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Linkages between Climate Change and Desertification

Smoke and desert dust stifle rainfall, contribute to drought and desertification

by Daniel Rosenfeld

"[These findings imply] that mankind may already have had a significant impact on tropical and subtropical rainfall in particular..."

Precipitation formation in clouds

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The precipitation efficiency of clouds is defined as the fraction of the water condensed in the cloud that is precipitated as rain or snow. The precipitation efficiency of a given cloud depends on the size of the cloud droplets, which in turn depends on the aerosols in the air, such as small particles of dust, smoke, and other kinds of particulate air pollution and natural substances. The reason for that dependence will become apparent from the following considerations.

To form one raindrop of modest size (1 mm diameter), one million small cloud droplets having a typical size of 10 microns (one micron is one thousandth of a millimeter) have to merge together. The coalescence of so many small droplets is quite a slow process, but it accelerates for larger cloud droplets, becoming faster by about an order of magnitude when the size of the cloud droplets is doubled. The size of the cloud droplets is determined primarily by the amount of condensed cloud water and the number of droplets among which this amount of water is divided. Aerosol particles that contain some soluble material, or that can at least become wet, can serve as nuclei around which the cloud water condenses. Therefore, a cloud ingesting air rich in such aerosols will contain a large concentration of small droplets and will precipitate more slowly than a similar cloud ingesting clean air, which forms small concentrations of larger droplets that coalesce faster into raindrops. If the lifetime of the cloud is short, it may dissipate before precipitation processes have had time to fully develop, and the cloud with the aerosol-induced smaller droplets will then precipitate less. However, aerosols can also enhance rainfall, if their particle size is very large. These large particles can serve as nuclei for large cloud droplets, which in turn accelerate the precipitation-forming processes.

This principle has been known for the last 50 years. However, it was not known whether the net overall effect of the aerosols would favor small particles, thus decreasing precipitation (e.g. Gunn and Phillips 1957), or large particles, thus enhancing precipitation (e.g. Eagen et al. 1974). This state of uncertainty prevailed until November 1997, when the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite (A cooperative project of NASA and NASDA, the American and Japanese space agencies) made possible the space-based, simultaneous monitoring of aerosols, cloud microstructure and precipitation over large areas.

Even before the launch of TRMM, it was possible to use measurements from operational NOAA weather satellites to retrieve data regarding cloud droplet effective radius (a quantity defined as the sum of the cube of the radii divided by the sum of the square of the radii of the particles in the measurement volume). It was found that clouds required droplets with effective radii of at least 14 microns for onset of precipitation (Rosenfeld and Gutman 1994). Satellite measurements of cloud particle size in clouds ingesting smoke from forest fires over the Amazon (Kaufman and Fraser 1997) and over Sumatra (Rosenfeld and Lensky 1998) showed that smoke caused cloud droplet sizes much smaller than the 14-micron precipitation threshold, whereas clouds in smoke-free areas were composed of drops larger than the threshold value. These findings strongly suggested that smoke hinders precipitation processes in clouds. However, this remained an indirect inference until the launch of TRMM satellite.

Smoke and precipitation

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TRMM was launched in the midst of an intense El Nino event that was associated with a severe drought in Indonesia. The Indonesian drought was further exacerbated by huge conflagrations of the rainforests, emitting extensive palls of smoke covering the whole region. Analysis of TRMM overpass over the island of Borneo, half smoke-covered, half smoke-free, and homogeneously covered with clouds of similar size, showed dramatic results. The clouds in the smoke-covered area were composed of small water droplets and did not precipitate, whereas the clouds in the smoke-free area were composed of large water droplets and precipitated readily. The measurements of the TRMM passive Microwave Imager (TMI) showed that the clouds in the smoky area contained ample water, but the TRMM precipitation radar (PR) could not detect any precipitation echoes, because all that water was in the form of small water droplets that did not coalesce into large raindrops (Rosenfeld 1999). These observations were replicated recently over the Amazon (Rosenfeld and Woodley 2001). The clouds in the smoky air precipitated only when their tops exceeded heights of about 6 to 6.5 km, which coincide with the isotherm of -10 degrees C in the tropics. At these temperatures, ice particles formed and provided alternative nuclei for the precipitation-forming processes.

Evidently, ice precipitation does form in the deep cumulonimbus clouds, even when the clouds are ingesting smoke. However, radar and aircraft observations in Thailand (Rosenfeld and Woodley 2001) indicated that even in the deepest clouds with the coldest top temperature, suppression of water droplet coalescence reduced their rainfall production to about half that produced by similarly deep clouds with active droplet coalescence. Aircraft measurements in clouds with suppressed coalescence showed that the small droplet size hindered freezing, in extreme cases keeping most of the cloud water in supercooled liquid phase until -37.5 degrees C (Rosenfeld and Woodley 2000). This is near the theoretical minimum allowed by the laws of thermodynamics. The cloud droplets then freeze homogeneously and are no longer available for conversion into precipitation. These observations were replicated by cloud model simulations (Khain et al. 2001), which provided a quantitative theoretical explanation.

Observations over the industrialized countries showed that it is not only smoke from burning vegetation that can suppress precipitation. Analyses of NOAA weather satellite data showed conspicuous tracks of reduced cloud droplets emanating from fixed points coinciding with major emission sources such as coal power plants, refineries, smelters, and large urban areas. Such pollution tracks were most visible in relatively pristine environments like Australia and Canada; the background in major industrialized areas such as the eastern U.S., parts of Europe and East Asia is so polluted that contributions of individual pollution sources are rarely evident there. Once again, using the TRMM satellite revealed that the clouds with tops warmer than -10 degrees C in these pollution tracks did not precipitate at all, whereas similar clouds outside the pollution tracks did precipitate. Furthermore, the measurements of the TRMM precipitation radar showed that some of the precipitation outside the pollution tracks formed as snow that melted into rain while falling through the clouds. (Rosenfeld 2000).

Dust and precipitation

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Desert dust is a major natural source of atmospheric aerosols that can potentially affect clouds. The impact of desert dust on rainfall was not known before the TRMM satellite was launched and applied to clouds forming in dust-laden air. The large sizes of some of these dust particles had led to the assumption that desert dust would enhance precipitation rather than decrease it. Scientists had expected that the largest dust particles would form "giant" cloud condensation nuclei and larger cloud droplets that would speed the formation of rain. However, laboratory analysis of Saharan desert dust transported to Israel showed that the particles contained very little water-absorbing matter (Rosenfeld et al. 2001). As a result, even large dust particles form relatively small cloud droplets. This has been confirmed by aircraft and satellite observations. NASA's TRMM spacecraft captured images of clouds over the Atlantic Ocean off the coast of northern Africa during a major dust storm in March 2000. The farther the clouds were from dust-filled air, the larger their water droplet sizes were. Rain was falling only from those clouds in dust-free air, even though all the clouds contained nearly equal amounts of water (Rosenfeld et al. 2001).

While the dust particles, in spite of their large size, act to suppress the coalescence of cloud droplets, they also serve as ice nuclei that enhance the formation of ice in the clouds. This works to restore some of the precipitation that was suppressed at the lower levels. Therefore, desert dust is probably a less potent aerosol for suppressing precipitation than is smoke from burning vegetation. However, the vast amounts and areal extent of desert dust in the atmosphere make it an important factor in suppressing potential raindrop formation. Furthermore, large amounts of dust or smoke can partially block solar radiation from arriving at the land surface and heating it, thereby suppressing the convection that produces the clouds in the first place. This radiative effect, by preventing cloud growth, can be as important in suppressing precipitation as the microphysical effect of reduction in cloud droplet size.

Implications

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Dust, therefore, provides a mechanism for amplifying the effects of desertification. Activities such as grazing and agricultural cultivation that expose and disrupt topsoil can increase the amount of dust blown into the air. More dust reaching rain clouds reduces their rainfall, which exacerbates drought conditions and contributes to the spread of desertification of the landscape. This suggests a new view of the decades-long drought in the African Sahel, which has been accompanied by increasing levels of airborne dust during rainy seasons. The higher dust frequency is not necessarily a result of the decreased rainfall, but may rather be its cause. It might well be that we can consider part of the desert dust as anthropogenic (i.e., having a human cause).

Similar considerations apply to the less arid areas in the subtropics, where population has been growing strongly without a parallel increase in standards of living. Traditional subsistence agricultural practices and grazing have therefore expanded at a comparable rate, as have emissions of smoke from agricultural burning and dust from topsoil disruption. This might explain the observed decreasing trend of precipitation over the tropical land areas of the northern hemisphere, which, according to Gribbin (1995), lost 10 to 15% of rainfall during recent decades.

This implies that mankind may already have had a significant impact on tropical and subtropical rainfall in particular, and through that on the whole global climate system in general. Unlike greenhouse gases, these impacts are immediate at both local and global scales, affecting water resources and global atmospheric circulation and weather patterns. Also unlike greenhouse gases, where the time and location of emission and its impacts are disconnected, there is immediate accountability to the emission of aerosol particulates. This implies, in turn, that implementing measures to halt such emissions could well have positive local and regional effects almost imediately. This opens new possibilities such as regulation of agricultural and other controlled fires, as well as other emissions, to days where no potential susceptible rain clouds are forecasted downwind. Before that happens, more research needs to be done for quantifying the potential impacts in terms of changes in the available amounts of water. For now, only the first few steps have been made.

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NASA's Tropical Rainfall Measuring Mission
http://trmm.gsfc.nasa.gov/

Changing our weather one smokestack at a time
http://earthobservatory.nasa.gov/Study/Pollution/pollution.html
From NASA's Earth Observatory web site, a report on Dr. Rosenfeld's research on the impact of air pollution on clouds

Droughts aggravated by dust in the wind
http://www.gsfc.nasa.gov/gsfc/earth/dust/rainfall.htm
From NASA's Goddard Space Flight Center, further information on Dr. Rosenfeld's research.

Sahara dust forecast
http://earth.nasa.proj.ac.il/dust/current/dust.html
From Tel-Aviv University, this web page provides 12-hour, 24-hour, 36-hour and 48-hour dust-loading forecasts for the entire Sahara region.

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