# Acid Deposition and a Warming Planet: Shared Emission Sources, Environmental Effects and Policy Responses


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***Abstract*—Air pollution and the changing climate are connected because several human activities release pollutants that influence both. Acid deposition mainly develops when sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) react in the atmosphere and return to the surface through wet or dry processes. Climate change, in contrast, is driven largely by the accumulation of heat-trapping gases such as carbon dioxide and methane. Although the two problems share some emission sources, their atmospheric behaviour, geographical reach and consequences are different. This paper reviews the chemistry and major sources of acid deposition, explains the greenhouse effect and the principal drivers of global warming, and compares their effects on ecosystems, infrastructure and people. It also considers the cooling influence of sulphate aerosols, the interaction between changing climate conditions and pollutant deposition, and the policy measures used to reduce emissions. Experience with acid-rain control demonstrates the value of measurable limits, monitoring and cooperation between countries. However, climate mitigation requires a much broader and longer-term transformation of energy, transport, industry and land use.**



***Keywords—acid deposition, acid rain, climate change, global warming, greenhouse gases, sulphate aerosols, emission control***


## I. Introduction

Industrial development has increased the release of gases and particles into the atmosphere. Some pollutants are transformed and deposited back on land or water over a relatively short period, while certain greenhouse gases remain in the climate system for decades or centuries. This difference helps explain why acid deposition is often experienced across a region, whereas global warming affects the entire planet. The two concerns are nevertheless connected because power generation, transport, manufacturing and other fuel-consuming activities can release more than one type of pollutant.

The scientific study of these issues developed over many decades. Robert Angus Smith used the expression “acid rain” in his nineteenth-century work on air pollution [1]. Later, research by Likens and Bormann helped establish acidified precipitation as a serious environmental concern in North America and Europe [2]. In climate science, Svante Arrhenius examined the warming influence of atmospheric carbon dioxide in 1896 [3], while long-term measurements of atmospheric $CO_2$ subsequently provided important evidence of its increase.

This paper examines the distinction between acid deposition and climate change, their sources and impacts, the ways in which they interact, and the lessons that environmental policy can draw from earlier efforts to control acid rain.

## II. Acid Deposition

### *A. Meaning and chemical process*

Rainwater is naturally mildly acidic. This occurs because carbon dioxide from the air dissolves in water and forms a weak solution of carbonic acid. The pH of unpolluted rain is therefore commonly close to 5.6. When atmospheric pollution makes precipitation more acidic than this natural level, it is generally described as acid rain. The pH scale is logarithmic: a change from pH 5.6 to pH 4.6 represents a tenfold increase in hydrogen-ion concentration.

The wider scientific term is acid deposition. It includes wet deposition, such as rain, snow and fog, as well as dry deposition in which acidic gases and particles settle directly on surfaces. This broader term is useful because environmental damage can occur even when acidic material does not arrive as rainfall.

### *B. Main sources*

Sulphur dioxide is released when sulphur-containing coal and oil are burned and during the processing or smelting of certain metal ores. Nitrogen oxides are produced when fuel burns at high temperatures. Power plants, industrial boilers and road vehicles are therefore important contributors. After entering the atmosphere, these compounds undergo chemical reactions involving oxygen, water and other substances, producing sulphuric and nitric acids.

Natural events, including volcanic activity and lightning, also release compounds containing sulphur or nitrogen. In

heavily industrialised areas, however, emissions from human activities are often the dominant source. Agriculture can add to the problem through ammonia released from fertilisers and animal waste; atmospheric reactions involving this ammonia contribute to the formation of particulate matter and acid-related deposition.

Air currents may carry these pollutants far beyond the location where they were emitted. As a result, acid deposition can cross national borders, making cooperation between neighbouring countries necessary.

### C. Environmental and human consequences

*Aquatic ecosystems:* Acidification of lakes and streams can increase the amount of aluminium released from surrounding soils into the water. These conditions can harm fish, including trout and salmon, and can also affect amphibians and the organisms on which aquatic species depend. Some lakes in Scandinavia, eastern Canada and the Adirondack region have experienced serious losses of fish populations.

*Soils and forests:* Acidic deposition can remove important nutrients, particularly calcium and magnesium, from soil. It may also increase the availability of aluminium, which can damage tree roots. Trees weakened by these changes become less able to withstand drought, frost and pest attacks. Forest decline observed in parts of Central Europe during the 1980s is one frequently discussed example.

*Buildings and monuments:* Acidic substances react with materials such as limestone and marble and can accelerate the deterioration of buildings, statues and historic structures. In India, concern about air pollution and its effects on the marble surface of the Taj Mahal illustrates the importance of protecting cultural heritage.

*Human health:* Touching acid rain is not generally considered the main health risk. The greater concern is exposure to the gases and fine particles associated with it, including sulphur dioxide, nitrogen oxides, sulphates and nitrates. These pollutants can irritate the respiratory system and contribute to poor air quality.

## III. Global Warming and Climate Change

### A. Difference between the terms

Global warming describes the long-term rise in the average temperature of the Earth's surface and lower atmosphere. Climate change is a broader expression: it includes this temperature increase as well as related changes in rainfall, ice cover, sea level and the frequency or intensity of some extreme events. Natural factors have influenced climate throughout Earth's history, but the IPCC's Sixth Assessment Report states that human activities have unequivocally warmed the atmosphere, ocean and land [4].

### B. How the greenhouse effect works

Energy from the Sun reaches the Earth and warms its surface. The warmed surface then releases energy as infrared radiation. Greenhouse gases absorb some of this outgoing energy and emit it in different directions, including back towards the surface. This natural process keeps the planet warm enough to support life. The concern is not the existence of the greenhouse effect, but its strengthening as human activities increase the concentration of heat-trapping gases in the atmosphere.

### C. Major greenhouse gas sources

Carbon dioxide ($CO_2$) is released mainly through the use of coal, oil and natural gas. Cement manufacture and the removal of forests are additional sources. Because a portion of emitted $CO_2$ remains in the climate system for a very long time, continued emissions add to long-term warming.

Methane ($CH_4$) comes from sources such as livestock, rice cultivation, waste disposal and leaks associated with fossil-fuel production and distribution. A methane molecule traps more heat than a $CO_2$ molecule over a given comparison period, although methane remains in the atmosphere for a shorter time.

Nitrous oxide ($N_2O$) is associated particularly with agricultural soils receiving nitrogen fertilisers, as well as certain industrial activities. Fluorinated gases are used in refrigeration, cooling equipment and industrial applications. Their atmospheric concentrations are generally lower, but some have a strong warming effect.

The IPCC estimated that the global average surface temperature during 2011–2020 was approximately 1.1°C above the 1850–1900 average [4]. Individual years can temporarily reach higher levels. A single year above 1.5°C should not by itself be treated as proof that the Paris Agreement's long-term temperature objective has been crossed; that objective concerns sustained global warming.

### D. Major impacts

Rising temperatures increase the likelihood and intensity of heat extremes in many regions. Ice loss from glaciers and major ice sheets, together with the expansion of warmer seawater, contributes to sea-level rise and increases risks for coastal settlements, river deltas and island communities.

A warmer atmosphere can hold more water vapour, influencing rainfall patterns. Some areas may experience heavier rainfall and flooding, while others face longer or more severe dry periods. The oceans absorb a substantial share of human-produced carbon dioxide; this changes seawater chemistry and makes it more difficult for corals and shell-forming organisms to build and maintain their structures. Marine heat can also contribute to coral bleaching.

Wildlife may respond to changing conditions by shifting towards cooler regions or higher elevations. Species that cannot move or adapt quickly may face population decline. Human communities are affected through risks to food supplies, water availability, health and livelihoods. People with fewer resources are often less able to prepare for or recover from these impacts.

## IV. How the Two Environmental Problems Are Connected

### A. Overlapping emission sources

The use of fossil fuels is an important common factor. For example, a coal-fired power station can release carbon dioxide, which contributes to warming, along with sulphur dioxide and nitrogen oxides, which contribute to acid deposition. Vehicles and industrial facilities can also emit mixtures of pollutants. Reducing dependence on coal, improving energy efficiency and expanding renewable electricity can therefore deliver benefits for both climate and local air quality.

*B. The role of sulphate aerosols*

The relationship is not entirely straightforward. Sulphur dioxide can be converted into small sulphate particles in the atmosphere. These particles scatter incoming sunlight and can influence cloud properties, producing a temporary cooling effect that offsets part of the warming caused by greenhouse gases. When sulphur emissions are reduced, this short-lived cooling influence also declines. Regulations that reduce sulphur pollution may therefore reveal some warming that had previously been masked.

This effect is not an argument for continuing harmful sulphur emissions. Reducing these pollutants protects human health, ecosystems and buildings. Rather, it shows why air-quality programmes should be designed alongside strong reductions in carbon dioxide and other greenhouse gases.

*C. Climate influences on deposition*

Changes in temperature, rainfall and wind patterns can affect the movement and deposition of air pollutants. Heat and drought may place additional stress on forests and soils already affected by acid deposition. In the opposite direction, ecosystems damaged by acidic inputs may be less resilient when exposed to climate-related stresses. Coastal environments can also be affected by different processes: carbon dioxide changes ocean chemistry, while nitrogen and sulphur compounds may reach coastal waters through atmospheric deposition.

*D. Differentiating related issues*

Acid rain and global warming are two different processes. Carbon dioxide is a large greenhouse gas however it is not the main cause of acid rain. Acid deposition is mainly due to sulphur and nitrogen compounds. Ozone layer depletion is another issue within the atmosphere involving chemicals that damage the ozone layer in the stratosphere. This was addressed internationally through the Montreal Protocol.

## V. Policy Action and Lessons

*A. Progress in controlling acid rain*

International agreements and national regulations have helped reduce acid-forming emissions. The 1979 Convention on Long-Range Transboundary Air Pollution created a framework for countries to cooperate on pollution that travels across borders, followed by agreements addressing sulphur and nitrogen emissions [5]. In the United States, the 1990 Clean Air Act Amendments established an emissions cap-and-trade programme for sulphur dioxide from power plants [6].

Pollution-control equipment, cleaner fuels and tighter emission standards have contributed to substantial reductions in sulphur dioxide in North America and Europe. Acid deposition has consequently declined, and some affected lakes and streams show signs of recovery. Ecological recovery is not immediate: fish populations may take time to return, and soils can remain depleted after years of nutrient loss. Some industrialising regions experienced worsening pollution before stronger controls were introduced. Measures adopted in China during the 2010s have helped reduce sulphur emissions.

*B. International efforts on climate change*

Climate policy has developed through a sequence of international agreements. The United Nations Framework Convention on Climate Change was adopted in 1992, followed by the Kyoto Protocol in 1997 and the Paris Agreement in 2015. Under the Paris Agreement, countries committed to holding the increase in global average temperature well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C [7].

Governments use several approaches, including carbon pricing, emissions trading, renewable-energy programmes, efficiency standards and net-zero targets. The cost of technologies such as solar panels, wind turbines and batteries has fallen, supporting the growth of cleaner energy. However, current action remains insufficient to meet the agreed temperature goals, and global greenhouse-gas emissions need to decline more rapidly [8].

*Why climate change mitigation is complex and drought can cause further stress to forest and soil*

There are several reasons why controlling the climate change impacts caused by acid deposition is harder than reducing acid deposition. Firstly, the ecosystems that have been damaged by acidic inputs may be less able to deal with the impacts of climate stress. Secondly, the amount of time that different pollutants stay in the atmosphere varies; many acid forming pollutants are removed quickly from the atmosphere, however, a large proportion of carbon dioxide affects the climate for a long period of time. Thirdly, sulphur was emitted in a few clear industrial sources however carbon dioxide is released from electricity generation, transport, buildings, industry, agriculture and land use. Finally, carbon dioxide can be reduced using technologies like flue gas scrubbers however there is no one solution to reduce carbon dioxide like there is for sulphur.

*C. Recommended approaches*

Mitigation strategies include increasing renewable energy, increasing energy efficiency, moving away from transport and heating to electricity, reducing methane leaks, conserving forests and creating a more sustainable food industry. Adaption strategies include investing in flood defences, cooling cities, growing drought resistant crops and having reliable early warning systems. Policies should be considered holistically. For example, if high emitting coal is replaced then carbon dioxide, sulphur dioxide, nitrogen oxides and soot can all be reduced at once. 2

Financial investment into pollution control, cleaner fuels and emissions standards along with sharing technology has helped greatly reduce sulphur dioxide in North America and Europe. Acid deposition has decreased and some lakes and streams impacted by acid deposition have started to recover. However, ecological recovery may take time with fish populations in some areas taking time to return and soils may still be lacking nutrients after years of losing them. Some areas that are industrialising suffered from increased pollution until stricter controls were put in place. In China, actions taken in the 2010s have helped to reduce sulphur emissions.

## VI. Conclusion

Acid deposition and global warming are two separate issues however they are connected due to similar sources of emissions and the overall impact of humans on the atmosphere. Acid deposition is mainly caused by sulphur and nitrogen compounds causing damage to water bodies, forests, buildings and human health from associated air pollution. Global warming is mainly caused by greenhouse gases causing long lasting changes to temperatures, rainfall, ice and sea level. The reduction of acid rain in many areas shows how setting clear emission limits, monitoring, the correct economic incentives and working with other countries can make positive changes to the environment. Climate change requires a more holistic approach as carbon dioxide is emitted throughout the economy and will have a large influence. The cooling effect of sulphate aerosols shows that environmental policies can sometimes have unexpected interactions. Working together to create cleaner air and quickly reducing greenhouse gas emissions will help to protect ecosystems and communities.

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