1. Clouds & Aerosols: A key challenge/question for Earth System Science in basic and applied research

It is commonly accepted in the climate modeling community that studies of the anthropogenic warming of the Earth with Global Climate Models (GCMs) depend heavily on parameterizations of still poorly understood cloud-radiative feedbacks, which have the potential to dampen or enhance changes in essential climatic variables. The complexity of these feedbacks defies easy representation in GCMs, ultimately translating into much uncertainty in our understanding and questionable predictions of climatic change. The situation worsens when interactions with natural and anthropogenic aerosols are included. Indeed, the Inter-governmental Panel on Climate Change (IPCC) persistently assigns “very low confidence” to aerosol, cloud and radiation interactions with even the sign of the resulting climate forcing remaining uncertain.

Given the extreme multi-scale nature of the aerosol-cloud-radiation system, spanning synoptic- to micro-scales, it is not surprising that the aerosol-cloud-radiation enigma has dogged the atmospheric sciences for over 30 years. The system is indeed riddled with convoluted non-linearities. Examples include: turbulent fluid dynamics (convection, entrainment, mixing); sensitive thermodynamical thresholds controlling phase changes (nucleation, evaporation, freezing); cloud-specific processes (condensational growth, particle coalescence, precipitation onset, aerosol scavenging, and so on); and of course their impacts on the atmospheric radiative energy budget and, from there, regional and global climates.

Among the challenges facing the community, the following interrelated trio stands out in terms of acute need of improved physical understanding, vastly better representation in GCMs, and crippling gaps in measurements:

1) intra-cloud variability and properties near cloud edges (both inward and outward directions around sides, tops and bottoms);
2) turbulent entrainment, subsequent mixing processes, turbulence in clouds, and their interactions with cloud microphysics;
3) the so-called aerosol “twilight” zone.

We need to address these challenges for all types of clouds, but especially for shallow (“puffy ”) cumulus clouds where, in essence, we are entering the poorly understood non-adiabatic regime and the aerosol-cloud continuum. This framework is closer to reality and holds the key to future model advancement.

Although these are small-scale phenomena, not usually considered to be accessible by space-based remote sensing observational techniques, they necessarily have observable cloud-scale signatures if they indeed affect the climate system. That means that they can be identified and quantified by judiciously merging cloud process models and remote sensing “systems,” which we define as everything that has to happen before stakeholders get what they really want. That would be geophysical properties, not just radiances or images. Thus, a remote sensing system consists in one or more functional sensors along with an operational data-processing pipeline, integrated as needed across sensors.

To translate the above challenges into remote sensing terminology, measurements and algorithms alike, we must “zoom-in” as much as possible onto the cloud-aerosol interface, i.e., cloud boundaries that are convoluted 3D entities. Moreover, we need to look for optical and microphysical structures inside clouds that will reveal previously invisible processes. For starts, this means that we must move past simple plane-parallel assumptions we currently make about clouds and aerosols, and embrace the full three-dimensional (3D) nature of cloud-aerosol systems.

2. Timeliness and readiness of addressing this challenge/question

To underscore the timeliness of acting on the cloud-aerosol-radiation-climate problem, which (we restate) is the most uncertain element in the prediction of future climate, both global and regional, we recall that the current El Niño event may be countering temporarily the global trend toward a warmer climate. In fact, we may again see marked increases in surface temperatures as the El Niño subsides, akin to what happened in the 80s and 90s.

To address the challenge of forecasting climate change, we need to zoom out from small-scale processes unfolding at cloud boundaries to the geopolitical realm. Simply put, we now ask what can go wrong if, for lack of understanding clouds and aerosols, we are unable to forecast future climate with enough skill to assess impacts on different regions?

We have all heard about the potentially dire consequences of climate change for sustainablity (hence the food supply), for air quality (hence public health), for water quality and quantity (hence both food supply and public health), for sea-level rise, and so on. In principle, this is enough to justify resources, increased as needed, to address the cloud-aerosol-radiation-climate problem that is holding back progress in future global and regional climate forecasting.

However, looking at an even broader context, we all know that there are climate-change deniers, or a least "minimizers," generously funded by energy sector and industrial interests, that are proactive in the arcane world of environmental policy, with potentially far-fetching ramifications into the funding of climate science research. These groups are quick to emphasize our lack of progress in our understanding of the climate system and in improving our forecasting skill. The subtext here is that if climate is not really changing, for all we know, then the question about anthropogenic forcing is moot. More precisely, the climate system may have an inherent ability to react (via feedback) to forcing, either natural or artificial, and thus remain stable.

It is also common wisdom that politically-related if not the same lobbying forces are generally fierce defenders of defense spending and whatever foreign engagement that may mean to sustain it. Paradoxically, the US DoD and the US Intelligence Community (IC) at large, starting with the White House, have decided that climate change is so real that has they have created dedicated taskforces to assess its National Security implications in both likely and worse-case scenarios; cf. https://www.cia.gov/news-information/press-releases-statements/center-on-climate-change-and-national-security.html, http://www.defense.gov/News-Article-View/Article/612710. The threat is that environmental stresses, irrespective of whether they are caused by natural processes or human activity, have the potential to generate political failures, ineffective governance, possibly violent unrest. These developments may in turn cause population displacements that will dwarf the already overwhelming and too-often tragic migrations what we are currently seeing coming from the Middle East, Central Asia, Northern and Equatorial Africa, not to mention Central and South America. We clearly need to improve our science-based grasp on global and regional climates, whether or not they are changing, whether or not human activity is a factor.

In view of its dominance of current uncertainty in climate forecasting, the cloud-aerosol-radiation-climate conundrum thus needs urgent attention. Moreover, since current science and technology are not effective in reducing uncertainty, this attention will require innovation from several sectors. Most notably, satellites cannot measure processes, only a limited set of outcomes. Thus, there needs to be an unprecedented collusion between sensor data and modeling systems. A combination of modeling innovation and Moore's law is enabling 3D Large-Eddy Simulation (LES) models with grid-spacing <10 m for boundary layer domains up to ~10s of km as a promising path forward. By coupling LES models with observational field campaigns (mostly in-situ aircraft), the cloud physics community is starting to make strides toward improved understanding of clouds; from there, we anticipate improved representations in GCMs.

We argue below that the remote sensing enterprise is not participating in this advance to its fullest potential. With the proper investments, it can however accelerate the necessary progress in understanding clouds and their interactions with aerosols and, from there, their representations in climate models.

3. Are space-based observations key to addressing this challenge/question?

a. Will existing and planned U.S. and international programs provide capabilities necessary to make substantial progress on the identified challenge and associated questions?
No. Although EOS-era observations have not yet been fully exploited, current operational retrieval methods have clearly outrun their utility. Moreover, planned US and international (e.g., EarthCARE) missions will not bridge in the short term the identified gap since new capabilities (e.g., polarization) come at the expense of others, mostly the desperately needed increase in spatial resolution.

If not, what additional investments are needed?
A whole new paradigm in full 3D cloud-aerosol retrieval is emerging in the specialized literature, often taking inspiration from advances in medical imaging. It capitalizes on increased computational prowess (i.e., Moore's law) combined with recent advances in inverse problem theory that have lead to practical implementations of 3D spatial reconstructions (i.e., tomography). In such problems, there are very many unknowns and at least a few times more observations. This is clearly research that NASA can benefit from. To this end, NASA will need to invest in the kind of cross-disciplinary teams that can develop the necessary breakthrough. There is also a related need for higher spatial resolution that can be obtained via:

- RT-based solutions for broader (gas-contaminated) spectral channels, for better SNR;
- compressed sensing;
- overhead assets and engagement of the US IC (cf. http://dels.nas.edu/Study-In-Progress/Improving-Understanding-Clouds/DELS-BASC-11-05?bname=basc).

b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions?
Suborbital (ground-based and airborne) observations can more readily attain the high spatial resolution we need to perform 3D reconstructions of cloud-aerosol mixtures. These data will also provide both validation material for the new tomographic reconstruction algorithms, and a unique access to the aerosols that affect key cloud microphysical processes unfolding at cloud base.

c. Anticipated scientific and societal benefits?
Apart from above-mentioned support of National Security issues via improved climate modeling, the IC will benefit from the new 3D atmospheric tomography capability since there is interest in quantifying 3D aerosol/cloud properties in the IC.

d. What science communities would be involved?
Applied math, computer science, statistical physics.