# The First Annual UFS Physics Workshop White Paper: Summary and Key Conclusions

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## 1. Introduction

The continuing advances in science and technology have made it possible for NOAA and collaborating organizations to develop the Unified Forecast System (UFS). The system will continue to be developed over the next decade to address the operational needs for improving weather prediction and climate projection. As the UFS application prototypes have become available to both research communities and operational centers, and continuous development of these applications is underway, the UFS Physics Working Group has recognized the need for organizing annual UFS Physics Workshops to discuss the latest advances in physics parameterizations that can be considered in further UFS physics development and implementation to address research and operation needs of the UFS users community.

The purpose of this white paper is to provide a comprehensive summary of the First UFS Physics Workshop conducted on 16-18 May 2023 at NCAR Foothill Laboratory, Boulder, CO. This workshop aimed to gather subject experts on cloud and precipitation observations, process understanding, and parameterizations to provide a comprehensive overview of the latest developments in cloud microphysics research. The annual workshop focused on providing a platform for scientists, operation researchers and students who are interested in UFS physics development to exchange ideas and collaborate on future UFS physics development projects. The workshop featured in-person and virtual oral presentations on state-of-the-art research and development that can help address questions about how to optimally parameterize physical processes and represent the hydrological, radiative, and dynamical impacts of clouds and precipitation across an increasing range of UFS applications, from the global to regional convective scales. Topics on how to make and use observations to constrain cloud microphysics parameterization development are also included. This document highlights the key insights, discussions, and outcomes of the workshop.

## 2. Workshop Objectives

The planned presentations and breakout discussions at the workshop focused on the following important themes relevant to the transition of research to operation in future UFS physics development:

a. What is the minimal complexity in cloud and precipitation microphysics parameterizations required for all operational applications?

b. Is a unification in the cloud and precipitation microphysics parameterizations possible for all operational applications?

c. How do we all in the UFS community efficiently and consistently represent the microphysical impacts of sub-grid heterogeneous clouds in the “gray zone”?

d. How do we efficiently and consistently represent aerosol-cloud interactions in convection and microphysics parameterizations?

e. How do we evaluate and improve the operational forecast of mixed-phase clouds, especially in the mid- and high-latitudes?

f. How do we use observations and/or large-eddy simulation (LES) to diagnose/evaluate and constrain parameterized cloud and precipitation processes?

g. What should be included in a research grade version of the UFS microphysics scheme (and other physics and chemistry components)?

h. How can we collaborate more effectively with the community at large on microphysics parameterization to address the UFS development needs?

Centering on these questions, the workshop was organized with the following objectives:

i. Identify the current challenges and opportunities related to the microphysics parameterization development in the UFS.

ii. Foster collaboration and knowledge sharing among the participants.

iii. Develop actionable strategies and recommendations to address the identified challenges in both operation and research using the UFS.

iv. Explore innovative ideas and potential solutions for long-term cloud microphysics development in the UFS.

The workshop brought together about 85 U.S. and international participants to discuss in person or virtually the above themes and provide various perspectives for cloud microphysics parameterization development in the UFS community according to the above mentioned objectives. It followed a structured agenda comprising the following sessions:

- Welcome and remarks on the workshop objectives.

- Invited and contributing presentations on Research and Development, Operational Needs and Ongoing UFS-R2O Development, Community Development, and Using Observations to Improve Microphysics Parameterization.

- Breakout sessions for interactive discussions and recommendation generation.
- Presentation and discussion of findings from breakout sessions.
- Summary and conclusion.

The workshop agenda and links to presentations are available on the meeting web site (https://psl.noaa.gov/events/2023/ufs_physics_workshop/ ) under the Agenda tab.

## 3. Key Conclusions and Recommendations

The workshop started with a series of presentations from subject matter experts focusing on the discussions of the state-of-the-art cloud microphysics parameterizations at a range of resolutions and the use of observational data sets and various techniques for evaluating cloud microphysics process parametrizations. This was followed by three breakout groups tasked with summarizing the conclusions and recommendations for each of the seven workshop themes. Many important insights and ideas emerged and were discussed extensively during the workshop for UFS cloud microphysics parameterization development, and the key conclusions and recommendations are summarized as follows.

### 3.1 Operational Needs and Ongoing UFS-R2O Development

To address NOAA's operational needs related to UFS applications and to support ongoing UFS-R2O development in the next 5 years, it is recommended at the workshop that the UFS community should continue focusing its effort on the development of aerosol-microphysics interactions and microphysical connections between various grid- and subgrid-scale cloud production processes. It is important for future UFS microphysics schemes to accurately account for regional differences in liquid and ice cloud nuclei amount and partition (e.g., mixed-phase clouds in the Arctic region vs. cumulus clouds over the tropics). Careful consideration of dynamics-physics coupling, particularly the handling of microphysics process coupling, should be part of this developmental effort. For global applications, such as the GFS, computing efficiency for including aerosol-microphysics interaction remains a concern, and research is required to address the question of how to effectively and efficiently parameterize aerosol-microphysics interaction. For regional UFS applications, it is recommended that research be conducted to parameterize the aerosol-microphysics interaction involving aerosols from biomass burning, sea spray, and anthropogenic emissions. At least, sulfate-based aerosols should be included in operational applications to account for their direct and indirect effect. Furthermore, regional UFS applications should account for the microphysical effects of simulating smoke and dust properties, as they are desirable for operational air-quality prediction.

Most workshop participants agreed that there is a need for developing a prognostic cloud scheme in the UFS with a consistent connection in microphysics between grid-mean and subgrid-scale cloud mass and cloud volume fraction. As illustrated at the workshop by some of the ongoing efforts in the UFS community, such a scheme will provide a physically-based means to phase out the use of “fake subgrid-scale clouds” that are seen only by radiation and do not interact with other physical parameterizations. It will allow a better representation of the interaction between aerosols, serving as liquid and ice cloud nuclei particles, and subgrid cloud inhomogeneity in a pristine environment coupled to sea ice. The latter is important for, among others, a UFS-Arctic application to assess mixed-phase cloud parameterizations and their interaction with sea ice in the Arctic.

## 3.2 Scientific Research and Development

The minimal complexity of microphysics parameterizations for operational UFS applications remains a subject of scientific research. However, most participants agreed that operational UFS microphysics schemes should include cloud water, rainwater, cloud ice, snow, and rimed ice (graupel and/or hail) as predictive hydrometeor variables. Double-moment formulations should be included in operational UFS microphysics schemes, at least for some of these hydrometeors. Effects of aerosols and ice nuclei (via simple emissions model or climatology) should be included in operational UFS schemes. In all operational UFS applications, the clouds should be coupled with radiation using hydrometeor particle radii. Parameterized microphysical processes should be scale-aware and depend on grid sizes for different applications. Future research should consider whether simplifying graupel and hail as one hydrometeor category is reasonable or whether the answer is application-dependent. For research applications of the UFS, there is a need for microphysics schemes to predict density/shape/rime fraction, and the need for this approach in operations needs to be evaluated. Since storm-scale and global UFS applications use different verification procedures and metrics, can a scheme designed for storm-scale applications be used globally (maybe with options)? The efficiency of using a complex scheme in a global model should also be considered in determining the minimal complexity of microphysics parameterizations.

A subject extensively discussed during the workshop is to what degree the "unified" microphysics scheme for UFS applications will be possible. Significant effort has been devoted to this goal over the past 3 years. For instance, the Thompson microphysics scheme was selected at the beginning of the UFS-R2O project with the explicit intention of unifying microphysics parameterization across applications in the UFS. However, there are configurational differences in aerosol awareness, sedimentation, and tuning. Although a potential benefit of unification is to align and coordinate better available resources on a common goal, the development philosophy and governance remain issues for research. Furthermore, new challenges emerge as global and regional UFS applications become less distinct. For example, global-regional two-way nest UFS applications need a "unified" microphysics parameterization scheme that works equally well at global and regional model resolutions. This need poses challenges, such as that hail may not need to be accounted for as a hydrometeor in global forecast applications at coarser resolutions, but it is necessary for storm-scale forecasts. Is it sensible for the "unified" scheme to include hail in the global applications at coarse resolutions? Another example is that phenomenon-/location-specific microphysics parameterizations may have advantages in the current regional UFS applications, but can they be generalized to work at resolutions for global applications? Would it make sense to develop a "unified" scheme with different degrees of complexity in which options can be selectively turned on and off in various UFS applications?

Most participants agreed that since all operational UFS applications require an accurate representation of cloud fraction in a grid box, assessing how complex the cloud fraction representation should be for subgrid cloud heterogeneity is necessary. Should it be prognostic or diagnostic? Is there sufficient observational information to validate the cloud fraction representation? How are parameterized in-cloud microphysics processes and cumulus/shallow cloud parameterizations consistently incorporated into the cloud fraction representation? Should a "unified" microphysics scheme be developed for a physically-consistent cloud fraction representation? Additional research should also be conducted to investigate the sensitivity of the cloud fraction representation to the model's vertical resolution.

During the workshop, some participants brought up discussions of using bin-spectral and Lagrangian super-droplet models along with AI/ML techniques to improve and further develop UFS microphysics parameterization schemes. These discussions also included using observations to evaluate uncertainties in parameterized hydrometeor fall speeds and mass-size characteristics. This observational evaluation would require forward radiation transfer models to compare with radar and satellite observations.

It was shown by some presentations at the workshop that the cloud microphysics scheme currently tested in the UFS prototypes (i.e., the Thompson scheme) can reasonably simulate the production of supercooled liquid water in North America as verified by aircraft. However, the scheme still struggled to represent the mixed-phase clouds in the Arctic region and the tropics. Using observations to evaluate and constrain the development of the parameterization of the mixed-phase cloud production process and its dependence on aerosol distribution is a top priority. Besides aerosol concentration and temperature, other factors, such as ice particle habitats, may contribute to the mixed-phase cloud formation and should be accounted for in the parameterization. LES and single-column model (SCM) evaluations should be used to detangle what is missing in the current parameterization. There is a need to include observed mixed-phase cloud cases in the public CCPP SCM library to evaluate the interaction between cloud microphysics and surface forcing and its sensitivity to vertical resolutions.

Further research and development are recommended to ensure that convection schemes in the UFS use aerosol information consistently with that used in the microphysics scheme, and they detrain clouds and number concentrations consistently with microphysics parameterization. Also, because detailed aerosol information affects precipitation efficiency and processes of cloud droplet autoconversion and rain evaporation, using aerosol information consistently between grid- and subgrid-scale cloud microphysics parameterizations to represent ice nuclei realistically will allow an accurate representation of supercooled water production in Arctic clouds where the supercooled cloud layer formation depends on radiative cooling and top-down sub-grid mixing. Observations are required in the recommended research to evaluate new developments.

There are two specific recommendations for further research and development to improve UFS microphysics parameterizations. One is that the future UFS physics suite should have a configurable and flexible microphysics scheme with optional components for processes and species and closer interactions with chemistry. This scheme should be coupled with the dynamics with proper fast and slow process separation. It should also provide diagnostic outputs of processes and liquid and ice properties (e.g., median volume diameter) as an option, which requires an increased CCPP and host model flexibility for new variables. To facilitate the development of such a scheme (or continued development of the Thompson MP scheme) for operational UFS applications, there should be continued community-wide communication to share the diagnostics from these operational UFS applications. It is also necessary to compare the UFS microphysics parameterization development with similar activities at other operational centers to see how they solve their problems. The other recommendation is that developers of the existing cloud and precipitation production schemes must be open-minded and receptive to community development contributions. Effective community-wide coordination is required to facilitate multiple developers working together to avoid a single point of failure in future development.

## 3.3 Using Observations to Improve Microphysics Parameterizations

The scope of presentations throughout the meeting consistently demonstrated the value of using observations of different types to validate physics schemes and model predictions. Participants recognized the need for additional observations including combinations of satellite, in situ, and other remotely sensed products to capture the full range of process scales and simultaneous measurement of multiple parameters. Participants noted, however, the frequent lack of direct consistency between observed and modeled variables, and encouraged the comparison of appropriate parameters when possible (e.g., radiation or optical depth as opposed to cloud fraction) and the potential development of instrument emulators (as opposed to direct use of retrievals).

All participants agreed that there is a need to use different cloud observations from satellite, radar, lidar, aircraft, surface, and passive remote sensing to evaluate cloud microphysics properties, radiative fluxes and precipitation simulated by the UFS physics to reduce compensating errors in the model. Future UFS evaluations should include comparing statistical relationships between different microphysical property observations and simulations to focus on evaluating individual process parametrizations. In particular, the representation of ice microphysics in weather and climate models is challenged by the range of ice particle shapes and sizes observed in field experiments, such as the Mid-latitude Continental Convective Clouds Experiment (MC3E), the North Slope of Alaska (NSA) and the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) campaigns. Typical microphysics parameterization schemes use various hydrometeor categories defined by prescribed physical characteristics (e.g., density, fall speed) that broadly describe particle type (e.g., cloud ice, snow, graupel). These characteristics are traditionally specified using empirical parameters (e.g., mass-size relations, projected area and size relations, fall velocity and size relations, single-scattering properties, size distributions characterized by gamma functions in terms of intercept, slope and shape parameters) derived from observations and held fixed or functions of other prognostic variables in models. Although some studies have investigated the sensitivity of simulated fields to choices of coefficients, no studies have examined the impact of including natural parameter variability on the UFS cloud and precipitation prediction.

All participants also agreed that additional UFS skill metrics based on using observed clouds and atmospheric radiation fluxes should be used in the UFS microphysics parameterization development to provide a more sensitive measure of future microphysics parameterization improvements in the UFS skill than the traditional skill measures. To this end, it is recommended that an effort be included in the ongoing microphysics parameterization development in the UFS to use observations taken during the MOSAiC campaign to test and improve microphysics and boundary layer processes needed to simulate the phase partitioning of cloud liquid and ice in Arctic mixed-phase clouds and strongly stably stratified boundary layers (and the coupling between these processes). Standard Arctic cases should be set up for SCM studies using the CCPP that will be made available to the UFS community. Other cases for using the UFS skill metrics based on field campaign observations should also be set up using observations from other field campaigns, such as the Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast USA (VORTEX-USA), to evaluate the impact of the improvements from the ongoing UFS microphysics parameterization development on the forecasts of the atmospheric boundary layer in terms of winds, temperature, and moisture.

Participants in an observations-focused breakout session noted several additional needs for specific observations and model-observation comparisons. The desire for more observations over oceanic regions, particularly the Southern Ocean and marginal ice zone was expressed. Observations in the far-Southern Ocean would provide pristine conditions and serve as a natural laboratory. Specific desired observation types included aerosols and cloud-aerosol interactions as well as high-resolution water vapor observations over more regions. Aerosol measurements, particularly at high-latitudes, were desired above and below clouds as well as at the surface, and segregation into ice- and water-friendly categories is needed. More consistent processing of observations (particularly in situ) is needed to better facilitate comparison of results across diverse field studies. To further enhance model-observation comparisons, the output of pdfs of key observational parameters like optical depth over simple average values from models is desired as is the regular output of parameters at specific sites (e.g., the ARM sites) with sustained measurements.

## *Acknowledgements*

We are grateful for all workshop participants whose enthusiasm and active engagement in presentations and discussions made the workshop successful. We thank Paul Kucera and Jennifer Bolton (NCAR RAL) for their dedicated work on the logistics to help host the workshop at NCAR and Barbara Deluisi (NOAA/Physical Sciences Laboratory) for her work on the workshop webpage. We appreciate the support from Kevin Garrett (NOAA Office of Science and Technology Integration (OSTI) Modeling Program) and Dorothy Koch (NOAA Weather Program Office), as well as the NOAA Unified Forecast System Steering Committee, Office of Naval

Research, NOAA/OAR Physical Sciences Laboratory, and NOAA/NWS/Environmental Modeling Center, which made the workshop possible.