BAMS Meeting Summary

Advancing NOAA's Subseasonal and Seasonal Applications and Enhancing Collaboration among Stakeholders, Modelers, and Researchers

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First NOAA's Subseasonal and Seasonal Applications Workshop

***What*:** Hosted by the Office of Science and Technology Integration (OSTI) Modeling Program in the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA), the first annual NOAA's Subseasonal and Seasonal (S2S) Applications Workshop provided a forum for about 330 participants (in-person and virtual) to discuss recent advances in NOAA's global S2S applications, compile stakeholder requirements and needs and use cases of those applications in developing forecast products/outlooks and downstream applications, and share experience and insights from S2S modeling systems such as those in the North American Multimodel Ensemble (NMME) and at the European Centre for Medium-Range Weather Forecasts (ECMWF) and Environment and Climate Change Canada (ECCC). The workshop discussed in depth the challenges and progress that NOAA has made in the past 5 years in developing the next-generation subseasonal Global Ensemble Forecast System (GEFSv13) and Seasonal Forecast System (SFSv1) under the Unified Forecast System (UFS) framework. The workshop aimed to identify essential points of engagement and collaboration across the S2S community and promote the formation of best practices and strategies in the development and implementation of operational S2S forecast systems through collaborative research and development endeavors.

***When*:** 4–6 September 2024

***Where*:** NOAA Center for Weather and Climate Prediction (NCWCP), College Park, Maryland

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1. Introduction

Organized by the Office of Science and Technology Integration (OSTI) Modeling Program in the National Weather Service (NWS), the first NOAA's Subseasonal and Seasonal (S2S) Applications Workshop took place at the NOAA Center for Weather and Climate Prediction (NCWCP) in College Park, Maryland, on 4–6 September 2024. This hybrid workshop hosted 330 registered participants across the public, private, and academic sectors of the Weather Enterprise (in-person and virtual) and featured 87 oral presentations and 45 posters (Fig. 1). The presentation slides, recordings, and posters are available at the web page https://vlab.noaa.gov/web/osti-modeling/workshops/2024/s2s-workshop. The primary objective of the workshop was to promote the advancement of the next-generation of the NOAA's subseasonal Global Ensemble Forecast System (GEFSv13; Stefanova et al. 2022) and Seasonal Forecast System (SFSv1) within the Unified Forecast System (UFS) framework (https://www.ufs.epic.noaa.gov). The SFSs that are designed to assist in the protection of the U.S. economy and lives are in need of

Fig. 1. The first NOAA's Subseasonal and Seasonal (S2S) Applications Workshop was a 3-day hybrid meeting held at the NCWCP in College Park on 4–6 Sep 2024.

an update since they are based on physical models that are more than a decade old. Modernization and implementation of UFS-based SFS systems continues NOAA's stewardship in this domain. Through a community modeling approach, NOAA seeks to advance these systems by fostering collaboration among model developers, researchers, and stakeholders/users in the public, private, and academic sectors. To that end, this workshop sought to identify essential points of engagement and collaboration across the S2S applications community. Ultimately, these collaborative efforts will guide and inform the formation of best practices and strategies in the development and implementation of operational S2S applications at NOAA.

The 3-day workshop provided a collaborative forum across eight themes with oral and poster presentations and panel discussions encompassing key areas of inquiry, development, and innovation within the S2S applications community. In doing so, this workshop covered several key topics related to NOAA's S2S applications. It gathered the latest stakeholder requirements and forecaster priorities for improving NOAA's S2S forecast systems, examined systematic model errors in the North American Multimodel Ensemble (NMME; Kirtman et al. 2014) and other S2S systems, and shared insights on enhancing S2S capabilities for prediction. Participants discussed best practices for initializing forecasts and explored the use of process-level diagnostics tools and verification metrics. Additionally, this workshop highlighted advancements in GEFSv13 and updates to UFS component models, introduced NOAA's "SFS Development Plan" and early SFSv1 results, and explored community engagement opportunities in GEFS and SFS development. Presentations and discussion also covered the potential of artificial intelligence/machine learning (AI/ML) methods to complement physics-based approaches in NOAA's S2S applications. Following the conclusion of the day 3 workshop sessions, a panel of subject matter experts (SMEs) across the S2S application community presented their feedback on and critiques of the NOAA's SFS Development Plan. Afterward, the workshop organizers opened up a community survey in which the workshop participants provided feedback and critiques to the SFS Development Plan directly.

2. Workshop outcomes

a. Stakeholder requirements and needs and forecasters' priorities in improving NOAA's S2S applications. On day 1 and into day 2 of this workshop, presentations on stakeholder requirements for NOAA's S2S applications sought to establish a better understanding of the current and anticipated needs of the S2S applications from the user community across the public, private, and academic sectors. Topics covered included current uses of the GEFSv12 (Zhou et al. 2022) and Climate Forecast System, version 2 (CFSv2; Saha et al. 2014), evaluations and shortcomings of the existing S2S forecast systems, and desired improvements of those forecast systems within the development and implementation of GEFSv13 and SFSv1. The findings from this session will guide operational S2S model design and evaluations and development priorities for future model versions (GEFSv13, SFSv1, and beyond). This paves an avenue for a continuous and synergistic communication between stakeholders/users and model developers. In tandem with this stakeholder requirements and needs session, talks and posters on forecasters' priorities for improving NOAA's S2S applications provided valuable insights into challenges and needs for applying the S2S model outputs in operational subseasonal and seasonal forecast outlooks. The presenters not only described the current uses of GEFSv12 and CFSv2 in developing S2S forecast outlooks but also identified additional improvements in the configuration of the GEFSv13 and SFSv1 model suites for both real-time forecasts and reforecasts. Presenters highlighted physics-based and data-driven AI/ML postprocessing applications and how they are employed to improve and enhance S2S predictions and forecast guidance messaging. The synthesis of S2S applications' stakeholder requirements and S2S forecasters' priorities collected during this workshop not only brought attention to gaps between requirements and the current capabilities of and recent updates in NOAA's S2S applications but also highlighted opportunities to promote the advancement of these forecast systems in the coming years. This compilation of subseasonal GEFSv13 and seasonal SFSv1 requirements and priorities summarizes as follows:

1) GEFSv13 (subseasonal)
   - Support Weeks 3–4 and Monthly Temperature and Precipitation Outlooks, Weekly and Monthly Drought Outlooks, and Weekly and Monthly Sea Ice Outlooks.
   - Support Week 2 U.S. Hazards Outlooks and Weeks 2–3 Global Tropical Hazards Outlooks.
   - Support downstream hydrological applications (Hydrologic Ensemble Forecast System and National Water Model).
   - Support coastal hazards (sea level and flooding) forecasts and extreme heat and wildfire outlooks.
   - Improve sea ice, surface winds, and wave forecasts to better support transoceanic shipping, polar routing, and cryospheric research.
   - Improve extreme precipitation, precipitation type, and snow depth forecasts.
   - Reduce warm bias over the U.S. central plains.
   - Improve handling of shallow cold air masses, low CAPE bias, and warm bias in heat waves.
   - Improve spatial resolution to capture terrain and islands.
   - Improve atmospheric river forecasts.
   - Improve flash drought outlooks via improved land modeling and initialization.
   - Expand forecast horizon for marine hazards.
2) SFSv1 (seasonal)
   - Support El Niño–Southern Oscillation (ENSO) Outlooks, Seasonal Temperature and Precipitation Outlooks, Seasonal Drought Outlooks, Seasonal Hurricane Outlooks, and Seasonal Sea Ice Outlooks.
   - Support coastal and lake forecasts and applications.
   - Support hydrologic forecasts and downstream applications.
   - Support marine hazards forecasts and applications.
   - Reduce model biases in long-term trends, planetary boundary layer processes, tropical processes, stratospheric dynamics, and climate modes and their teleconnections.
   - Reduce ENSO false alarm forecasts.
   - Address "slow propagation of the Madden–Julian oscillation (MJO)" bias.
   - Address the overly frequent forecasting of warm anomalies over the CONUS.
   - Address the temporal discontinuities in initial conditions used to initialize seasonal reforecasts.
   - Improve ensemble design, spread, and reliability.
   - Improve capturing of seasonal extreme phenomena.
   - Improve land surface model processes for drought impact prediction.

b. Sources of predictability and model biases, improvements and best practices in data assimilation, and process-level diagnostics and metrics. On day 2 of this workshop, presentations on comparative S2S model evaluations and diagnostics explored key sources and drivers of S2S predictability and identified essential metrics for quantifying and ranking S2S model performance. The NMME intermodel comparisons identified sources of common model biases and errors. The workshop engaged the broader NMME users' community on sharing experiences and lessons learned to address persistent model biases and common forecast errors. Furthermore, this session highlighted various postprocessing methods for bias correction and model calibration that enhance forecasting skill in addition to recent developments in S2S models.

A parallel day 2 session on best practices in initializing global S2S forecast systems explored the current deficiencies in the initial conditions (ICs) of slow-varying Earth system components that underlie potential forecasts of opportunity and seasonal predictions, e.g., from the memory of ocean, land, and sea ice. The S2S forecast initialization deficiencies highlighted during this session were addressed through various ensemble perturbation and advanced data assimilation (DA) methods that more skillfully handle previously identified sources of error within such ICs, including the transition to weakly coupled and strongly coupled DA approaches. This session also consolidated coupled reanalysis requirements for the initialization of global S2S models and the importance of consistency between initial conditions for historical reforecasts and those for real-time forecasts. The anticipated improvements in NOAA's data assimilation capabilities were largely attributed to the development of the Joint Effort for Data Assimilation Integration (JEDI) framework (https://www.jcsda.org/jcsda-project-jedi) as a conduit within the greater UFS infrastructure, which in turn sets the stage for demonstrable improvements in forecast skill within the pending upgrades to NOAA's S2S forecast systems, e.g., GEFSv13 and SFSv1.

To better track the evolution of S2S forecasting and prediction skill over the years and under the conditional phenomena that support forecasts of opportunity at these time scales, it is crucial to not only develop and employ a common set of performance-oriented forecast skill metrics but also support process-level metrics that evaluate how well Earth system models represent the physical mechanisms that underlie key sources of predictability, such as the MJO and ENSO and their teleconnections. A day 2 parallel session on process-level diagnostics and evaluation metrics featured key process-level diagnostics to be considered for SFSv1, delved into viable applications of community-developed forecast verification software packages, e.g., the National Center for Atmospheric Research (NCAR) Developmental Testbed Center (DTC) MetPlus Toolbox (Jensen et al. 2024), and delineated potential avenues of UFS community collaboration on evaluation endeavors. This session also highlighted recent developments and advancements in the Environmental Modeling Center's Verification System (EVS) and the Climate Prediction Center's Versatile Verification System (VVS), both of which employ DTC's MetPlus Toolbox. The VVS is designed to expand the MetPlus Toolbox so that it encompasses monthly and seasonal forecast verification capabilities adaptable to individual and multimodel ensemble forecast systems. Ultimately, such developments and advancements in NOAA's model evaluation applications will allow the S2S application user community to better diagnose sources of conditional forecast errors and more efficiently correct for those sources of errors via statistical postprocessing methods.

c. Advances in UFS infrastructure and progress in GEFSv13 and SFSv1 development. Toward the end of day 2 and into day 3 of this workshop, presentations provided comprehensive updates into the ongoing development of the subseasonal GEFSv13 and seasonal SFSv1 and noted advances and improvements in the associated UFS infrastructure and Earth system component models. The GEFSv13 session highlighted the crucial upgrade of the GEFS infrastructure to a six-way coupled model, as shown in Fig. 2, which will allow NOAA to expand its range of S2S forecast capabilities and products for sea ice, ocean, wave, and aerosol predictions, among others. This GEFSv13 session also delved into this model's ongoing transition-to-operations (T2O) activities, with a focus on comparative evaluations of the GEFSv13 prototypes and the revealed improvements in subseasonal forecast skill compared to the GEFSv12 and CFSv2 models for both performance-based and process-based metrics. Furthermore, presentations within this session delineated additional user requirements for real-time and historical hindcast-based GEFS applications for the validation and calibration of downstream products, such as hydrological forecast systems. Presentations also elaborated upon the outstanding forecasting gaps and biases in the current GEFSv13 prototypes that will need to be addressed in future GEFS versions.

The day 3 sessions covered key modeling community contributions to the UFS infrastructure, including the specific component models, e.g., the Finite-Volume Cubed-Sphere dynamical core (FV3 dycore; Harris et al. 2021) and Common Community Physics Package (CCPP) for atmospheric processes (Heinzeller et al. 2023); the Modular Ocean Model, version 6 (MOM6; Adcroft et al. 2019), for ocean; the Los Alamos Sea Ice Model, version 6 (CICE6; Hunke et al. 2017), for sea ice; the Noah Land Surface Model with multiparameterization (Noah-MP LSM; Niu et al. 2011) for land surface processes; the Goddard Chemistry Aerosol Radiation and Transport model (GOCART; Chin et al. 2002) for atmospheric composition; and the WAVEWATCH III for ocean surface waves (WW3DG 2019), and coupling infrastructure such as the Community Mediator for Earth Prediction Systems (CMEPS). This UFS session also discussed specific upgrades in model physics and configurations that show early promise in improving forecast skill in the S2S time frame while minimizing computational cost, e.g., a hydrostatic option in the FV3 dycore, scale-aware physics updates in the Noah-MP land surface model, sea ice–wave coupling, and hybrid vertical levels and eddy-permitting and eddy-resolving resolution options in the MOM6 ocean model.

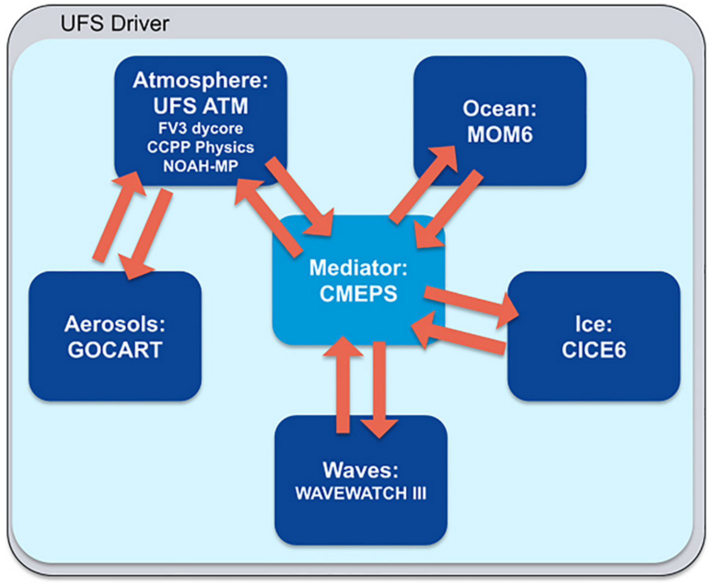

Fig. 2. GEFSv13 model configuration and six-way coupled infrastructure with UFS component models and CMEPS, adapted from NOAA's SFS Development Plan.

Last, a day 3 session on early progress within SFSv1 development provided an overview of the current iteration of the "SFS Development Plan" and explored upgrades within the model physics and configurations of the UFS component models for the SFSv1 prototypes. Presentations within this session not only highlighted advances within the UFS that the SFSv1 will leverage in development and implementation but also revealed early findings from SFSv1 baseline experiments, avenues in infrastructure and workflow development, and best practices and strategies for generating an SFS reanalysis and related reforecasts. This session also brought to attention the logistical challenges for the SFSv1 development and outstanding forecasting errors and model biases that need to be addressed in the years ahead, which necessitates continuous feedback from the S2S applications community.

d. SFS Development Plan feedback. The SFS Development Plan feedback and recommendations that were compiled from the workshop panelists and participants yielded points of consensus as well as diverging critiques. There is agreement that any updates to CFSv2 will add value in of itself, given that S2S predictive systems and the underlying science have advanced significantly since CFSv2's implementation in 2011. Also, there is further concurrence that the employment of a UFS modeling infrastructure that supports a multitude of common component models eases the development of UFS-based S2S forecast systems. In that regard, advancements in the subseasonal GEFSv13 would aid in the development of the SFSv1 at the seasonal scale. Nonetheless, workshop panelists and participants found that the current iteration of the SFS Development Plan, while ambitious, is too conservative, with limited innovations in forecasting and too much focus on well-known and well-established issues in the underlying science. This plan would benefit from connecting itself to active and adjacent NWS strategic plans and initiatives and establishing a framework for greater collaboration with subject matter experts and modeling centers external to NOAA.

Upon consideration of the model components in development, the aggregate feedback of the SFS Development Plan emphasized that it would be beneficial to align the focus of SFS development with the known targeted sources of seasonal predictability and the relative dependence of specific Earth system phenomena and their underlying physics on the spatial and temporal scales of interest for subseasonal and seasonal applications users. Such an approach would require SFS developers to weigh the costs and benefits of added UFS complexities to the existing seasonal forecast system, e.g., coupled waves and aerosol models, the expected forecasting skill gained by incorporating those complexities, and the human and computational resources available to support model development and subsequent operationalization and implementation. Priorities should align with the essential stakeholder needs and requirements as they pertain to improved seasonal forecasts of variables such as SST, 2-m temperature, precipitation, and sea ice. An additional cost versus benefits consideration in SFS development was whether it was pragmatic to directly tie the implementation timeline of SFSv1 to the completion of the associated 40+-yearlong reanalysis dataset for the initialization of the SFSv1 reforecast from 1980 to the present. While there was some contention about the underlying logistics of generating an SFSv1 reanalysis dataset, there was general agreement about the length of the time frame required to generate a reliable reanalysis dataset and the ensuing derived reforecasts, which approximates to a 5–7-yr cadence to update a 40-yrlong reanalysis dataset. A careful consideration has been given to whether established “replay” methods (https://psl.noaa.gov/data/ufs_replay/), such as those using the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5; Hersbach et al. 2020) and the ECMWF’s Ocean Reanalysis System 5 (ORAS5; Zuo et al. 2019) dataset, could be used to skillfully initialize seasonal reforecasts in the interim before a reliable reanalysis dataset can be completed.

It is also recommended that the SFSv1 development evaluations should progressively shift from an end-product focus (SST, 2-m temperature, precipitation, sea ice extent, etc.) to a focus that prioritizes evaluations of the underlying physical processes that are critical for capturing sources of subseasonal and seasonal predictability. This development and evaluation approach would lend itself to improved subseasonal and seasonal forecasting skill through inherent advancements in physics and dynamics, model components, and coupling across model components, as opposed to external postprocessing methods such as bias/trends correction and model calibration. However, with concerns about the length of the SFS development and implementation timelines and the cadence of future SFS upgrades, it is more pragmatic to frame the evaluation of the SFSv1’s maturity in terms of the existing and anticipated model prototypes’ forecast skill improvements over CFSv2, which could potentially expedite the operationalization of SFSv1 ahead of its target date in 2028 while allowing CFSv2 to remain active as a point of comparison. In doing so, a more frequent cadence of SFS model upgrades can be established, and with that, a more feasible list of model innovations can be implemented within each upgrade period.

3. Concluding remarks

The continuing advancement of NOAA’s S2S forecast systems and the refinement of our understanding of the current gaps and opportunities for improvement within those forecast systems require an adaptive and integrative framework of collaboration among model developers, researchers, and stakeholders/users. To support a community-wide engagement within such a collaborative framework of developing NOAA's S2S forecast systems, the 2024 NOAA's Subseasonal and Seasonal Applications Workshop provided a forum among the S2S applications community to better define stakeholder requirements and forecasters' priorities for the pending upgrades to NOAA's S2S applications and to address common sources of errors and biases among all S2S forecast systems, including the NMME suites. Common to all S2S forecast systems are model initialization strategies, process-level and operation metrics to quantify models' performance, and understanding of sources of S2S predictability.

This forum discussed recent advancements in community components that would be leveraged in the UFS Earth system model infrastructure to enhance the S2S forecast skill and denote the current development trajectory of NOAA's SFSv1. Additionally, this forum culminated in a consolidation of community-wide feedback and recommendations that will not only guide the general strategy for NOAA's SFS development endeavors but also build the groundwork for drafting a "SFSv1 Implementation Plan" and the establishment of best practices that will guide future upgrades to NOAA's S2S forecast systems that are agile and adaptive to S2S community needs. Overall, this workshop was successful in its inaugural iteration, opened up multiple avenues of engagement across the S2S applications users' community, and set the stage for accelerating NOAA's S2S forecasting capabilities and readiness to address the ever-evolving needs of model users and stakeholders alike.

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