Addressing the Aerosol-Cloud-Precipitation Interaction Problem through Process Understanding

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Nearly every cloud on Earth is formed by condensation of water vapor onto small aerosol particles called cloud condensation nuclei (CCN). However, as the 2007 National Research Council (NRC) decadal survey in Earth science and applications from space noted, "…the interactions between the chemical and physical properties of condensation nuclei aerosols and cloud water and ice, with the ensuing formation of a variety of precipitation patterns, are not adequately understood, modeled, or predicted." Since that survey our ability to model the interaction between aerosols, clouds, and precipitation has advanced across a range of scales from simulations of individual clouds and cloud systems to global climate models (GCMs). This progress has been facilitated by laboratory studies, measurements from ground-based observatories, and data obtained during field campaigns with instrumented aircraft and ships, at times supplemented by observations from existing satellite systems such as AMSR-E, CALIPSO, CloudSat, and MODIS in the A-Train. Concurrently, there has developed a greater appreciation for the interaction among different processes relating aerosols, clouds, and precipitation with radiation in the atmosphere. For example, changes in anthropogenic emissions couple to changes in aerosol concentrations, which in turn couple to changes in cloud droplet number, which ultimately affects how clouds reflect solar radiation. These interactions are complicated by the impact of meteorology and large-scale motion on the generation, transport, and removal of aerosols, and cloud formation and precipitation processes.

It has long been recognized that space-based observations are fundamental to improving our understanding and ability to model aerosol-cloud-precipitation effects in the Earth's atmosphere. Ground-based observations provide limited geographical coverage, and field campaigns are typically spatially and temporally constrained. Space-based observations provide the capability to study large-scale geographic variations around the globe, examine seasonal cycles, and observe long-term changes. However, progress in these areas has been stymied by the difficulty of observing important aspects of aerosols and their interactions in the atmosphere from space, including details of the vertical distribution of aerosols, activation by aerosol species, ambient supersaturation, the presence of giant CCN, and turbulence and entrainment processes. It is further critical to observe the important aerosol-cloud-precipitation interactions as they evolve over time – from the so-called Lagrangian perspective – which is impossible to accomplish with temporally instantaneous observations provided by a satellite in low Earth orbit (LEO).

In 2007, the NRC Earth science decadal survey identified aerosol-cloud interactions as the largest source of uncertainty in GCMs. This evaluation had not changed by the time of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2013, which found that aerosol-cloud interactions continued to be the largest source of uncertainty in model calculations of total radiative forcing. While GCMs are key to future predictions of climate change – important for understanding the societal impacts of a changing world – according to the IPCC report there remains *low confidence* in the representation and quantification of cloud and aerosol processes in these models. To reduce GCM uncertainty it is critical to have suitable and reliable observational constraints, but it is not sufficient to simply tune the models into agreement with observations. Instead, a better fundamental understanding of the complex, underlying micro- and macro-physical processes is required, leading to their appropriate model representation. This is especially important as the spatial resolution of GCMs continues to improve and new parameterizations of aerosol-cloud-precipitation processes continue to be developed and implemented.

The 2007 NRC decadal survey recommended three missions in the 2013-2020 timeframe related to the societal challenges of climate prediction and air quality: the Aerosol-Cloud-Ecosystems (ACE) mission, the Geostationary Coastal and Air Pollution Events (Geo-CAPE) mission, and the Global Atmospheric Composition Mission (GACM). The ACE mission was endorsed to "narrow the uncertainty in climate predictions and improve the capability of models to provide more precise predictions of local climate change, including changes in rainfall." Unfortunately, for a variety of reasons NASA has pushed the ACE mission out beyond the 2020 timeframe. Although the instruments proposed for the ACE mission – an aerosol lidar; a multiangle, multiwavelength, polarimetric imager; and a cloud radar – would greatly enhance our understanding of the interactions between aerosols, clouds, and precipitation, a single LEO satellite is incapable of resolving aerosol-cloud-precipitation processes that occur on time scales of minutes. The Geo-CAPE mission could address the timescale issue by making observations from a geostationary orbit. This mission, however, seems to have been largely supplanted by the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument, selected by NASA as part of its Earth Venture Instrument (EVI) program, which was instituted in response to the 2007 NRC decadal survey. Unfortunately, the spatial resolution (around 8 km x 4.5 km) and temporal sampling (1 hour) are insufficient to observe aerosol-cloud interactions at the appropriate scales, which are on the order of tens of meters and tens of minutes. Information on aerosol vertical distribution and composition would also be limited. Instruments in geostationary orbit, which are about 50 times farther away from Earth than instruments in LEO, typically trade spatial resolution and sensitivity for temporal sampling. For the GACM mission, which does not currently appear on NASA's future missions schedule, the 2007 NRC decadal survey recognized that to measure "profiles of aerosols and atmospheric structure to better than 150 m, an active system operating in a polar LEO is required." Some of the recommended capabilities will be realized by the atmospheric lidar (ATLID) on the joint European Space Agency/Japanese Aerospace Exploration Agency (ESA/JAXA) Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) mission scheduled for launch in 2018. Further assets, such as a multiangle polarimetric imager and an ultraviolet-visible-near infrared sounder, will fly on ESA's Sentinel satellites in the next few years as part of the Copernicus program.

However, even with these investments, particularly by international agencies, the ability to address the problem of aerosol-cloud-precipitation interactions through improved understanding atmospheric processes will be greatly constrained due to insufficient spatial or temporal resolution or insufficient instrument sensitivity – particularly in the lowest part of the atmosphere. The way forward – which demands contributions from a broad range of science communities including laboratory and theoretical work, instrument and algorithm development, and field deployment – requires a dedicated constellation of satellites in LEO along with coordinated field campaigns that can establish robust statistical relationships among observable quantities that can then be used to unravel the underlying micro- and macro-physical processes that fundamentally couple aerosols, clouds, and precipitation in the Earth's atmosphere. The essential space-based observations include sensitive cloud profiling radars, aerosol lidars, and multiangle polarimetric imagers on multiple satellites working together. Constellations of small satellites have been proposed to the NASA Earth Venture Missions (EVM) call by the Jet Propulsion Laboratory and other institutions. These concepts take advantage of improvements in the capabilities of micro satellites (CubeSats), miniaturization of instrument hardware, economies of scale that allow multiple instruments to be built for less than the cost of multiple units, and technologies permitting many satellites to be delivered into orbit on a single launch vehicle. A new generation of highly sensitive, technically capable, micro-satellite suitable, active and passive instruments is getting ready for space demonstration via the NASA InVEST program and others. NASA also solicits proposals for Earth Venture Sub-orbital (EVS) projects and has funded field campaigns such as DISCOVER-AQ with the goal of better understanding aerosols and their impact on air quality, and ORACLES, which will look at the relationship between biomass burning aerosols and clouds. The NASA Earth Venture program could benefit by creating stronger links between EVM space-based missions and EVS sub-orbital projects.

A combination of a constellation of micro satellites able to observe the details of aerosol-cloud-precipitation interactions with sufficient spatial resolution at intervals within a period of 30 minutes or so with well-coordinated suborbital aircraft, ship-based, and ground-based measurements would substantially help address GCM uncertainty in future predictions of climate change, including sea level rise and changes in water availability. While large-scale, independent, single-satellite missions have their role, now is the time to take a more focused approach to the problem of aerosol-cloud-precipitation interactions in the climate system because now we know what we don't know.

Summary

1. What are the key challenges for Earth System Science in the coming decade?

One key challenge is reducing the uncertainty in the representation of aerosol-cloud-precipitation interactions in GCMs to improve the fidelity of these models for predicting the societal impacts of future climate change. Fundamental to addressing this challenge is a detailed understanding of the important aerosol-cloud-precipitation processes as they evolve over time in the Earth's atmosphere.

2. Why is this challenge timely to address now especially with respect to readiness?

GCMs are continually improving in terms of their spatial resolution and representation of atmospheric processes, and it is critical to have suitable and reliable observational constraints. Recent technological advances are mature enough for capable instruments to be incorporated into a constellation of micro satellites that can observe aerosol-cloud-precipitation processes over time. Coordinating this information with suborbital observations will yield results beyond what is possible from existing and proposed single satellite systems.

3. Why are space-based observations fundamental to addressing this challenge?

Space-based observations provide the capability to study large-scale geographic variations around the globe, examine seasonal cycles, and observe long-term changes. However, space-based observations alone will be insufficient to address the challenge of better understanding aerosol-cloud-precipitation processes due to the difficulty of observing important micro- and macro-physical details. Therefore, close coordination between space-based and suborbital observations is critical.