Decadal Survey RFI:

Improving the Representation of Cloud Scale Processes Through the Integration of Observations and Models

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Q1: 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?

A big challenge for NASA's Earth System Science over the coming decade will be how to utilize its current and future capacities in Earth observations and Earth system modeling to address the supply and demand for available fresh water, influenced by growing populations and changing climates. At its core, the hydrological cycle is driven by weather systems that have exhibited wide variability in regional precipitation extremes over the past decade. While weather covers storm-scale phenomena with time scales from minutes to weeks, it also covers the sub-seasonal time scale that bridges weather with longer-term climate and societal implications, such as drought, water storage and supply, agricultural practices and food supply.

NASA has made significant investments within the past decades on weather-related observations, modeling, and science and technology that address specific components of the hydrological cycle. A key challenge for the coming decade will be the coupling and integration of a wide variety of weather-related Earth observations with increasingly sophisticated and interconnected Earth system models. Observations from precipitation and cloud missions such as TRMM/GPM and CloudSat, respectively, have succeeded in observing the global mapping of precipitation, its regional variability, and dimensional characteristics and features of precipitating cloud structures such as their vertical structure (*Zipser et. al*., 2006; *Liu*, 2011). Yet a more complete understanding of the physical and dynamical *processes* leading to precipitation development are not well understood. The joint dynamics and microphysics governing the evolution of embryonic cloud droplets and ice crystals to precipitation-sized hydrometeors that influence the intensity and severity of weather systems, are not well represented by current cloud resolving model (CRM) resolutions and parameterizations (*Varble et. al*., 2014). For example, as the CRM resolution becomes finer, so does the sensitivity to the associated choices of parameterizations for unresolved sub-grid processes (*Bryan and Morrison*, 2012). The generation of supersaturation within the model and the subsequent aerosol activation and droplet growth is highly sensitive to the simulated vertical velocity (*Saleeby and Cotton*, 2004). Therefore, incorrectly representing vertical velocity can result in incorrect nucleation rates, cloud droplet numbers and sizes, and the vertical distribution of cloud water throughout the cloud.

Improvements to convective and microphysical parameterization schemes have been impeded in the past by several factors, including the lack of collocated observations of vertical velocity and microphysical characteristics on convective spatial and temporal scales, and shortfalls in our understanding of the multiple ways in which ice species nucleate, form and grow. From an observational perspective, it is difficult to observe and represent these multi-scale interactions that are critical to convective organization and evolution from infrequent, intermittent satellite or aircraft-based observations of quickly evolving processes. More frequent and collocated observations are desired to enhance the capability to resolve the spatio-temporal details regarding the vertical motion, microphysical processes, and the feedbacks between the vertical motion and the microphysical processes, necessary to properly validate the simulate the role of convective storms in the vertical and horizontal transport, redistribution and processing of atmospheric water vapor, latent energy and momentum, trace gases and aerosols.

As the increasing number of space-based weather-related Earth observations comes the challenge to integrate the information gained from these cloud-process observations back into both CRMs and numerical weather prediction (NWP) models via data assimilation. Advancements in 4D-variational assimilation systems now routinely assimilate GNSS radio occultations and radiances from microwave and infrared sounders onboard operational low Earth-orbiting weather satellites, but the latter data are often “thinned” or blacklisted once they get too close to clouds, and their horizontal resolutions are more representative of the environment surrounding severe weather, as opposed to the conditions within the cloud systems themselves. Also, certain channels are not used in the over-land observations. As a result, only a very small percentage of the cloud and precipitation affected observations are assimilated into NWP models (*Bauer et. al*., 2011). For microwave radiances, radiative transfer models (forward and adjoint) are the forward operators that allow a mapping or “bridge” between observation and model space (*Bennartz and Greenwald*, 2011). Therefore, the same cloud process observations cold lead to improvements in the forward operators to maintain better consistency in model-observation space, improving the model’s ability to assimilate and retain observations in and near clouds.

A recent NASA workshop on scientific challenges in the weather focus area (http://science.nasa.gov/earth-science/focus-areas/earth-weather/) identified a sustained modeling and assimilation framework, together with the transition of research-type Earth observations into operational systems at NOAA/NWS, as central to the ongoing development and success of NASA’s Weather Focus Area. Therefore, in the coming decade, a major challenge to water cycle science, weather applications and operational utilization will be the *integration* of observations of cloud scale processes to into CRMS to correctly represent vertical motions, microphysical processes, and the feedbacks between the vertical motion and the microphysical processes, and the use of the knowledge gained into improve the utilization and retention of cloud and precipitation-affected observations in model data assimilation systems.

Q2: Why are these challenge/questions timely to address now, especially with

respect to readiness?

Weather is often envisioned in terms of its severity, such as tornadic activity, flash floods, large hail, snowstorms or landfalling hurricanes. However, weather is also the opposite of these conditions, such as sustained periods of heat and scant precipitation, or more subtle changes such the freezing level and its effects on snowpack retention and water supplies. These conditions can change quickly from one year to the next, but the needs and requirements for water-related applications require adequate planning and steady investment thereafter. The observational capabilities of the NOAA's geostationary and sun-synchronous low Earth-orbiting platforms (GOES-R series and JPSS, respectively) will extend current sounding capabilities (CrIS/ATMS) and near cloud-top imaging (VIIRS) well into the next decade. While NASA's most recent and near-future observing missions are positioned to observe phenomena that are related to various components of the water cycle (e.g., precipitation from GPM, soil moisture from SMAP, evapotranspiration from ECOSTRESS, groundwater from GRACE-FO, surface water from SWOT), there is a observational gap for frequent cloud process observations of vertical air motion of fine spatial (1-km or less) scale, and direct observations *within* the clouds and boundary layer at the time scales of the cloud-to-precipitation processes, such as cloud nucleation and the aforementioned vertical transport. Increasingly, there are now many microwave component technologies, compact radar systems at cloud/precipitation relevant frequencies (35 GHz and above) antenna designs, satellite orbits (including geostationary) and constellation strategies, and signal processing techniques that have been brought down to a reasonable cost and level of complexity to make cloud-scale process observations feasible, including several which have been already demonstrated. These opportunities can be explored through more frequent and coordinated opportunities such as NASA's Earth Ventures (EV) or related programs. For the needs for assimilation of cloud and precipitation affected radiances and radar observations, an expanded and sustained investment to the NASA/NOAA/DoD Joint Center for Satellite Data Assimilation (JCSDA) through its partner agencies is recommended, and a natural forum to train future scientists with the specialized knowledge needed in this topic area.

Q3: Why are space-based observations fundamental to addressing these challenges/questions?

The physics that describe weather systems cross telescoping spatial and temporal scales. Surface networks and radars require dense spacing and careful intercalibration, represent mostly near-surface meteorology, are more abundant and available in certain parts of the world, and are mostly over land. Space-based observations provide the more globally complete picture of weather systems, but are currently taken from various low-Earth orbiting satellite platforms with different orbits, scanning strategies, sensor designs or operating bands. Cross-calibration programs such as the CGMS Global Space-Based Intercalibration System (GSICS) have already recognized this and have programs in place to monitor the quality of satellite observations taken from self-similar sensors. The GPM mission, with its asynchronous orbit and partner/constellation-based observational design, and the A-Train with its space/time-aligned sensor formation flying, represent current complementary collections of observations that are more useful to cloud-to-precipitation process studies relevant to water cycle modeling, but provide an incomplete picture. Future space-based microwave observations that *concurrently* capture the finer-scale microphysical and dynamical time scales of the cloud-to-precipitation process, and the localized environmental conditions, are at the core of improvements to CRM modeling and assimilation into NWP models. The high frequency and collocated nature of these observations would present significant spatio-temporal details regarding the vertical motion, microphysical processes, and the feedbacks between the vertical motion and the microphysical processes.