Aerosol effects on convective clouds

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Clouds and precipitation play crucial roles in the Earth's energy balance, global atmospheric circulation and the water cycle [1,2]. Basic knowledge about clouds' properties and rain formation is critical for the understanding of the current climate and for future climate predictions, availability of fresh water and the ability of the atmosphere to clean itself. Aerosol effects on clouds are recognized as a major component of the total anthropogenic effect on climate and on the water cycle. Understanding the different cloud feedbacks initiated by changes in aerosol properties poses one of the greatest challenges in climate, cloud physics and radiative transfer. Human activities like fossil fuels and biomass burning, or desertification can contribute significantly to an increase in the aerosol loading and changes in aerosol properties. The strong sensitivity of the climate system to clouds, and the steadily increasing demand for water resources, makes it a problem of major importance.

1. General

Why is the estimation of aerosol effects on clouds and precipitation challenging? The answer lies within two poles: the inherent complexity of the microphysical and dynamical processes involved and the complexity in measuring and modeling them.

Scales (in time and space) are a key component in understanding both the processes and the modeling-measurements results. A single cloud, and on a larger scale, a cloud field, form a classical example of a complex system. Numerous dynamic and thermodynamic, radiative and chemical processes are acting and interacting in a spatial scale range from aerosol nucleation ($<10^{-6}$m) to the size of a cloud field ($>10^{5}$m). Many of the processes are coupled creating a complex web of feedback loops on all scales. As in many dynamical systems cloud response to changes in the environmental conditions will not be linear. Some of the effects can be damped by negative feedbacks, resulting in relatively small changes in the average cloud properties, while others can result in an escalation of the cloud system into a different state, resulting in dramatic changes in lifetime, coverage, morphology and precipitation.

Development of clouds and cloud fields depends on the environmental conditions and on the distribution of atmospheric aerosols (natural and man-made) that serve as cloud condensation nuclei (CCN) and ice nuclei (IN). Environmental conditions such as temperature and humidity profiles, winds, heat and moisture surface fluxes and their evolution in time, determine the potential of clouds to form, grow and to develop warm (liquid only), mixed, or cold phase precipitation. Changes in aerosol loading and properties may influence cloud and rain development by either affecting the CCN/IN concentrations and properties, a pathway we refer to as microphysical, or by changing the atmospheric environment – the environmental pathway.

The superposition of the microphysical and environmental effects on cloud coverage, cloud vertical development [3] and on thunderstorm electrical activity [4], was shown to be associated with increasing amount of anthropogenic smoke. Of course the two pathways are coupled and changes in the atmospheric temperature and humidity profiles may strongly affect the microphysical properties and vice versa. But such classification is useful since it provides a general metric to all anthropogenic effects.

2. Invigoration

The microphysical pathway describes the processes that involve nucleation of new droplets and ice particles and the evolution in their properties and size distributions. More aerosols result in more and smaller droplets. As clouds are highly non-linear, this single change may set in motion a series of many feedbacks that affect the cloud properties and rain processes. Changes in the concentration and size-distribution of droplets will change condensation/evaporation rates, latent heat release, and the rates of collision coalescence of droplets [5] [6,7]. The mixed and cold parts of the cloud (containing ice) will also be affected by the change in the droplet sizes and concentration. In addition the availability of IN will be changed, thus igniting a series of additional feedbacks in the mixed and cold phase regions [8,9]. These changes will affect the rain processes (early-warm rain and then cold rain), the dimensions and lifetime of the clouds [10] and their optical properties [11].

Among the expected effects of the addition of aerosol, are the suppression of the development of warm rain and the delay of cold precipitation [12] [13]. It was suggested that increase in aerosol loading can invigorate convective clouds and amplify convective rain-rate [14]. Invigoration is initiated by changes in the droplet size distribution, smaller drops have smaller terminal velocities and are less efficient to be collected therefore per a given updraft will reach higher in the cloud. This will feedback on the location and rate of latent heat release in the cloud and is likely to further push the droplets higher in the cloud while suppressing warm rain [4,15-17,18]. Another expected positive feedback takes place in the transition to the cold phase, when the smaller droplets are expected to freeze higher in the atmosphere releasing the freezing latent heat in colder background temperatures, and creating larger buoyancy above it. Additional buoyancy allows invigoration of the clouds, causing stronger updrafts, larger hail, a greater likelihood for intense convection [15,9] and more electrical activity [19]. The anthropogenic effects on precipitation reaching the ground are even more complex and stand at the end of this “food chain” of cloud feedbacks. Changes in the atmospheric profile and the droplets’ activation rates and size distribution will initiate a series of feedbacks that eventually will determine whether a droplet, initiated at a size of few microns, can grow three orders of magnitude within a cloud lifetime to the size of a rain drop (few mm) and reach the surface. Numerous observations and modelling studies have been conducted to estimate if there is a clear trend linking changes in aerosol loading to changes in ground precipitation [20,21]. Some studies suggest a decrease in the rain-rate and total rain amount from deep convective clouds [22,23], others show no clear effect [24] and a few suggest rain rate enhancement by aerosols [25]. A recent study [14] showed that in line with cloud convective invigoration the thicker polluted clouds produce stronger rain-rates. The relationship is apparent over land and ocean in the tropics, subtropics and mid-latitudes.

The overall effect of aerosol on cloud characteristics and precipitation production is far from clear and depends on the cloud type, size and environmental conditions.

3. References

1. Baker, M.B. and T. Peter, *Small-scale cloud processes and climate.* Nature, 2008. **451**(7176): p. 299-300.
2. Trenberth, K.E., J.T. Fasullo, and J. Kiehl, *Earth's Global Energy Budget.* Bulletin of the American Meteorological Society, 2009. **90**(3): p. 311-323.
3. Koren, I., et al., *Smoke invigoration versus inhibition of clouds over the Amazon.* Science, 2008. **321**(5891): p. 946-949.
4. Altaratz, O., et al., *Lightning response to smoke from Amazonian fires.* Geophysical Research Letters, 2010. **37**.
5. Warner, J., *A reduction in rainfall associated with smoke from sugar-cane fires-an inadvertent weather modification.* J. Appl. Meteorol., 1968. **7**(2): p. 247.
6. Xue, H. and G. Feingold, *Large eddy simulations of tradewind cumuli: investigation of aerosol indirect effects.* J. Atmos. Sci., 2006. **63**: p. 1605-1622.
7. Altaratz, O., et al., *Aerosols' influence on the interplay between condensation, evaporation and rain in warm cumulus cloud.* Atmospheric Chemistry and Physics, 2008. **8**(1): p. 15-24.
8. Rosenfeld, D. and W.L.K. Woodley, *Deep convective clouds with sustained supercooled liquid water down to -37.5 [deg]C.* Nature, 2001. **405**: p. 440-442.
9. Khain, A., D. Rosenfeld, and A. Pokrovsky, *Aerosol impact on the dynamics and microphysics of deep convective clouds.* Quarterly Journal of the Royal Meteorological Society, 2005. **131**(611): p. 2639-2663.
10. Jiang, H., et al., *Aerosol effects on the lifetime of shallow cumulus.* Geophysical Research Letters, 2006. **33**.
11. Twomey, S., *The influence of pollution on the shortwave albedo of clouds.* J. Atmos. Sci., 1977. **34**: p. 1149-1152.
12. Rosenfeld, D., *Suppression of rain and snow by urban and industrial air pollution.* Science, 2000. **287**: p. 1793-1796.
13. L'Ecuyer, T.S., et al., *Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds.* J. Geophys. Res., 2009. **114**(D9): p. D09211.
14. Koren, I., et al., *Aerosol-induced intensification of rain from the tropics to the mid-latitudes.* Nature Geosci, 2012. **5**(2): p. 118-122.
15. Andreae, M.O., *Smoking rain clouds over the Amazon.* Science, 2004. **303**: p. 1337-1342.
16. Koren, I., et al., *Aerosol invigoration and restructuring of Atlantic convective clouds.* Geophysical Research Letters, 2005. **32**(14).

17. Koren, I., et al., *Aerosol-induced changes of convective cloud anvils produce strong climate warming*. Atmospheric Chemistry and Physics, 2010. **10**(10): p. 5001-5010.
18. Koren, I., G. Feingold, and L.A. Remer, *The invigoration of deep convective clouds over the Atlantic: aerosol effect, meteorology or retrieval artifact?* Atmos. Chem. Phys., 2010. **10**(18): p. 8855-8872.
19. Khain, A.P., N. BenMoshe, and A. Pokrovsky, *Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification.* Journal of the Atmospheric Sciences, 2008. **65**(6): p. 1721-1748.
20. Levin, Z. and W.R. Cotton, eds. *Aerosol Pollution Impact on Precipitation, A Scientific Review*. 2009, Springer: Berlin.
21. Khain, A.P., *Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review.* Environmental Research Letters, 2009. **4**(1).
22. Huang, J., C. Zhang, and J.M. Prospero, *Aerosol-Induced Large-Scale Variability in Precipitation over the Tropical Atlantic.* Journal of Climate, 2009. **22**(19): p. 4970-4988.
23. Jiang, J.H., et al., *Clean and polluted clouds: Relationships among pollution, ice clouds, and precipitation in South America.* Geophys. Res. Lett., 2008. **35**(14): p. L14804.
24. Jones, T.A. and S.A. Christopher, *Statistical properties of aerosol-cloud-precipitation interactions in South America.* Atmos. Chem. Phys., 2010. **10**(5): p. 2287-2305.
25. Lin, J.C., et al., *Effects of biomass-burning-derived aerosols on precipitation and clouds in the Amazon Basin: a satellite-based empirical study.* J. Geophys. Res., 2006. **111**(D19): p. D19204.