulting aerosol emissions high up in the atmosphere are infamous for altering monsoon circulations and precipitation patterns around the world, even triggering severe droughts in Eastern China and India.

Aerosols created by burning fossil fuels can also impact the climate, although the effects are somewhat different at the ground level. And as human civilizations attempt to reduce their emissions of these harmful particles, they are inadvertently generating unwelcome side effects, too.

Understanding aerosols

Ever since the first Earth Day was observed in 1970, the global average temperature has been accelerating at the rate of 1.7 degrees Celsius per century. Before 1970, the rate of warming was only 0.01 degrees C per century. At the current rate, the Intergovernmental Panel on Climate Change (IPCC) warned that the average global temperatures could rise by more than 2 degrees Celsius by 2100, which would unleash devastating impacts on the planet.

"When we talk about the causes of human-driven climate change, a lot of attention is given to greenhouse gases like carbon dioxide and methane, but the anthropogenic aerosols component is rarely mentioned," said Scott Barrett, a vice dean at Columbia University's

School of International and Public Affairs and the Lenfest-Earth Institute Professor of Natural Resource Economics.

Aerosols (also known as particulate matter or PM) are a mix of suspended liquid and solid particles in the air with distinctive chemical compositions. The smaller the size of an aerosol, the more severe its health impacts. Particulate matter with a diameter of less than 2.5 microns ($PM_{2.5}$) can easily infiltrate the lungs. $PM_{2.5}$ has been associated with higher rates of respiratory, autoimmune, and neurological disorders than a comparatively bigger PM with a diameter of 10 microns or less—also known as PM_{10}.

Scientists estimate that 90% of aerosols in the atmosphere are naturally occurring, such as dust, pollen, plankton, and sea salt. On average, up to 80% of the particulate matter in coastal areas comes from sea salt. Waves breaking and bubbles bursting at the ocean surface make sea salt aerosols stay suspended in the air, said Faye McNeill, an atmospheric chemist and professor at Columbia University's School of Engineering. The good news is that most natural sources of aerosols have remained at constant levels without any significant fluctuations—giving less cause for concern.

But anthropogenic or human-made aerosols are the opposite. They are constantly emitted from vehicles, coal power plants, factories, oil refineries, agricultural areas, industrial facilities, ships, and wood burning, among other activities. Since the industrial revolution began in the Global North, the presence of anthropogenic aerosols in the atmosphere had steeply increased along with greenhouse gases. As the air got more and more polluted in the U.S., by 1970, the general public and environmentalists were concerned over poor air quality.

Despite the obvious sources of air pollutants, in 1981, President Ronald Reagan claimed that trees cause more pollution than automobiles do.

"This led some people to believe that cutting down all the trees will reduce air pollution. Obviously, that is not the solution," said McNeill, who leads Columbia Climate School's Clean Air Toolbox for Cities, a project that is working toward cleaner air in Jakarta, Indonesia, Indore, India, and Nairobi, Kenya.

"It is true that trees emit volatile organic compounds. But unhealthy levels of ozone pollution form only after these naturally occurring volatile organic compounds react with nitrogen oxides—which get emitted when coal, oil, and natural gas are burned," added McNeill.

The majority of anthropogenic aerosols are made in the atmosphere from gas molecules. For example, during the coal burning process, the sulfur present in coal becomes oxidized and gets released into the atmosphere as sulfur dioxide gas. The gas then reacts with clouds, water vapor, and other pre-existing compounds before it transforms into sulfate aerosols that have a cooling effect on the lower atmosphere.

"Various chemical and physical transformations lead to the polluted state that we would see in an urban area," McNeill explained.

Aerosols: A double-edged sword

In the United States, sulfur dioxide emissions gained widespread attention in the 1970s due to acid rain. When sulfur dioxide mixes with water in the air, it results in sulfuric acid raining down on those locations.

Air pollution hangs over a steel industry plant in 1973. Over time, the Clean Air Act dramatically reduced such harmful pollution — a big win for public health. However, with more sunlight reaching the Earth's surface through cleaner air, global warming was exacerbated. Credit: John Alexandrowicz/U.S. National Archives and Records Administration

At the time, industrialized countries in the Global North were collectively emitting such high levels of sulfur dioxide from their coal power plants and vehicles that it was the equivalent of over a dozen Mount Pinatubo volcanic eruptions.

The U.S. federal government implemented the Clean Air Act during the 1990s to clamp down on the sources of sulfur dioxide pollution and prevent acid rain pollution. In Europe and Canada, governments mandated that scrubbers should be installed on all industrial smokestacks. Countries in the Global North also passed legislation that made it compulsory for vehicle owners to use exhaust emission control devices. Hefty fines were imposed on polluters. These regulations worked.

For more than three decades, the Global North witnessed a dramatic decrease in $PM_{2.5}$ and ozone pollution levels. The U.S. Environmental Protection Agency reported an 80% decline in anthropogenic sulfur dioxide emissions between 1990 and 2014. Within the same period, deaths related to air pollution in the U.S. were halved. Forests that were damaged from acid rain started recovering.

Even though reducing aerosol emissions has immense public health and ecological benefits, researchers say it is crucial to take into account the impact of such reductions on climate change. While the Global North succeeded in cutting down aerosol pollution, they continued burning huge amounts of fossil fuels like coal. That resulted in the warming of the northern hemisphere.

"Before these policies were enforced, industrialized countries were increasing their carbon dioxide emissions at the same pace as they were increasing the levels of atmospheric aerosols," explained McNeill. "But then they disrupted the cooling effects of short-lived aerosols by cutting down on their sulfur dioxide and nitrogen oxide emissions."

Scientists refer to this phenomenon as uncovering global warming. Before industrialized countries collectively got rid of sulfate aerosols, warming was already occurring on a global scale—albeit at a slower pace.

The only way to simultaneously deliver benefits for public health and climate change is by transitioning to renewable energy, said McNeill. In that case, both anthropogenic aerosols and greenhouse gas emissions would be reduced.

Similar to sulfate particulate matter, other anthropogenic aerosols like nitrates and airborne microplastics also scatter and deflect solar radiation back to space, leading to atmospheric cooling. Certain forms of organic carbon could also have a net cooling influence by scattering sunlight away from the Earth's surface.

On the other hand, black carbon and brown carbon absorb sunlight and have a warming influence on the planet—so cutting their emissions has dual benefits for public health and the planet's temperature.

The aftermath of phasing out sulfur dioxide emissions

To better understand the complex relationship between aerosols and climate change, Columbia researchers analyzed the impacts of drastically lower levels of sulfur dioxide emissions in the northern hemisphere on other parts of the world.

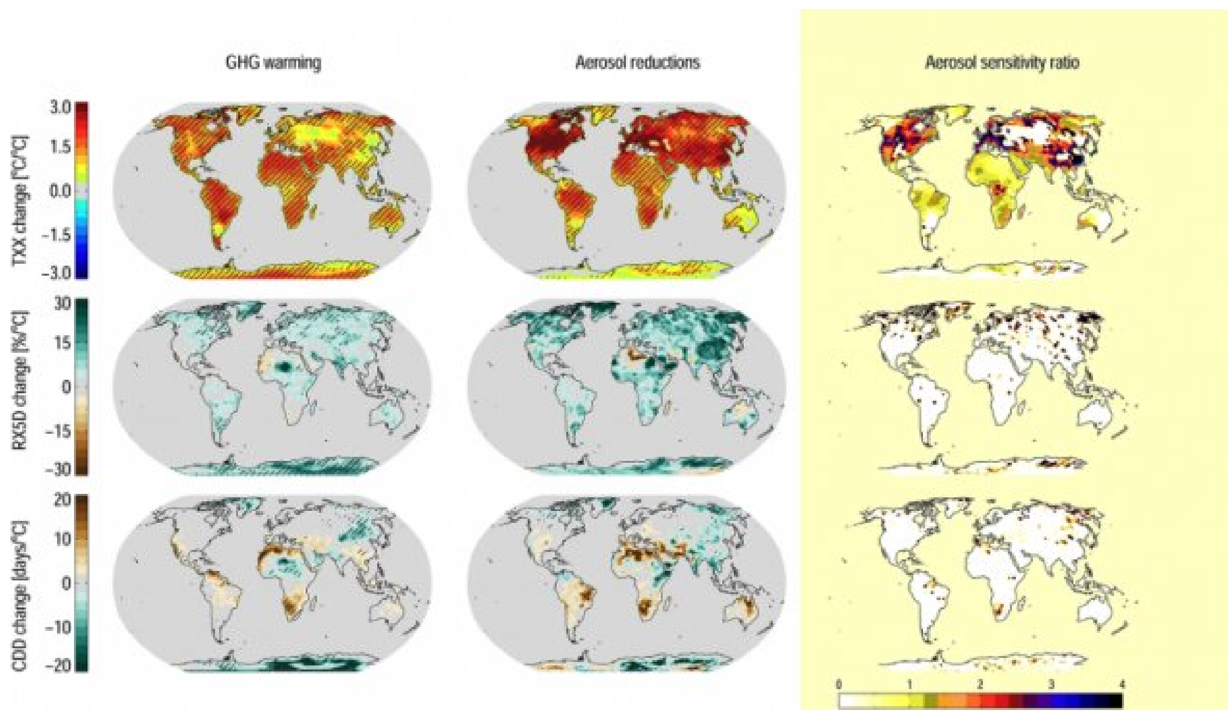
Interestingly, they found that cleaner air in the Global North ended up influencing monsoon patterns in Africa's Sahel region and South Asia in entirely different ways.

"Lower levels of sulfate aerosols in the northern hemisphere ended up changing the energy balance of the Earth's system and affected the dynamics of how air moves around the planet. That has far-reaching impacts on the southern hemisphere," explained Arlene Fiore, formerly an atmospheric scientist at Columbia Climate School's Lamont-Doherty Earth Observatory, who is now a professor at the MIT Center for Global

Change Science.

Dan Westervelt, an atmospheric scientist at Lamont-Doherty Earth Observatory, observed with colleagues that once the northern hemisphere started experiencing faster warming, the tropical rain belts shifted in a northward direction—thereby resulting in [substantially more rainfall]() in Africa's Sahel region. While local aerosol emissions might also be playing a role in these anomalies, rainfall patterns have become far more erratic than usual in most of the Sahel.

"These interconnections are concerning and fascinating all at the same time. What we do in the northern hemisphere affects other regions and can have downstream impacts," added Fiore.



Extreme weather sensitivity to changes in greenhouse gases (left column) and aerosol removal (middle column). Projected effects on maximum daily temperature (TXx) are shown in the top row. Below that, maximum 5 day precipitation (RX5D) and consecutive dry days (CDD). Credit: Samset et al./ *Geophysical Research Letters*, 2018

But African countries are not the only ones grappling with the side effects of lower concentrations of anthropogenic aerosols in the northern hemisphere.

In a 2022 study published in the journal *Science Advances*, researchers proved that the North Atlantic has also witnessed more extreme weather events with decreasing aerosol emissions. Since the implementation of the Clean Air Act more than 30 years ago, hurricane seasons became more frequent and intense in the North Atlantic region compared to prior decades.

On the other side of the globe, industrialization and economic growth have significantly increased the concentration of sulfate aerosols in India and China over the last four decades. This had a cooling influence on the land surface despite global warming. The difference between the temperatures of the land and ocean also decreased. That, in turn, drove down the intensity of monsoonal winds and resulted in fewer tropical cyclones and typhoons in South and East Asia in that time span, said Westervelt.

Westervelt's work showed that on the Indian subcontinent, higher levels of sulfate aerosol emissions caused less rainfall over the Indo-Gangetic plain. At present, Bangladesh, Pakistan, and India have the most polluted air in the world.

Pick your poison: $PM_{2.5}$ vs. ozone pollution

In 2014, the Chinese government announced it was "declaring war against air pollution." Four years after allocating billions of dollars for clean air, major cities in China successfully cut down their $PM_{2.5}$ concentrations by 32 percent. Unfortunately, that positive development led to a negative outcome: a spike in ozone pollution.

Ozone pollution forms when nitrogen oxides (that are emitted from burning fossil fuels) and volatile organic compounds react with each other in the presence of sunlight. Unlike the ozone layer high up in the atmosphere that protects us from harmful ultraviolet rays, on-the-ground ozone pollution is a threat to public health.

Repeated exposure to ground-level ozone can trigger chest pain and coughing, reduce lung function, and may permanently damage lung tissue. Ozone pollution has also been associated with cardiovascular disease and stroke. Westervelt and colleagues have calculated that cutting down ozone pollution by 60% would save 330,000 lives in China by 2050.

Climate change has made ozone pollution a lot worse than before in many parts of the world. Warmer temperatures ramp up reactions between nitrogen oxides and volatile organic compounds that get trapped in the lower atmosphere. Researchers observed that getting rid of aerosols or fine particulate matter is another reason why Chinese cities are experiencing a spike in ozone pollution.

Previously, high levels of $PM_{2.5}$ in the air acted like sponges that efficiently absorbed the radicals responsible for generating ozone pollution. The aerosols consistently inhibited ozone production. By aggressively tackling the sources of sulfur dioxide emissions, China inadvertently tinkered with the atmosphere's chemistry. Once the sulfate-dominated $PM_{2.5}$ concentrations started depleting, more sunlight and radicals were left behind to produce ground-level ozone, according to a study published in *PNAS*.

The need to address global inequalities

Climate scientists and innovators worldwide are grappling with the multiple challenges involved in reducing emissions of greenhouse gases and air pollutants while also promoting healthy economic development.

"This issue has not been prioritized during international climate negotiations. The focus is still on what individual countries could do for reducing their greenhouse gas emissions," said Barrett. "Policymakers need to develop an approach that addresses both the economic interests of developing countries like India, as well as the collective interests of other nations."

He emphasized that India—one of the world's top three emitters of greenhouse gases—desperately needs financial and technological support from industrialized countries. This will prevent India from replicating China's history of unsustainable growth that not only undermines India's future development but also that of the rest of the world—thanks to greater surges in aerosol and greenhouse gas emissions.

While there are no straightforward solutions for tackling such complex and nuanced issues, experts like McNeill say it highlights how proposed geoengineering technologies (that would use aerosols to temporarily reduce global warming) can have unintended consequences.

"Every country is interconnected through the atmosphere and global trade," added Barrett. "We need to transform the economic system for better mitigation strategies."

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