PERSPECTIVES: ATMOSPHERIC SCIENCE

How Pollution Suppresses Rain

Owen B. Toon

Submicrometer-sized particles suspended in the atmosphere may have as great an impact on Earth's climate as the greenhouse gases that have accumulated in the atmosphere over the past century. Aerosols affect climate directly by scattering sunlight back to space and indirectly by augmenting the numbers of droplets within clouds. These effects cool Earth, counteracting the greenhouse effect (*1*). On page 1793 of this issue, Rosenfeld (*2*) provides evidence from satellite data that aerosol pollution suppresses precipitation, making the indirect effect of aerosols on climate even more substantial than previously thought.

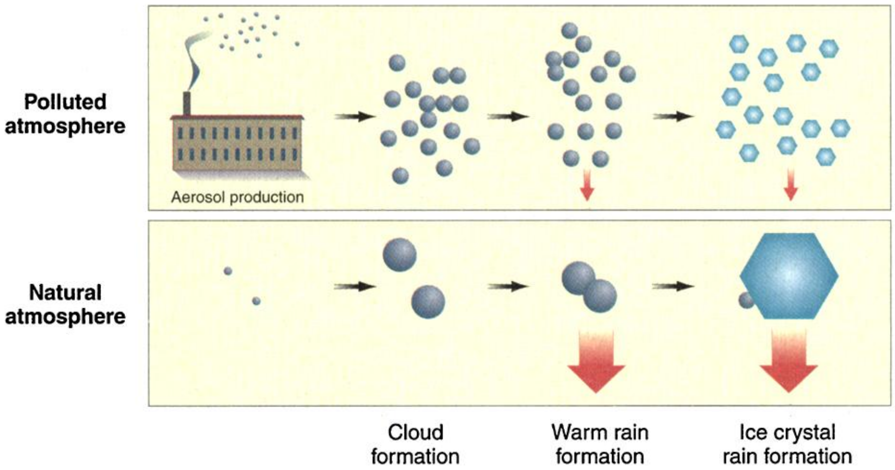
It remains unclear whether aerosols offset the greenhouse effect only slightly or cancel it entirely. This uncertainty stems from inherent difficulties in quantifying the impacts of aerosols on climate. In contrast to greenhouse gases, which remain in the atmosphere for a long time and are nearly uniformly distributed, aerosols tend to be concentrated near their sources and are highly variable in space and time. Their sizes range from clusters of a few molecules to sand, spores, and insect parts—a size range equivalent to that from baseballs to planets. Throw in further variables such as concentration, composition, optical properties, solubility, activity as ice formation nuclei, and particle shape, and it is understandable why, despite important advances in in situ (*3*, *4*) and satellite measurements (*5*), aerosols have remained so elusive to full characterization anywhere in the atmosphere.

Our rather primitive understanding of how aerosols modify cloud properties (see the figure on the right) goes back to Twomey (*6*). Pollution greatly augments the number of particles in the atmosphere. Each cloud droplet originates on a preexisting particle, and increasing the number of particles thus increases the number of cloud droplets. However, the temperature and the atmospheric motions driving cloud formation, rather than the number of droplets, control the mass of water condensing in the cloud. Therefore, if there are more cloud droplets, they will on average be smaller in size. A cloud containing smaller particles has a larger droplet surface area than a cloud with big particles for the same amount of condensed water. The optical depth of the cloud, a measure of the reflectivity of the cloud, is directly proportional to the surface area, and therefore pollution should lead to more reflective clouds.

Twomey's insights were largely ignored by the climate modeling community—perhaps because it seemed unlikely that such a simple analysis could capture the behavior of such a complex object as a cloud—until Coakley *et al.* (*7*) reminded the community of satellite images of ship tracks. Such tracks (see the figure on the next page) occur when a passing ship adds particles to a low-lying cloud deck. The clouds reflect more light to space in long lines where the ship exhaust is sufficiently concentrated, just as predicted. Some regions over the oceans have so few natural aerosols that cloud formation is suppressed (*8*). In these regions, injected particles from a passing ship will trigger new clouds.

Rosenfeld (*2*) presents the first images of pollution tracks over land. Ship tracks may be more obvious than pollution tracks, because the maritime air contains many fewer ambient particles than does continental air. Ship tracks and pollution tracks by themselves probably are not important to climate because they cover such a small area of Earth. However, they serve as a Rosetta stone for the potential impact of more widely distributed aerosol pollution on clouds. Climate modelers have made estimates of the magnitude of the indirect effect of aerosols on cloud reflectivity (*9*). However, much still remains to be learned about how aerosols modulate different types of clouds (*10*), alter the area covered by clouds, change their lifetimes, and modify their precipitation rates. Decreases in precipitation rates would alter the amount of surface moisture that might be used by humans. They will also induce changes in cloud reflectivity, lifetime, and area that may be as important for climate as the changes in reflectivity caused by the increased numbers of cloud droplets as a result of added aerosols (*9*).

Ship track measurements have yielded hints, but not clear evidence, that drizzle is affected by exhaust from ships. Rosenfeld (*2*) now demonstrates a clear widespread influence of aerosol pollution on continental precipitation. There are several mechanisms by which aerosols can suppress precipitation. Warm rain occurs when liquid cloud droplets fall into each other and coalesce to form much larger droplets. A typical cloud droplet grown from the vapor is about 10 μm in radius. Such particles fall a few centimeters per second and can travel only a few centimeters in dry air before evaporating, which is why we observe clouds suspended in our atmosphere. In contrast, a typical raindrop is a few millimeters in size, falls several meters per second, and can fall many kilometers through dry air before evaporating. About 10^6 cloud droplets must collide and coalesce in order to make a precipitation-sized drop. The rate at which a falling drop sweeps up other drops depends on the fall velocity, cross sectional area, and likelihood that falling particles actually touch and coalesce. Each of these process-



Processes by which aerosols affect clouds. The polluted cloud contains eight times as many droplets of half the size, twice the surface area, twice the optical depth, and higher reflectivity than the natural cloud.

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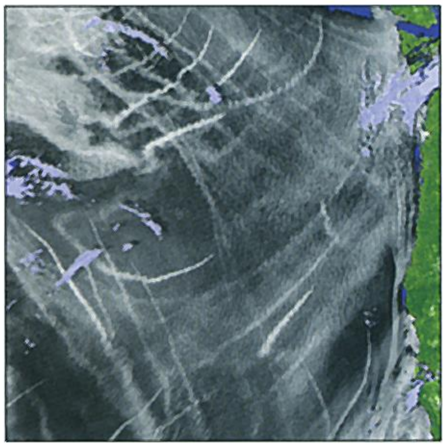
es varies approximately as the square of the radius for cloud drop–sized particles. In the example shown in the figure on the previous page, the droplets in the unperturbed cloud sweep up about 64 times the volume of air containing other droplets as the ones in the polluted cloud. Consequently, the polluted cloud would be much less likely to rain.

A complicating factor is the possible presence of giant soluble particles in the pollution, which could act as seeds for large droplets and initiate the precipitation process. Giant soluble particles are used in some modern cloud seeding efforts, and there is evidence of pollution-induced rainfall due to such particles.

Precipitation can also form in clouds below the freezing point, if ice forms. Ice has a lower vapor pressure than liquid water, and ice particles therefore grow rapidly to very large sizes by stealing vapor from surrounding liquid droplets. Large ice crystals then coalesce with liquid droplets to form rain. Ice crystals in the lower atmosphere form on ice nuclei, which constitute less than one out of every thousand particles in the ambient atmosphere. Ice nuclei are often composed of clay minerals. Many pollutant aerosols, such as sulfates, are not ice nuclei. A pollution source could add a few ice nuclei and induce precipitation. Alternatively, it could destroy ambient ice nuclei by coating them in sulfate or add so many ice nuclei that precipitation is suppressed (see the figure on the previous page).



Aerosol modification of marine clouds. A false color image of ship tracks (white streaks) in a boundary layer cloud deck (mottled white) offshore from the northwestern United States (green). Cloud-free ocean is dark blue, high-altitude clouds are light blue. The image was produced with the same type of Advanced Very High Resolution Radiometer satellite data that Rosenfeld (*2*) used to investigate pollution tracks.

Rosenfeld's (*2*) satellite observations indicate substantially reduced precipitation downwind of the pollution source. Multiple types of satellite sensors provide information about the mechanisms for precipitation suppression. Further satellite observations should determine how widespread the influence of aerosols on precipitation may be and whether it varies with the type of pollution or the properties of the clouds. Rosenfeld's work also points to locales where in situ observations should be made to pinpoint the mechanisms by which pollution affects clouds. Such knowledge may allow us to estimate how widespread the aerosol interaction with cloud precipitation may be in our globally polluted world.

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PERSPECTIVES: CELL CYCLE

Piecing Together the p53 Puzzle

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The delays that cells experience in G_1, S, or G_2 phases of the cell cycle after damage to DNA are collectively called DNA integrity checkpoints. There are two manifestations of these delays. The first is the transient arrest seen at G_1, S, or G_2 (independent of the key tumor suppressor protein p53) that gives the DNA repair machinery time to shore up the damage before division continues. The second (dependent on p53) is apoptosis or prolonged, probably permanent, G_1 delay that results in removal of damaged cells from the population. A failure to halt at these checkpoints leads to genomic instability and an increased likelihood that the cell will become cancerous. Studies in yeast have identified a network of DNA integrity checkpoint proteins (including four conserved kinases) that regulate the cell's entry into and exit from these cell cycle checkpoints. The *ATM* gene—mutated in the disease ataxia telangiectasia, which is characterized by a marked predisposition to cancer—is related to the yeast checkpoint kinase Rad3/Mec1. This is consistent with the inability of cells that lack ATM to halt at cell cycle checkpoints after DNA damage.

Mammalian homologs of the four yeast checkpoint kinases have been identified, suggesting that organisms from yeast to human have similar protein pathways for regulating these checkpoints. On page 1824 of this issue, Hirao *et al.* (*1*) report that mouse cells deficient in the checkpoint kinase CHK2—a homolog of yeast Cds1/Rad53—have several defective checkpoints after exposure to ionizing radiation (*1*). They further show that CHK2 stabilizes p53, a key player in regulating the prolonged G_1 arrest checkpoint. In another recent study, Bell *et al.* identified *CHK2* as the gene implicated in a small number of families with the cancer predisposition syndrome Li-Fraumeni, who do not have germ line mutations in *p53* (*2*). Together, these findings emphasize the importance of checkpoint kinases in preventing genomic instability and progression to cancer.

The p53-dependent transcription of target genes responds to a diverse range of cellular signals that affect cell proliferation and DNA integrity checkpoints (*3*). In undamaged cells that are dividing normally, p53 is highly unstable, with a half-life measured in minutes. After DNA damage induced by ionizing radiation (which is the only type of damage discussed here) the half-life increases significantly, leading to accumulation of p53 and transcription of target genes such as p21 and BAX. The outcome of this increased transcription depends on the type of cell but usually is manifest as a very prolonged (possibly irreversible) G_1 arrest or apoptosis (*4, 5*).

The instability of p53 depends on Mdm2, which binds to its amino terminus and targets it for ubiquitination and degradation. Preventing the interaction of p53 with Mdm2 is sufficient to promote its stabilization. At least 11 posttranslational modifications of p53 have been reported in response to DNA damage, and the relationship between these and p53 stability has attracted much attention. Although there are many conflicting reports in the literature, some data have suggested that phosphorylation of amino acids Ser^{15} and Ser^{20} is involved. In

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