Clouds and Climate: Unravelling a Key Piece of Global Warming

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Anthropogenic emissions have altered the composition of the global atmosphere during the 20th century. Evidence that these changes have led to a discernable influence on global climate is mounting. Yet, the global climate system is complex, replete with intricate feedbacks, and it has proved challenging to attribute observed climate changes unambiguously to anthropogenic emissions.

While few chemical engineers are actively involved in global climate research, federal policy decisions relating to mitigation of greenhouse gas and other emissions have the potential to exert an enormous impact on industries in which chemical engineers play a prominent role. Many in these industries keep close watch on the development of scientific understanding associated with predictions of global climate change. We review here one of the most critical, and most uncertain, pieces of the climate puzzle, the role of aerosols and clouds in the global energy balance.

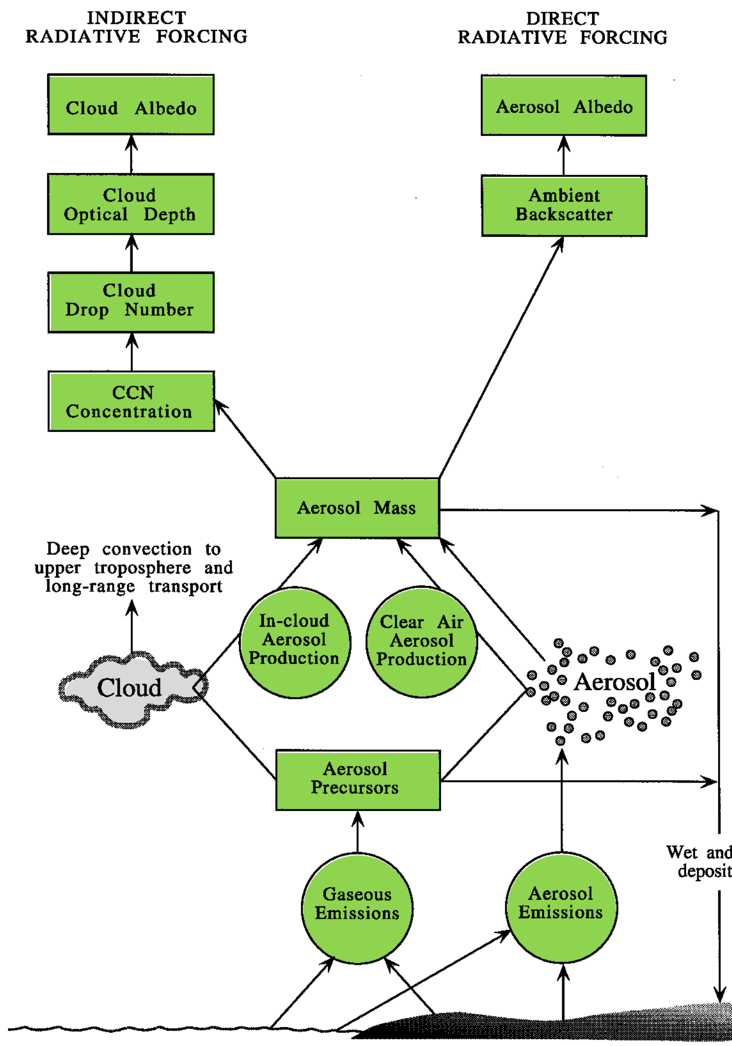

Figure 1. Direct and indirect mechanisms of aerosol effects on radiation and climate.

Global albedo

The Earth's climate system continually adjusts to maintain a balance between incoming energy from the sun and that radiated back to space. Energy goes back to space from the Earth in two ways: reflection and emission. The fraction of solar energy that is reflected back to space is called the albedo: oceans have low albedo; deserts, ice, and snow have high albedos. On a global average, about 30% of incoming solar radiation is reflected back to space. Radiation emitted by the Earth is mostly at infrared (IR) wavelengths.

No element of the climate system is more influential to the global energy budget than clouds. Because a cloud generally has a higher albedo than the surface underneath it, the cloud reflects more radiation back to space than the surface would in the absence of the cloud, in this way leaving less radiation available to heat the surface and the atmosphere. The situation is not that simple, however. Whereas low, thick clouds primarily reflect solar radiation and cool the surface of the Earth, high, thin clouds transmit most of the incoming solar radiation. Like air itself, however, high, thin cirrus clouds absorb Earth's radiation and then emit infrared radiation both out to space and back to the Earth's surface. Because such clouds are high, and thus cold, the energy radiated to space is lower than it would be without the cloud. The portion of the radiation thus trapped and sent back to the Earth's surface causes a warming of the surface and atmosphere. Although low stratocumulus clouds also emit longwave radiation both to space and toward the Earth's surface, their temperature is essentially that of the surface so that they radiate at the almost same intensity as the surface and do not greatly alter the infrared radiation sent to space. The overall effect of these opposing influences is globally a net cooling, although whether a given cloud will heat or cool the surface depends on the cloud's altitude and size, as well as the properties of the particles that comprise the cloud.

Impact of anthropogenic emissions on clouds

Cloud optical properties are controlled by the sizes of the droplets in the cloud, which, in turn, are controlled by the availability of atmospheric particles that serve as cloud condensation nuclei (CCN). "Background" aerosol particles, which would be present in the absence of humans, are supplemented by particles from anthropogenic sources, either directly in the form of soot or other components, or indirectly from conversion of gases such as SO_2 and nitrogen oxides. Twomey (1977) suggested that an increase in atmospheric aerosols from anthropogenic emissions, and thus an increase in CCN, would lead to a reduction in the radius of cloud droplets since the same amount of water is spread over more condensation nuclei. For the same liquid water content, a cloud with more smaller drops has a higher albedo than one with fewer larger drops. A "brighter" cloud reflects more radiation back to space and leads to planetary cooling. In addition to altering cloud albedo, changes in the cloud droplet size distribution may also alter cloud lifetime, further influencing global albedo. The clouds that exhibit the greatest sensitivity to changes in the CCN population are those in clean maritime air masses. Climatologically, these marine clouds are the most important on Earth, as they cover vast areas of the oceans. It is interesting to note that the impact of increasing particle concentrations at high altitudes, which would produce more numerous and smaller cirrus ice particles, would be to increase IR emissivity more than cloud albedo, and thus lead to more heating, a reverse Twomey effect.

There is observational support for the effect of increasing atmospheric particle concentrations on clouds. Analysis of satellite data by Han et al. (1994) showed that Northern Hemisphere marine clouds have consistently smaller mean drop sizes than those in the Southern Hemisphere, where anthropogenic emission levels are significantly less. There is a consistent upward trend of cirrus fractional cloudiness in dense air traffic corridors in the last two decades; areas of low air traffic do not exhibit such a trend. A reduction in transmission of solar radiation by clouds of as much as 8% per decade has been observed at several sites in Germany from 1964 to 1990 (Liepert and Kukla, 1997). The reduction in transmission of 8%/decade is roughly consistent with the approximately 30% increase in global anthropogenic SO_2 emissions over that period. Finally, ship tracks (cover) are direct evidence of the effect of high aerosol concentrations on cloud albedo.

To predict cloud droplet number concentration, N_d, in a climate model requires representations of both the CCNspectrum and the dynamic and thermodynamic properties of the cloud. At present, neither aerosol nor cloud properties are sufficiently well understood for physically-based prediction of N_d in global models. What is currently done is to relate N_d to some available aerosol property. The mass concentration of sulfate aerosol is predicted in global models, and one empirical approach is to relate N_d to sulfate aerosol mass either by assuming a sulfate size distribution (Jones et al., 1994) or by using observational data (Boucher and Lohmann, 1995).

The global impact of anthropogenic emissions on clouds is determined not just by the instantaneous mean albedo of clouds but also by their geographic extent. The extent of cloudiness is intimately connected to cloud lifetime; the longer the lifetime, the higher the extent of the cloudiness. The longevity of a cloud is determined by a delicate balance between the sources and sinks of condensed water (see, for example, Albrecht, 1989). Suffice it to say that the relationship among cloud lifetime, precipitation, and aerosols is one of the most complex in all of atmospheric science and is not likely to be represented fundamentally in global climate models anytime soon.

The principal atmospheric gas concentrations that have increased over the last century are CO_2, CH_4, N_2O, and chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2). The observed increase in CO_2 from about 280 parts per million by volume (ppm) in the preindustrial era to about 364 ppm in 1997 has come largely from fossil fuel combustion and cement production. The atmospheric mixing ratios of CH_4 and N_2O have increased from about 700 parts per billion (ppb) and 275 ppb to 1,721 ppb and 312 ppb, respectively, in 1994. The additional amounts of these so-called greenhouse gases increase the IR energy absorbed by the atmosphere, thereby exerting a warming influence on the lower atmosphere and the surface. The radiative influence of an increase in a greenhouse gas concentration can be computed as the change in downward flux at the tropopause, a quantity called the radiative forcing and expressed in $W \cdot m^{-2}$. The sum of greenhouse gases is estimated to have produced a radiative forcing of $+2.5\,W \cdot m^{-2}$ (Houghton et al., 1996).

Global climate models

Predicted responses of the climate system to increases in greenhouse gases and aerosols are based on models that simulate fundamental geophysical processes. Most current model simulations of Earth's climate indicate that the increase in greenhouse gases will lead to an increase in the average surface air temperature; a doubling of current atmospheric CO_2 is predicted to produce an equilibrium temperature increase of 2.0 ± 0.6°C (Kattenberg et al., 1996). Models that have been used to study climate change are necessarily simplified representations of the climate system, however. The relatively coarse resolution of the models (typically 3° or roughly 300 km) limits their ability to accurately represent processes that occur on smaller scales, and a major process in this regard is clouds and precipitation. Whether average global cloudiness would increase or decrease in a future greenhouse-enhanced world is not yet established.

Global climate models have been used to estimate anthropogenic direct and indirect aerosol radiative forcing (Figure 1). For sulfate aerosols, estimates of global mean direct forcing range from –0.3 to – 1.2 $W \cdot m^{-2}$, depending on the predicted global burden of sulfate, the assumed hygroscopic behavior of the particles, and whether associated inorganic species such as nitrate and ammonium are accounted for. Thus, serving to cancel greenhouse warming in those regions of the Earth where aerosol levels are high, principally the industrialized areas of the Northern Hemisphere, aerosol cooling establishes gradients in global heating and cooling that may actually exacerbate climatic effects. While cloud responses to a warmer, smoggier atmosphere are uncertain and could be the gremlin lurking in the climate greenhouse, these responses are unlikely to change the signs of either greenhouse heating or aerosol cooling.

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