Understanding aerosol-cloud interaction processes with high spatiotemporal resolution observations from space

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1. *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?*

Aerosol-cloud interaction (ACI) is recognized by the IPCC as not only one of the main sources of uncertainty in our knowledge of anthropogenic climate forcing, but also as the key components in the forcing-feedback mechanisms that affect hydrological cycles, which have a wide range of impacts on weather, agriculture, air quality, and Earth's energy balance.

Aerosols and clouds interact in complex ways. Aerosol particles serve as cloud condensation nuclei (CCN) and ice nuclei (IN) that affect cloud composition and radiative properties. In addition, aerosol particles can modify clouds by changing atmospheric heating rates through the aerosol direct radiative process. Changes in cloud properties also affect precipitation formation processes, which in turn feed back on cloud dynamics in highly nonlinear ways. Furthermore, the radiative effect of the aerosol-cloud system is very sensitive to its relative position in the vertical atmospheric column. For instance, the presence of absorbing aerosols above clouds can potentially exert strong atmospheric heating, which may lead to longer cloud lifetimes through the so-called semi-direct effect. On the other hand, clouds affect the formation and evolution of aerosols. Clouds provide important media for heterogeneous chemistry to transform precursor gases into secondary inorganic and organic aerosols. Aerosol particle number concentration and size distribution can be modulated by a variety of mechanisms during cloud processing. Scavenging of aerosol particles by clouds and precipitation is the most important pathway for removing aerosols from the atmosphere. These interactions occur on very short time scales (e.g., minutes to hours).

Despite many research efforts in the past decades, establishing clear relationships among aerosols, clouds, and precipitation is still a significant challenge. Such difficulty is in part due to inadequate observations to account for the large spatial (including vertical) and temporal inhomogeneity of aerosols and clouds, to distinguish aerosols from clouds (and vice versa), and to understand the causal relationships in different cloud regimes. It will require new or integrated observing systems with enhanced capabilities to make substantial progress. The following key questions should be addressed:

- How does aerosol-cloud interaction change Earth's climate and environment?
- What are the radiative and microphysical properties of aerosol and clouds in different cloud regimes (e.g., marine stratocumulus, trade-wind cumulus, deep convection) and in different environments (e.g., polluted, fire, dust-influenced, and clean marine)?
- How do the above-mentioned properties evolve at different spatial and temporal scales, from the individual cloud scale (few kilometers and tens of minutes) to the cloud life cycle (tens to few hundred km and few to 24 hours) and the regional scale (few hundred to thousands of km and few days)?
- How can we deduce the aerosol-cloud interaction processes in a particular cloud regime and certain environment from the suite of observations?
- How can we disentangle the causal relationship between aerosol and clouds from their common association with large-scale meteorology?

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

Considering the importance of aerosol-cloud-precipitation-climate interactions and feedbacks, especially in a rapidly changing climate, and the slow progress so far on assessing these interactions, the coming decade should be an era of making break-through progress in addressing this issue.

In the past decades, remote sensing of aerosols and clouds have been conducted from the low-earth orbiting (LEO) satellites with both passive (including MODIS, VIIRS, MISR, OMI, PARASOL) and active sensors (CALIOP, CATS on ISS, and CloudSat radar). The passive sensors have the advantage of extended spatial coverage to retrieve/derive a number of aerosol and cloud properties, including aerosol optical depth, absorption, particle size and shape; cloud fraction, optical depth, effective particle radius, cloud top temperature and height. However, they have no capability to resolve vertical structure of aerosols and clouds, and their aerosol retrievals are ambiguous in the vicinity of clouds. In contrast, the active sensors measure vertical profiles of aerosols and clouds with minimal artifacts to make retrieving additional parameters possible (e.g., aerosol in the vicinity of or above clouds, and cloud droplet concentration), but their small spatial footprint limits understanding of the stated problems to only a statistical sense. Fundamentally, the low temporal frequency of polar-orbiting satellite observations impedes investigation of aerosol-cloud interaction processes, such that the investigation has to be carried out via a statistical analysis of aerosol-cloud relationships over a monthly or seasonal time scale when aerosols and clouds have changed significantly. The problem is further complicated by the tendency that both aerosols and clouds correlate strongly with meteorological conditions that evolve throughout the day. As a result, the aerosol-cloud relationships from the polar-orbiting satellites can only be viewed as "association"; no causality mechanisms can be determined from the once-a-day observations.

A geostationary platform would be ideal to measure time-resolved aerosols and clouds simultaneously to observe the joint evolution of aerosols and clouds and offer the opportunity of deducing the causal/feedback processes. For example, the ABI instrument to be onboard the NOAA GOES-R satellite (to be launched in 2017) has the MODIS-like capability of retrieving aerosol and cloud properties but with much higher frequency (every 5-15 minutes in regular mode and 30 seconds in a special mesoscale mode). However, it inherits the drawbacks of passive sensors and also has no capability to measure aerosol-related gas species or aerosol absorption, which affects atmospheric circulation and cloud lifetime. Although some of these parameters will be measured by the NASA geostationary mission TEMPO (Tropospheric Emissions: Monitoring Pollution, expected to be launched by the end of 2010s), the coarse pixel resolution (2.1x4.7 km), pre-determined geographic coverage (North America), and different viewing geometry from GOES-R constrain the ability of joint TEMPO+GOES-R approach to address the stated ACI questions.

To make a significant leap forward in understanding ACI, a dedicated, integrated observing system should be established. Considering that the ACI is almost certainly regime dependent, we recommend a focus on cloud regimes (e.g., marine stratocumulus, trade-wind cumulus, and deep convection) locally and regionally as the first priority in order to make tractable progress. A core observing system includes:

- Space-based remote sensing at high temporal frequency (e.g., geostationary satellite) with sufficient spectral range (UV to IR) and spatial resolution to observe clouds, aerosols and relevant gases concurrently
- Arrays of surface networks with active sensors (lidar and radar) to resolve the vertical structure of aerosol and cloud properties
- In-situ measurements to provide microphysical and chemical details that cannot be obtained by remote-sensing

The core observing system emphasizes regime-focused, high spatial and temporal resolution observations. It embraces the existing remote sensing capabilities but overcomes a number of deficiencies to enhance the quality and extend the quantity of key parameters regarding ACI. **Table 1** lists the required basic parameters (directly measured, retrieved, or derived).

Table 1. Required basic parameters and possible observation platforms.

Parameter	*Platform*
Aerosol-related:	
AOD, AAOD (or SSA), spectral AOD	Satellite (GEO, LEO), surface
Aerosol extinction and absorption, vertically resolved	Surface (lidar), satellite (lidar), airborne
Aerosol size distribution	Airborne, surface (lidar), satellite
Aerosol precursor gases	Airborne, surface (in-situ), satellite
Aerosol hygroscopicity	Airborne, surface
CCN and IN	Airborne, surface (and inferred from proxies)
Cloud-related:	
Cloud cover, optical depth, albedo	Satellite
Cloud top temperature, emissivity, height	Satellite, surface, airborne
Cloud base updraft, height	Surface (radar, lidar), airborne
Column and vertically resolved cloud phase, droplet concentrations, size distributions, liquid/ice water path	Satellite, surface, airborne
Other:	
Precipitation (including drizzle)	Surface (radar), satellite (radar)
Profiles of RH, temperature, water vapor	Surface (sounding or radar), airborne, satellite

The regional observing system should be coordinated with global observations from LEO satellites equipped with active sensors and multi-angle polarimeter imagers (such as ACE) that offer a large scale view of aerosol and cloud properties once a day.

Making regime-focused observations also provides best support for fine-scale models (e.g., cloud-resolved model, large eddy simulation model) developments and improvements, which can resolve (rather than empirically approximate) the aerosol-cloud interaction processes. The fine-resolution modeling of regime-specific processes can provide global models with robust parameters.

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

Only space-based observations from geostationary platforms can achieve continuous, large-area coverage many times per day, which is essential for the study described above. No other platforms are able to meet this fundamental requirement. These regular space-based observations must also be made as part of an integrated system including in-situ and ground-based remote sensing observations and modeling systems capable of combining these diverse observations.

North and South Americas and surrounding oceans can be the regions to establish the first regional observing system, for their diverse aerosol environments (pollution, biomass burning, transported dust, and marine) and cloud regimes (deep convection, marine stratocumulus, and trade-wind cumulus), and particularly for logistical feasibility. There are established infrastructures of ground-based networks over the U.S. and South America (e.g., MPLNET, AERONET, NOAA networks) that can be expended or reformed to best complement the satellite observations. Possible study areas include: Offshore California (marine stratocumulus), Gulf of Mexico (trade-wind cumulus), and Amazonia (deep convection).