Aerosol-Cloud Interactions: Why they continue to matter

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November 2, 2015

This white paper focuses on cloud modification by aerosols, collectively known as Aerosol-Cloud Interactions (ACI). ACI generally falls into two broad categories: cloud albedo/emissivity effects and cloud lifetime/precipitation effects. The two categories encapsulate the following physical processes taking place when aerosol perturbations interact with developing and/or existing clouds: aerosol perturbations change the number concentration and size distribution of cloud particles (droplets, ice crystals) which in turn change cloud radiative properties (reflectance, transmittance, absorbtance/emittance); aerosols change cloud microphysical characteristics (particle numbers and sizes, amount of condensate) in ways that affect the temporal evolution of cloud systems and the amount, type (liquid, frozen), and onset/duration of any precipitation they produce.

What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Anthropogenic aerosols induce a radiative forcing (RF) on the climate system through direct interaction with atmospheric radiation (not discussed here), but also via modification of cloud radiative properties (one of the subjects of this white paper). The latter forcing mechanism is extremely important because even small cloud changes can have relatively large RF impacts compared to those from changing concentrations of greenhouse gases. For instance, brighter clouds due to ACI can partially or fully counteract warming by other forcing mechanisms.

Quantifying cloud changes due to aerosols poses a dual challenge from both observational and modeling standpoints. Quite simply, it is difficult to attribute cloud changes solely to ACI, and it is equally, if not more, challenging to seek observational confirmation of modeled ACI behavior. A fundamental stumbling block in observing ACI is that retrievals of spatiotemporally collocated aerosol and cloud properties are notoriously difficult. Not only are aerosols underneath and above clouds hard to detect and characterize, except in specific configurations, and then only with appropriate instrumentation, but even aerosols interspersed in the clear areas of cloud formations cannot be measured accurately because of intricate cloud contamination effects. Another critical aspect of ACI attribution is ensuring that comparisons between clean (low aerosol loading) and polluted (high aerosol loading) conditions are performed for atmospheric states that are otherwise the same. This makes imperative to infuse any attempts to observe ACI with information about the instantaneous atmospheric state.

Lastly, a critical question is how susceptible current-day clouds are to ACI. This entails essentially a breakdown of anthropogenic ACI already incurred vs ACI that can still occur. In other words while strong ACI potential may exist for certain clouds and environments, for other situations a large fraction of ACI may have already been realized (obviously, "reversal" of ACI effects in a cleaner environment is also possible). Such a breakdown seems feasible only with a coordinated approach that combines modeling (what has happened in the past or may occur in the future) with observations (the current state of aerosols and clouds).

Why are these challenge/questions timely to address now especially with respect to readiness?

With climate change upon us it is urgent to observe important components of the climate system and narrow the range of model-based climate sensitivity (surface temperature change due to a doubling of CO_2). ACI affects the surface energy balance, possibly also the patterns and strength of precipitation, and has even been suggested as a solar management technique in a geoengineering context.

Our understanding of the type of measurements that are optimal in either separate or combined configurations to retrieve aerosol and cloud properties, in isolation or co-occurrence settings, has improved rapidly in recent years (e.g, the A-Train). Such measurements are a prerequisite for the more challenging step of applying appropriate analysis to unearth the fingerprints of ACI. Of utmost importance is coordination that allows both passive (imagers with and without polarization/multi-angle capabilities, IR/MW sounders) and active (lidars, radars) views of clouds and aerosols. The A-Train has many of these capabilities and has provided a glimpse of what is potentially achievable, but not yet within reach. Much has been learned about distinguishing between aerosols and thin clouds and other cloud contamination. EarthCare will continue the motif with enhanced in some respects, and reduced in others, capabilities. Operational LEO and GEO satellites have increasingly powerful and better characterized instruments that can provide retrievals of reasonable quality for filling many sampling gaps. Observations of precipitation will continue to improve with GPM-inspired technologies and enhanced strategies on how to merge disparate rainfall products.

Modeling ACI has also made great leaps in a wide range of atmospheric model classes. Increasing computer power allows implementation of ACI-relevant bin microphysics schemes for aerosols and clouds in Cloud Resolving Models and Large Eddy Simulation Models. Even atmospheric models with GCM heritage can now be run at high horizontal resolutions of ~10 km or below where convection is explicitly resolved. Aerosol microphysical schemes and two- or three-moment cloud schemes can now be accommodated in ~100 km resolution GCMs representing explicit radiative and precipitation/lifetime aspects of ACI. It is critical that the verisimilitude of all these models and schemes be validated against observations, and to establish the best practices to accomplish this.

Why are space-based observations fundamental to addressing these challenges/questions?

Only space-based observations can offer global or near-global coverage to study a problem as geographically diverse as ACI. Space views also provide the extensive spatial perspective that allows us to compare nearly simultaneously ACI signals between similar cloud regimes affected either weakly or strongly by aerosols. Moreover, from the vantage point of space certain incarnations of ACI such as cloud brightening are easier to detect and monitor (think "ship tracks").

A key factor, of course, in deciding whether the costly investment of a space mission is justified to study an important problem such as this is the technological maturity of the instruments to be placed in orbit. Arguably, the technical readiness level is satisfactory and the prospects of further improvement in the near future are very good (e.g., ACE-funded instrument development). A variety of smaller-scale programs for pilot studies and missions will continue to inform the appropriate sampling and spatiotemporal coverage strategies, orbital characteristics, and coordination of measurements, including constellation configurations, ideally suited for investigating ACI. Such programs have also been providing guidance on calibration requirements and how to control payload size and power requirements.

Please focus on the role of space-based observations and comment on:

a. Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?

Existing programs provide some capability to study ACI, but really are no more than a teaser on what can be accomplished with better instruments and a sustained commitment on a multifaceted optimized observation strategy. A major problem with several existing capabilities is that they are approaching end-of-life; sustaining measurement coordination is already becoming increasingly difficult. Existing and forthcoming operational GEO and LEO assets will help, but they lack the specialized technology that intensive studies of ACI require. The planned PACE mission has some ACI potential, especially if a polarimeter is added, but a different main focus is expected to drive instrument and algorithm design away from ACI relevance.

To study ACI, monitoring of specific observables is required. For clouds this includes spatial extent, vertical location, amount of condensate, and the number and size of particles; ideally we also need vertical profiles of condensate and particles. We also need information on precipitation including drizzle. From the aerosol side, we seek the vertical distribution of loading, particle size and radiative properties, and, critically, the fraction of aerosol particles than can serve as cloud condensation nuclei (liquid cloud) or ice nuclei (ice and mixed-phase clouds). Knowledge of aerosol properties must extend to locations with frequent cloud presence. Also needed is updraft velocity which determines the fraction of CCN and IN that activate/nucleate. Finally, knowledge of the dynamic/thermodynamic environment in which clouds form is required.

The investments needed to study ACI were described in sufficient detail in various ACE study reports submitted to NASA HQs. Skipping the details here due to space limitations, a mission to study ACI would ideally require a combination of a high spectral resolution lidar, an imaging polarimeter with multi-angle capability, *W*-band and multi-frequency Doppler radar, a wide swath VIS-IR imager with high resolution in parts of the spectrum, and microwave through submillimeter radiometers. These instruments collectively provide the capability to measure most of the observables listed above in mixed cloud-aerosol environments and at the resolutions and sampling volumes necessary for process studies.

b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs;

Space-based observations of ACI can benefit from ground capabilities that target aerosols and cloud. Such capabilities include networks supported by US and international agencies, as well as multi-instrument "supersites" at either fixed locations or deployed for particular campaigns. Opportunities for collocated ground-suborbital-space measurements should be a major factor in designing an ACI-focused space mission. For climate impact studies, space measurements targeting ACI should be combined with a variety of other observations and re-analysis data that resolve the atmospheric dynamic and thermodynamic structure, including temperature and humidity, as well as surface conditions. Linking to simulations by cloud and global models is also highly desirable.

c. The anticipated scientific and societal benefits

The scientific and societal benefits stem from substantially better knowledge of the climate system and the direction it is heading. Cloud feedback has the potential to be a strong factor in how future climate will look like, yet it is so uncertain due to the difficulties of simulating realistic clouds in climate models, that any leaps in monitoring cloud evolution in an environment of manageable anthropogenic aerosol pollution will be an important factor in policy making. The understanding and monitoring ACI is also paramount because of its prominence as a potential solar radiation management technique.

d. The science communities that would be involved.

A wide range of science communities in the environmental, climate, weather, air quality, and modeling arenas would potentially be involved. All are expected to influence the design and implementation of enhanced ACI observations. The commitment to focus on ACI as a key atmospheric process for climate change may influence the priorities of international meteorology and climate coordinating groups and will certainly merit close scrutiny in future IPCC assessments.