<u>Title</u>: Constraining Atmospheric Ice Processes with Coincident Measurements of Ice Mass and Cloud Vertical Motion

<u>White Paper Description</u>:
Recent advances in active and passive satellite instrumentation have positioned NASA to advance the frontier of climate predictability by fostering the development of advanced cloud parameterizations through simultaneous measurement of cloud dynamics, ice content, and precipitation yield.

<u>Principal Author:</u> Tristan S. L'Ecuyer, *Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison*

<u>Co-author:</u> Steven A. Ackerman, *Department of Atmospheric and Oceanic Sciences and Space Science and Engineering Center, University of Wisconsin-Madison*

<u>Narrative of White Paper</u>:

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?

Much of the remaining uncertainty in future climate projections can be traced to an inadequate representation of the cycling of water through Earth's atmosphere through the critical series of processes that couple the hydrological and energy cycles of our planet. Of particular importance are the processes that govern the formation and maintenance of cloud systems and the resultant precipitation that supplies the fresh water that sustains life on Earth. These cloud and precipitation processes act over a continuum of spatial and temporal scales. Representing the accumulated impacts of local-scale processes on the large-scale climate system poses a significant unresolved challenge in climate modeling, which is clearly illustrated by the large discrepancies in ice water path and precipitation distributions derived from various GCM model simulations.

These differences arise from the varied approximations used to represent the microphysical and macrophysical properties of ice clouds in each model. The underlying lack of knowledge of ice cloud processes responsible for these discrepancies is evident in the wide range of ice masses and precipitation efficiencies among cloud resolving models (CRMs). Cloud simulations by models participating in the GCSS WG 2 Idealized Cirrus Model Comparison Project, for example, span more than an order of magnitude across state-of-the-art CRMs while the use of different ice microphysics schemes in a single CRM can change rainfall accumulations by a factor of two or more the simulation of a continental convection.

The fact that models produce widely varying ice contents has little more than academic relevance if the climate is not sensitive to ice cloud processes. However, ice clouds dominate the radiative energy budget of regions where they are present and play a key role in precipitation processes. As a result, modern climate models exhibit significant variability in the strengths of cloud feedbacks leading to a wide range in their predicted climates. Even more disturbing from a societal perspective is the fact that models disagree on the extent to which precipitation patterns may respond in a future climate. Narrowing the spread in cloud feedback and precipitation distributions in models will require accurate representation of the full spectrum of ice-phase precipitation processes across the varied environments around the globe.

A key challenge for improving the predictive capabilities of global climate models is ***accurately parameterizing the coupled radiative and hydrologic impacts of the complete spectrum of precipitation systems around the globe.*** While observations have, to some extent, been used to identify model deficiencies such as a precipitation intensity distribution that is skewed toward light rain, an under-representation of the diurnal cycle of convection, and significant under-estimation of the magnitude of cloud radiative effects in the southern oceans, observations to date do not provide sufficient information to directly improve model representations of the underlying physical processes. This stems, in part, from the fact that current observations do not have the needed accuracy to resolve inter-model differences in ice water path. In addition, current observing systems fail to provide the explicit measure of in-cloud dynamics required to connect model biases to the physical processes that govern linkages between the Earth's energy and water cycles.

In the coming decade, the challenge of improving the representation of ice-phase processes in global models can, however, be met through coordinated deployment of advanced active and passive satellite instrumentation that have been realized through NASA science and technology investments. Simultaneous observation of the integrated ice mass, its vertical structure, and small-scale vertical motions in the convective, stratiform, and non-precipitating anvil regions of global precipitation systems would satisfy the need for measurements to directly influence the development of improved parameterizations of ice processes in global models. All of these quantities can be measured with current space-ready technologies enabling a new paradigm for improving climate prediction through Earth observation.

To interface with climate model parameterizations, observations are required at the cloud-process-resolving scale and must exhibit sufficient temporal and spatial sampling to distinguish different cloud morphologies and meteorological processes. Of particular importance to climate prediction is quantifying the contributions to upper tropospheric ice production from deep convection as opposed to synoptic lifting. Such a classification would enable the development and testing of new self-consistent representations of ice cloud processes and cloud systems. Similarly, the rates of ice fallout control how much condensate remains in the air relative to that which falls to the ground as precipitation or is evaporated in the intervening atmosphere. Small changes to ice particle fall speed parameterizations can substantially modify model climates, by modifying the upper tropospheric water and radiation budgets. Reducing uncertainties in modeled fall speeds through direct measurements can, therefore, significantly improve the representation of cloud cover and radiative cooling in the atmosphere and, by extension, precipitation since atmospheric radiative cooling is directly connected to precipitation through energy balance constraints.

Progress in improving the representation of cloud processes in climate models requires close coordination of the cloud and precipitation remote sensing and climate modeling communities. Observations provide the essential data sets to test the models' representation of processes, while models are used to diagnose processes in great detail and quantify feedbacks. It is expected that the implementation of improved parameterizations facilitated by these new satellite observations will significantly reduce uncertainties in climate predictions on both global and regional scales, and, in turn, provide better projections of impacts on water availability to policy makers.

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

There is a pressing need for a mission dedicated to observing cloud and precipitation processes. Radar and sub-millimeter radiometer technologies have advanced significantly since the last Decadal Survey and have demonstrated the capability to acquire the necessary observations. Likewise, increases in computing power can be expected to reach the point where global models can resolve scales of relevance to individual convective cores. Important advances in the representation of moist physical processes are required to allow models to operate on such scales.

The NASA Earth Science Weather Focus Area hosted a community workshop in April 2015 to produce a report examining the scientific challenges and opportunities in NASA related weather research. The 70 invited participants in attendance, that included individuals from government agencies, academia, the private sector, and other national and international organizations suggested that one of the key questions NASA should seek to address is: *What processes determine cloud microphysical properties (ice clouds in particular) and their connections to aerosols and precipitation?* Furthermore, to address this question the panel noted a need for "***observational estimates of the vertical velocity within convective systems...***"

No current or planned observing system addresses the need for simultaneous measurements of ice water path and vertical motion at the scales required to isolate convective processes. Such observations require a combination of vertical profiling through the cloud system with complementary column-integrated constraint with broader spatial coverage that can only be provided by a multi-frequency Doppler radar and a sub-millimeter radiometer. The only planned international mission with related technology is the European EarthCARE mission that aims to provide the first measurements of Doppler velocity from space. However the target 1 ms^{-1} Doppler accuracy of the EarthCARE radar at an along-track resolution of 10 km is far too coarse to resolve convective processes and the strong attenuation and multiple scattering encountered at W-band limits its utility in strong convection. The Decadal Survey should, therefore, strongly recommend that NASA pursue a mission for addressing cloud processes through simultaneous measurements of ice mass and vertical motion. A majority of the instrument design challenges associated with the required technologies have been addressed through recent NASA technology development investment. We suggest that by leveraging an appropriate combination of the resulting assets, NASA is poised to push the frontiers of improving climate predictability through Earth observation through a mission dedicated to assessing ice processes directly.

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

From the deep convective towers that transport vast quantities of heat vertically in the west Pacific to the isolated trade cumuli that dot the tropical transition zones to the organized mesoscale convective systems that produce flooding rains at midlatitudes the character of convection varies widely across the globe. Responses in the lifetime, spatial coverage, precipitation yield from any of these cloud regimes can exert significant influences on the climate system. It is, therefore, not sufficient to develop models that address only one or two properties of convection in selected regions. Given the highly variable nature of convective cloud processes, space based global observations are the only approach for realizing the advanced understanding of the full spectrum of convection around the globe that is required to advance climate model prediction in the coming decades. No previous satellite mission has been designed specifically to connect accurate measurements of vertically integrated ice mass, in-cloud vertical motion, and precipitation. There is a critical need for such observations to inform the development of new parameterizations of ice cloud-precipitation processes in global models.