Cloud and Cloud-Aerosol Interactions and Feedbacks

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Clouds in the atmosphere are integral components of the Earth system. They substantially alter the amount of solar radiation absorbed by the planet as well as reduce the thermal emission to space. By the condensation of vapor into cloud liquid and ice and subsequently into precipitation, they become the source of water and snow for the surface which is particularly important over land. The latent heat release associated with phase changes as well as the modifications to atmospheric radiative transfer are also critical for altering atmospheric and oceanic circulations. Aerosols can play a major role in determining the number and size of cloud droplets and ice crystals, which can have substantial effects on the reflectivity of clouds, the formation of precipitation, and cloud lifetime.

Changes in both temperature and atmospheric aerosols in response to human activities are expected to have major impacts on clouds, and these cloud changes will substantially affect the evolution of the Earth System. The uncertain response of clouds to climate warming (i.e. the cloud feedback problem) is the leading uncertainty in estimates of Earth's climate sensitivity – that is, how much warming will occur for a given increase in carbon dioxide. The uncertain response of clouds to changes in the emissions of aerosols due to human activities is a leading uncertainty in determining the radiative forcing that drives changes in the Earth system. Significant gaps remain in our understanding and modeling of clouds and cloud-aerosol interactions, and these gaps inhibit our ability to predict the drivers and responses of the Earth system, including how the water cycle and large-scale circulation respond to change. Advances in observation, theory, modeling, and computing present important opportunities for improving predictive understanding of clouds and its regional and global consequences.

Grand Challenge Question: *What processes drive clouds and their interactions with aerosols, temperature and other factors, and how can we use such understanding to guide the improvement of cloud representations in the models used to predict changes in the Earth System?*

Addressing this grand challenge question will require improved diagnostic analyses in observations of the relationships between clouds and environmental conditions including aerosols, temperature, and other cloud-controlling factors. However, observations alone are insufficient for determining process-level interactions, so it is necessary to also use "benchmark" models that resolve cloud processes such as Large-eddy simulations with grid spacings < 250 m, even as these models have some limitations. Advances in understanding then will hopefully allow for improvements in the Earth System Model cloud and aerosol parameterizations that cause large uncertainty in model projections. The scale of cloud problem is broad because clouds come in many forms and result from various fluid motions on a wide range of scales.

Expertise across RGMA projects offers a unique opportunity to advance our understanding of cloud and cloud-aerosol interactions by organizing research onto the following science questions: [We invite further additions to or comments on the following list. Keep in mind that each question should be a bit more specific than the general language above, but not super-specific. Following the RGMA meeting, the breakout chairs will condense the list to a small number of all-encompassing questions.]

- What processes determine the temperature and aerosol sensitivities of clouds? What are the relative roles of microphysical processes, atmospheric turbulence and convection, radiation, and the large-scale environment in determining these sensitivities? How do these sensitivities vary with cloud type?
- Does constraining the temperature sensitivity constrain the aerosol sensitivity, or the other way around? Which processes are relevant to both sensitivities, and what physical mechanisms explain these relationships?
- What is the role of clouds and cloud-aerosol interactions in determining the amplitude of natural modes of variability (e.g. PDO, ENSO) and climatological distributions of precipitation (e.g. ITCZ and monsoon locations) and their changes over time?
- What is the role of clouds and cloud-aerosol interactions in determining other aspects of climate variability, including extreme precipitation and high-impact events?
- Can machine learning approaches be used to encapsulate in new Earth System Model parameterizations the cloud and aerosol information explicitly represented by high-resolution process models or observations?
- How do clouds and cloud-aerosol interactions affect climate change in other components of the Earth System such as the ocean, cryosphere or biosphere?

Description of Challenges and Current Research in RGMA

[This section will undergo further revision to better reflect current research in RGMA.]

RGMA has been supporting research in the diagnosis of clouds in models and observations, which is necessary both to determine the role of clouds and cloud-aerosol interactions in the Earth System and to improve their representation in models. RGMA scientists have excelled in the creation of diagnostic tools and frameworks that have led to improved model representations of clouds and greater scientific understanding. These diagnostic techniques can be categorized into three areas of work:

1. **Tools to measure clouds in models.** In order to minimize the influence of observational limitations, RGMA scientists have developed codes that answer the question what would a satellite retrieve if the real world had the clouds of an Earth System model? These codes, called “satellite simulators”, have been developed for a variety of satellite cloud products and collected into a widely distributed software package known *COSP* (Bodas-Salcedo et al. 2011). COSP has been used by all of the world’s Earth System models to permit a more apples-to-apples comparison of clouds with observations and between models. Similarly, a polarimetric radar simulator has been developed to directly compare with radar signals in cloud properties.

2. **Frameworks to identify cloud sensitivities and behaviors.** RGMA scientists have developed so-called ‘cloud-controlling factor’ analysis techniques which enable diagnosis in observations of how clouds depend on the environmental parameters that control them (Klein et al. 2017). This is useful for both model evaluation and as a means to predict future changes in the Earth system. Models can also be integrated in weather-forecast mode, to separate the role of parameterization errors from errors in the large-scale environment using the Cloud-Associated Parameterization Testbed (CAPT) approach and to enable comparison to single-point cloud process observations such as have been collected by DOE’s Atmospheric Radiation Measurement (ARM) program. RGMA scientists have also pioneered the use of idealized modeling frameworks such as aquaplanets (global models configured with a global ocean with high degree of symmetry), radiative convective equilibrium on the sphere (aquaplanet in a non-rotating reference frame with homogeneous forcing), and single-column models (model physics run at a single grid point). These idealized frameworks often accentuate inter-model differences and stress the importance of cloud representations in climate forcing and feedbacks. Additional modeling approaches developed and utilized by RGMA scientists include (a) “cloud locking” experiments to precisely isolate the role of cloud radiative effects, (b) regionally-refined model frameworks to simulate mesoscale convective systems with high-resolution over the continental United States, (c) a “pseudo-global warming” approach applied to regional models to examine the response of hailstorms to anthropogenic warming, and (d) perturbed physics experiments to pinpoint the sensitivity of cloud behaviors to model physical parameters and enable observations to constrain model physics.

3. **Techniques using multi-model ensembles to constrain the predictions of cloud response to Earth system change.**RGMA scientists have been leaders in developing advanced techniques that quantify the radiative impacts of clouds, such as the *Approximate Partial Radiative Perturbation (APRP)* and *cloud radiative kernels*. These techniques have been used to determine the first ever quantifications in Earth System models of the magnitude of cloud feedbacks from

separate changes in cloud amount, optical depth, and altitude. In order to determine which of the simulated cloud responses to climate warming are correct, RGMA scientists have been at the forefront of the development of the *emergent constraint* technique (Hall et al. 2019). An *emergent constraint* is a physically explainable empirical relationship between an aspect of current climate and an aspect of climate change that emerges from multi-model ensembles such as CMIP. If the observations of the aspect of current climate have less uncertainty than the range of model simulations, then the future might be constrained. RGMA scientists have discovered a number of *emergent constraints* for cloud feedbacks, particularly in the area of the temperature sensitivity of marine low clouds.

RGMA also supported process-level modeling and analysis work in aerosol-cloud interactions, which has led to improved understanding. For example, by using the field campaign data, orographic mixed-phase clouds over California were found to be susceptible to the long-range transported dust and marine aerosols which nucleates ice crystals effectively (Fan et al. 2017). It was also shown that the effect on convective cloud properties, precipitation, and hail from the joint changes in the anthropogenic aerosol and the land surface as a result of urbanization is much larger than the sum of individual effects (Fan et al. 2020; Lin et al. 2020), emphasizing a nonlinear amplification effect when those factors are working together. Aerosols were also found to consistently increase cloud anvil coverage for various mesoscale convective systems, which would strongly impact cloud radiative forcing (Chen et al. 2020).

Research Gaps and Future Directions

Current research supported by RGMA is making great strides in improving understanding and modeling of clouds and cloud-aerosol interactions. To address the grand challenge and science questions identified above, more research highlighted below is needed to bridge major remaining gaps in order to transform our predictive understanding of cloud processes: [Again, we encourage your contributions to and comments on the following list which the breakout co-chairs will condense after the RGMA meeting]

Short Term (3- 5 years) Research Goals

- Critically evaluate the cloud characteristics and aerosol-cloud interactions of the new CMIP6 Earth System models using advanced diagnostic techniques, specially designed numerical experiments, and diverse observations in order to identify which improvements in DOE models are most needed
- Exploit advances in DOE Atmospheric Radiation Measurement and other ground-based, in-situ, and satellite observations to provide critical constraints on model representation of cloud processes and aerosol-cloud interactions while providing

feedback to observational communities on what further observations are needed for model improvement

- Use model-data fusion techniques such as Emergent Constraints applied to multi-model ensembles to identify the specific cloud processes and aerosol-cloud interactions most critical to reducing uncertainties in model projections
- Apply Machine Learning techniques to model simulations and observational data to identify the critical steps needed to improve model predictions of cloud processes and aerosol-cloud interactions
- Synthesize all available observational and modeling evidence using novel statistical approaches to provide a comprehensive assessment of cloud feedbacks and associated uncertainties.
- Derive critical insights from high-resolution simulations that resolve cloud and aerosol processes as a bridge between observations and Earth System models
- Devise and apply diagnostic methods that target the role of clouds in climate variability in observations and models, and provide a critical assessment of current models' ability to capture links between clouds and climate variability.

Long Term (10 years) Research Goals

- Quantitatively reduce the uncertainty in cloud feedback and aerosol-cloud interactions using observations and high-resolution process models, while simultaneously focusing development of Earth System Models on critical sources of spread such as cloud microphysics and turbulence parameterizations. *(Questions: Is it futile to try to narrow the spread in the Earth System Models? Will analysis of observations and process-resolving models be sufficient to narrow uncertainty, even while inter-model spread in Earth System Models is not reduced?)*
- Perform diagnostic analyses supporting validation and development of global convection-permitting models (non-hydrostatic atmospheric models with resolution ~1 km) so that they are able to credibly simulate cloud feedbacks and aerosol-cloud interactions
- Gain a good understanding of how clouds and aerosol-cloud interactions influence the predictability of weather and climate extremes through integrating high-resolution model simulations with observational constraints. *(Question: What does predictability mean in this context?)*
- Cultivate linkages between cloud research and biophysical research to provide pathways toward more skillful Earth System Prediction, including the carbon cycle and atmosphere-biosphere feedbacks.

- Using explainable deep learning to facilitate science understanding of cloud and aerosol processes
- Gain a quantitative understanding of cloud radiative forcing and precipitation through aerosol interactions with deep convective clouds globally. *(Questions: Is it appropriate to single out this cloud type? Why aren't their similar questions for other cloud types?)*
- Determine the role of clouds processes and aerosol-cloud interactions in climate variability through targeted model experiments, careful diagnosis of clouds in model simulations, and deep analysis of observational data sets *(Question: Does this duplicate the last Short-Term Goal?)*
- Quantitatively establish the role of regional cloud feedbacks on the global energy balance and hydrologic cycle.
- Improve computational efficiency for global cloud-resolving models using advanced computing technology and artificial intelligence

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