IMPACT OF AEROSOLS ON THE HYDROLOGICAL CYCLE

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Anthropogenic aerosol particles such as sulfate and carbonaceous aerosols have substantially increased the global mean burden of aerosol particles from preindustrial times to the present-day. These aerosol particles can interact with clouds and precipitation by acting as cloud condensation or ice nuclei. Thus they have an influence on the radiative balance of the Earth-Atmosphere system but they could have an influence on the hydrological cycle. While the cloud albedo enhancement (Twomey effect) of warm clouds received most attention so far and traditionally is the only indirect aerosol forcing considered in transient climate simulations, here I discuss the multitude of effects. These indirect effects can be subdivided into different contributing processes, as summarized in Table 1 (see over) and shown in Figure 1 (see page 217).

The cloud-albedo effect, i.e. the distribution of the same cloud liquid water content over more, hence smaller, cloud droplets leading to higher cloud reflectivity, is a purely radiative forcing. The other effects involve feedbacks in the climate system. The albedo effect cannot be easily separated from the other effects; in fact, the processes that decrease the cloud droplet size per given liquid water content also decrease precipitation formation, hence prolonging cloud lifetime (cloud lifetime effect). The glaciation effect refers to an increase in ice nuclei resulting in a rapid glaciation of a supercooled liquid water cloud due to the difference in vapour pressure over ice and water. Unlike cloud droplets, these ice crystals grow in an environment of high supersaturation with respect to ice, quickly reaching precipitation size, and with that can turn a non-precipitating into a precipitating cloud. The thermodynamic effect refers to a delay in freezing by the smaller droplets causing supercooled clouds to extend to colder temperatures.

TABLE 1.

Effect	Cloud Types Affected	Process	Sign of Change in TOA Radiation	Sign of Change in Precipitation
Cloud albedo effect	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	Negative for water clouds, positive or negative for ice clouds	n/a
Cloud lifetime effect	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	Negative	Negative
Glaciation indirect effect	Mixed-phase clouds	An increase in ice nuclei increases the precipitation efficiency	Positive	Positive
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing supercooled clouds to extend to colder temperatures	Positive or negative	Positive or negative

Aerosol Effects on Water Clouds and Warm Precipitation

The indirect aerosol forcing of increasing cloud albedo for warm clouds does not have any direct impact on precipitation and therefore is not discussed any further. In addition aerosols increase the lifetime of clouds because increased concentrations of smaller droplets lead to a decreased drizzle production (Albrecht, 1989). It has proven difficult to devise observational studies that can separate the cloud lifetime from the cloud albedo effect; thus, observational studies in most instances provide estimates of the combined effects. Similarly, climate modeling studies cannot easily separate the cloud lifetime indirect effect once aerosol are interacting with clouds.

Evidence of a cloud lifetime effect due to anthropogenic emissions of aerosols and their precursors stem, for instance, from the absence of a drizzle mode in ship tracks that perturb marine stratus cloud decks off the coast of California (Ferek *et al.*, 1998). Also regionally this effect is found

when separating polluted from clean clouds off the Atlantic coast of Cana-
da (Peng *et al.*, 2002). One remaining problem is that most climate models
suggest an increase in liquid water when adding anthropogenic aerosols,
whereas newer ship track studies show that polluted marine water clouds
can have less liquid water than clean clouds (Platnick *et al.*, 2000; Coakley
and Walsh, 2002). Ackerman *et al.* (2004) attributed this phenomenon to
enhanced entrainment of dry air in polluted clouds in these instances. On
the other hand, satellite observations have been used to conclude that the
aerosol indirect effect is likely primarily due to an increase in cloud cover,
rather than an increase in cloud albedo (Kaufman *et al.*, 2005).

Smoke from burning vegetation reduces cloud droplet sizes and delays
the onset of precipitation (e.g., Warner and Twomey, 1967; Andreae *et al.*,
2004). Also, desert dust suppresses precipitation in thin low altitude clouds
(Rosenfeld *et al.*, 2001; Mahowald and Kiehl, 2003). Givati and Rosenfeld
(2004) evaluated changes in orographic precipitation over the last 100 years.
They indicated surface precipitation losses over topographical barriers by
15-25% downwind of major coastal urban areas in California and in Israel
likely caused by aerosols. Contradictory results are found regarding the sup-
pression of rainfall from aerosols in Australia (Rosenfeld, 2000; Ayers, 2005).

Global Climate Model Estimates of the Total Anthropogenic Aerosol Effect

The global mean magnitude of the cloud albedo effect since pre-indus-
trial times is estimated between -0.5 and -1.9 W/m^2 from different climate
models and the cloud lifetime effect to be between -0.3 and -1.4 W/m^2
(Lohmann and Feichter, 2005). Thus, whether the cloud lifetime or the
cloud albedo effect is more important, is still an open question. Whereas
some models predict that the cloud albedo effect is four times as important
as the cloud lifetime effect, other models predict that the cloud lifetime
effect dominates over the cloud albedo effect (Figure 2, see page 218). If the
individual indirect effects values are summed up, the indirect effect could
amount to almost -3 W/m^2. This exceeds estimates from simple inverse
models, that start from the observed land temperature raise and increased
ocean heat uptake in the 20th century, which bracket the overall indirect
aerosol effect to be between 0 and -2 W/m^2 (Anderson *et al.*, 2003). Thus,
either climate model predictions of the cloud albedo and/or cloud lifetime
effect are too large, or a counteracting effect is missing.

One possible counteracting effect is the glaciation aerosol effect by
which an increase in ice nuclei will cause some supercooled droplets to

freeze. Because the vapor pressure is lower of ice than over water, the ice crystals quickly grow at the expense of cloud droplets (Bergeron-Findeisen process) and the supercooled liquid water or mixed-phase clouds turns into an ice cloud. Because the precipitation formation via the ice phase is more efficient than in warm clouds, these glaciated clouds have a shorter lifetime than supercooled water clouds (Rogers and Yau, 1989).

Motivated by laboratory studies, Lohmann (2002) and Lohmann and Diehl (2006) show that if, in addition to mineral dust, hydrophilic black carbon aerosols are assumed to act as ice nuclei at temperatures between 0°C and –35°C, then increases in ice nuclei in the present-day climate as compared to pre-industrial times result in more frequent glaciation of supercooled stratiform clouds and increase the amount of precipitation via the ice phase. This decreases the global mean cloud cover and leads to more absorption of solar radiation. Whether the glaciation or warm cloud lifetime effect is larger depends on the chemical nature of the dust (Lohmann and Diehl, 2006). Likewise, the number and size of ice particles in convective mixed phase clouds is sensitive to the chemical composition of the insoluble fraction (e.g., dust, soot, biological particles) of the aerosol particles (Diehl and Wurzler, 2004).

Aerosols and Sahel Drought

Several studies have considered the response of a global climate model (GCM) with a mixed-layer ocean to indirect aerosol effects (e.g., Williams *et al.*, 2001; Rotstayn and Lohmann, 2002) or to a combination of direct and indirect aerosol effects (e.g., Feichter *et al.*, 2004; Kristjansson *et al.*, 2005). All of these found a substantial cooling that was strongest in the Northern Hemisphere, with a consequent southward shift of the Intertropical Convergence Zone (ITCZ) and the associated tropical rainfall belt (Figure 3, see page 219). Rotstayn and Lohmann (2002) went on to suggest that aerosol effects might have contributed to the Sahelian droughts of the 1970s and 1980s. The southward shift of the ITCZ was less pronounced in the Feichter *et al.* (2004) study than in the other studies, perhaps due to their more complex treatment of cloud droplet nucleation, which tends to give less weight to the effects of sulfate than simpler schemes do. In contrast, Chung and Seinfeld (2005) considered the response of a GCM to direct forcing by black carbon aerosols, and found a northward shift of the ITCZ due to enhanced warming of the Northern Hemisphere.

Effects of Aerosols/Clouds on the Solar Radiation at the Earth's Surface

By increasing aerosol and cloud optical depth, emissions of aerosols and their precursors from human activity contribute to a reduction of solar radiation at the surface ('solar dimming') between 1961-1990 (e.g., Gilgen *et al.*, 1998; Liepert, 2002; Stanhill and Cohen, 2001). The decrease in solar radiation at the surface resulting from the increases in optical depth due to the direct and indirect anthropogenic aerosol effects is more important for controlling the surface energy budget than the greenhouse gas induced increase in surface temperature. There is a slight increase in downwelling longwave radiation due to aerosols, which in the global mean is small compared to the decrease in shortwave radiation at the surface. This has been shown in equilibrium simulations with a global climate model coupled to a mixed-layer ocean model with increasing aerosol particles and greenhouse gases from pre-industrial times to present-day (Liepert *et al.*, 2004; Feichter *et al.*, 2004), and in transient simulations (Roeckner *et al.*, 1999). The other components of the surface energy budget (thermal radiative flux, sensible and latent heat fluxes) decrease in response to the reduced input of solar radiation, which may explain the observations of decreased pan evaporation over the last 50 years reported in several studies. As global mean evaporation must equal precipitation, a reduction in the latent heat flux in the model led to a reduction in precipitation (Liepert *et al.*, 2004). This is in contrast to the observed precipitation evolution in the last century and points to an overestimation of aerosol influences on precipitation, or to an important ice cloud aerosol indirect effect. The decrease in global mean precipitation from pre-industrial times to the present may, however, reverses into an increase of about 1% in 2031-2050 as compared to 1981-2000, because the increased warming due to black carbon and greenhouse gases then dominates over the sulfate cooling (Roeckner *et al.*, 2006 and Figure 4, see over).
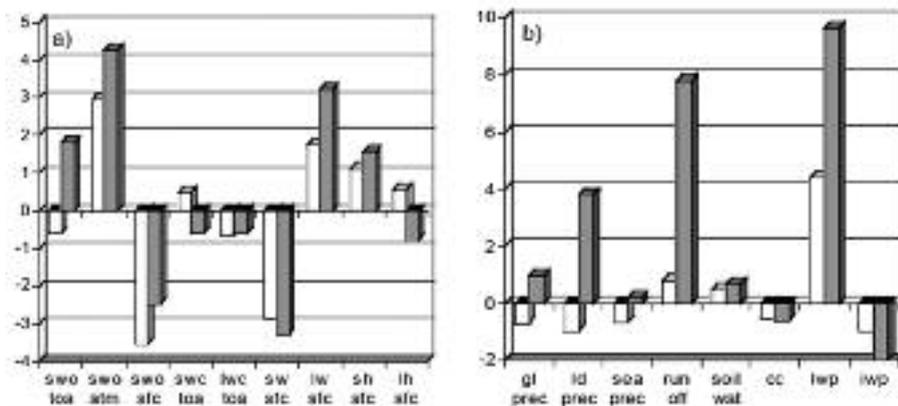
Figure 4. Changes in annual and global mean heat fluxes (left, units are Wm^{-2}) and components of the hydrological cycle (right, percentage changes) between 2031-2050 and 1981-2000 [grey columns] and between 1981-2000 and 1861-1880 [white columns] (adapted from Roeckner *et al.*, 2006).

Notations: toa=top-of-atmosphere, atm=atmosphere, sfc=surface, swo=net clear-sky, shortwave radiation; swc, lwc=shortwave/longwave cloud forcing; sw, lw=net shortwave/longwave radiation; sh, lh=sensible/latent heat flux (negative upward); prec=precipitation; evap=evaporation (positive upward); soil wat=soil water; cwv=column water vapor; cc=total cloud cover; lwp, iwp=cloud liquid water/ice path.

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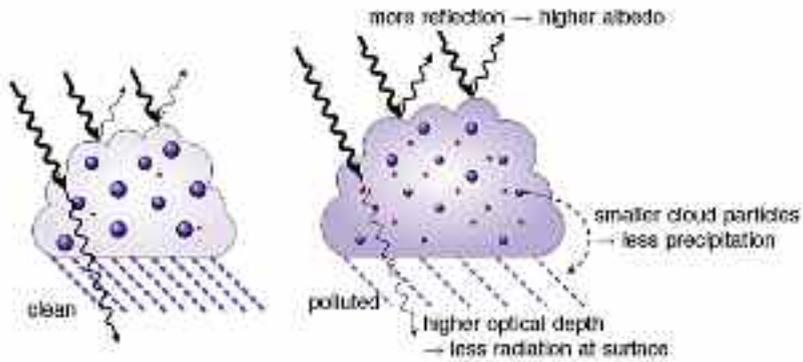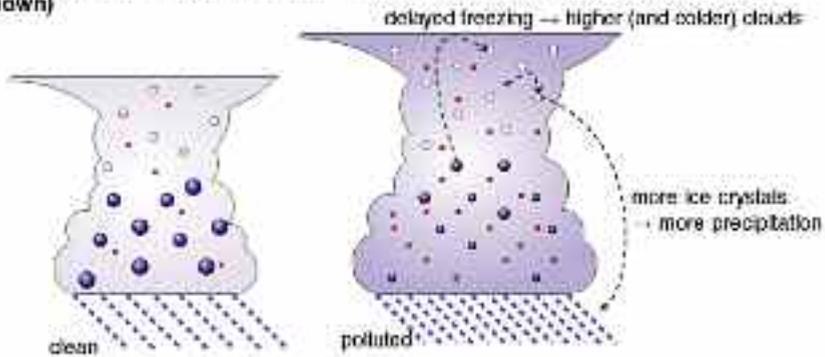
Figure 1. Schematic of the aerosol effects discussed in Table 1 (page 105).
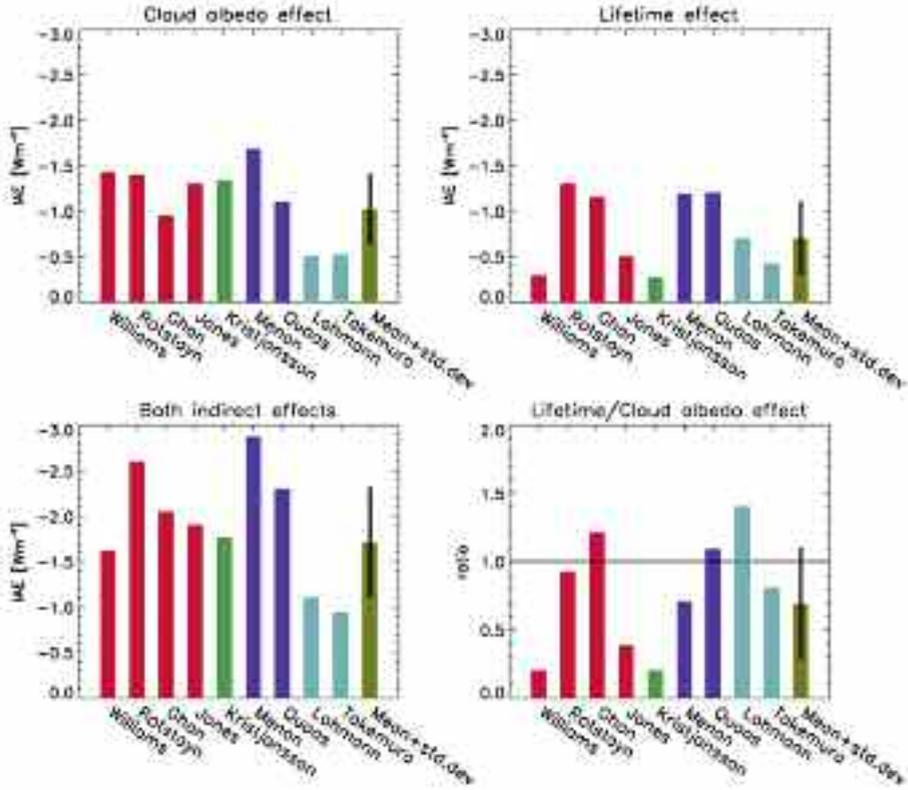
Figure 2. Global mean cloud albedo effect, lifetime effect, both effect and the ratio lifetime effect/cloud albedo effect for different models considering only anthropogenic sulfate aerosols (red bars), of anthropogenic sulfate and black carbon (green bars), of anthropogenic sulfate and organic carbon (blue bars), of anthropogenic sulfate and black, and organic carbon (turquoise bars) and the mean plus standard deviation from all simulations (olive bars), adapted from Lohmann and Feichter (2005).
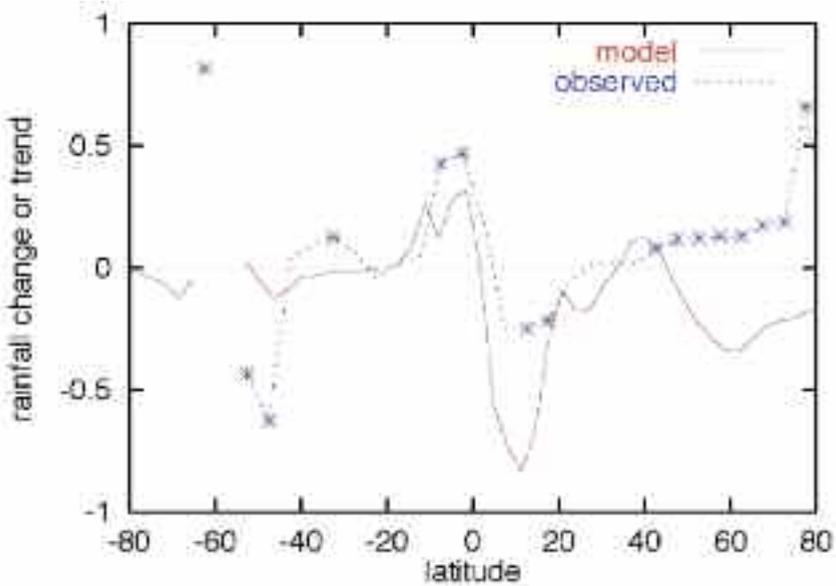
Figure 3. Zonally averaged trend in observed annual-mean precipitation over land for the period 1901-1998 after Hulme *et al*. (1998) in mm day^{-1} per century (blue dotted line) and zonally averaged difference in annual-mean precipitation over land between the present-day and pre-industrial simulations in mm day^{-1} (solid red line). Points at which the observed trend is (is not) significant at the 5% level are shown as asterisks (pluses). Courtesy of Rotstayn and Lohmann (2002).