NOAA

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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NOAA's SEASONAL FORECAST SYSTEM (SFS) DEVELOPMENT PLAN

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1. EXECUTIVE SUMMARY

In Fiscal Year 2023, the United States Congress allocated resources to support the development of a new operational Seasonal Forecast System (SFS) at the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA), paving the way for the replacement of the Climate Forecast System Version 2 (CFSv2), the current operational seasonal forecast system at NWS's National Centers for Environmental Prediction (NCEP). While the implementation of CFSv2 in 2011 marked a significant advancement in operational capabilities, the demand for a state-of-the-art seasonal forecast system, along with a contemporary reanalysis and reforecast database has persistently ranked as one of the primary requirements among forecasters and stakeholders for many years.

In response to the congressional appropriation, the Office of Science and Technology Integration (OSTI) in NOAA's NWS, and the Weather Program Office (WPO) in NOAA's Oceanic and Atmospheric Research (OAR) jointly established an SFS Application Team (AT), following which an SFS Project was formally launched on October 1, 2023. The SFS AT is composed of model developers and forecasters from NCEP's operational centers, researchers from OAR laboratories and the National Center for Atmospheric Research (NCAR) as well as collaborators from wider research and academic communities. The SFS is being developed as a new Application within the Unified Forecast System (UFS), NOAA's new community modeling framework for operational and research applications. The SFS Project is currently in its first year, and is expected to follow a multi-year agile development strategy. The first operational version is anticipated to be released in Fiscal Year 2028, with ongoing incremental improvements in subsequent versions. The SFS aims to make significant progress in seasonal predictions for precipitation, drought, temperature, tropical cyclone frequency, and weather extremes, benefiting decision makers across the public and private sectors.

The SFS will build upon and extend the capabilities of NOAA's Global Ensemble Forecast System (GEFS) version 13, which is under transition to operation currently, with a focus on accurately representing slowly varying processes in land, oceans and sea-ice, as well as capturing key seasonal and subseasonal scale phenomena such as El Nino - Southern Oscillation (ENSO), Madden Julian Oscillation (MJO), Quasi Biennial Oscillation (QBO), global monsoons, severity and frequency of extreme events such as flash drought, flooding, atmospheric rivers, hurricanes, heat waves, among other hazardous events. Over the coming years, new SFS appropriations are expected to bridge critical gaps in the current operational system, including coupled Data Assimilation (DA), improved physics characterization of processes in land, oceans, sea-ice, aerosols, development of land vegetation and groundwater, sea-ice growth and melt, ocean mixing, and atmospheric ozone, which are vital for subseasonal and seasonal scale predictions. A new reanalysis for the coupled atmosphere-ocean-sea ice system will be produced for climate monitoring and post-processing and calibration of longer range forecasts.

Through collaboration with NOAA's Earth Prediction Innovation Center (EPIC), the SFS AT is exploring comprehensive utilization of commercially available cloud computing resources for model development, reanalysis, reforecasts, and potentially for operational production runs. The strategic use of cloud resources will facilitate seamless data and code sharing, foster collaborative efforts within the community, and promote the integration of cutting-edge technologies such as Artificial Intelligence / Machine Learning (AI/ML) in operational model development, DA and forecast product generation.

This document presents developmental objectives for 3-5 years and will serve as a high-level strategic guideline for NOAA management and leadership as well as for the UFS community partners. This plan is expected to assist in the prioritization of funding for both internal and external projects supported by NOAA, related to the development of subseasonal and seasonal modeling systems. Additionally, by releasing the operational model development priorities in the public domain, it is expected that NOAA's collaborations with its community partners become further transparent and efficient, which is critical for accelerating operational model development and ensuring timely research to operations transitions.

A summary of key developmental priorities is listed in Section 11, while detailed descriptions of each developmental focus area can be found in Sections 4 - 10.

2. INTRODUCTION

The practice of forecasting monthly and seasonal averages of atmospheric and oceanic conditions dates back to the 1950s, which began following the discovery of statistical relationships between large-scale circulation patterns and temperature anomalies in the atmosphere and oceans across different regions (Walker, 1924; Wallace and Gutzler, 1981, among others). While originally the seasonal predictions were made by leveraging empirical statistical relationships between various meteorological fields, dynamical seasonal predictions using General Circulation Models (GCMs) began in the 1980s. Initially, atmosphere-only models were used, and later, coupled atmosphere-ocean models were employed.

The Weather Research and Forecasting Innovation Act of 2017, enacted on April 18, 2017, referred to herein as the Weather Act, defines seasonal timescale as the period from 3 months to 2 years and subseasonal as the period from 2 weeks to 3 months. While the seasonal and subseasonal are two distinct forecast timescales with somewhat overlapping sources of predictability, the term, subseasonal to seasonal (S2S) is currently being used in the community to loosely refer to both these timescales. The National Academies Report on Strategies on Subseasonal and Seasonal Forecasts made this observation and chose to use the S2S acronym to refer to both subseasonal and seasonal timescales in their report (National Academies of Sciences, Engineering, and Medicine. 2016, See Box 1.1, therein). In this document, we will follow the currently accepted community nomenclature and use the S2S acronym to refer to both subseasonal and seasonal timescales.

Beyond the weather timescale, predictability comes from natural modes of variabilities such as the El Niño-Southern Oscillation (ENSO) as well as other low-frequency processes in the ocean, sea-ice, snow cover and land (Fig. 1). External forcings due to greenhouse gases, anthropogenic aerosols, land use changes, and volcanic eruptions also contribute to predictability in this timescale. The S2S Research Implementation Plan published by the World Meteorological Organization (WMO) identifies Madden Julian Oscillation (MJO), soil moisture, snow cover, stratosphere-troposphere interactions, and oceanic variabilities as key coupled Earth system processes that should be further studied and modeled in order to advance S2S forecasts (WMO, 2013). Additional sources of S2S predictability are teleconnections manifested in large-scale, low-frequency circulation patterns that modulate skill and reliability providing windows of forecast opportunity and extratropical response to tropical organized convection, resulting in global impacts through the poleward propagation of Rossby wave trains. Accurately representing these processes requires sophisticated coupled Earth system models that account for air-ocean-land-cryosphere interactions. Since coupled Earth system processes are important in the seasonal timescale, current seasonal forecast systems consist of component models to represent processes in the atmosphere, ocean, land and cryosphere.

2.1 Current Operational Seasonal Forecast System at NOAA

The current operational seasonal prediction model at NOAA is the Climate Forecast System Version 2 (CFSv2; Saha et al. 2014), which was implemented in 2011. The CFSv2 is an atmosphere-land-ocean-sea ice coupled model with a spectral triangular truncation of 126 waves (T126, about 100 km horizontal resolution) and 64 vertical layers in the atmosphere. The ocean component is the Modular Ocean Model version 4 (MOM4) from the Geophysical Fluid Dynamics Laboratory (GFDL) with 0.5 to 0.25 degree horizontal resolution and 40 vertical levels. Although CFSv2 was instrumental in remarkable skill improvements in operations when implemented (Fig. 2), major enhancements and upgrades to the modeling system along with a modern reanalysis and reforecast database have been long overdue.

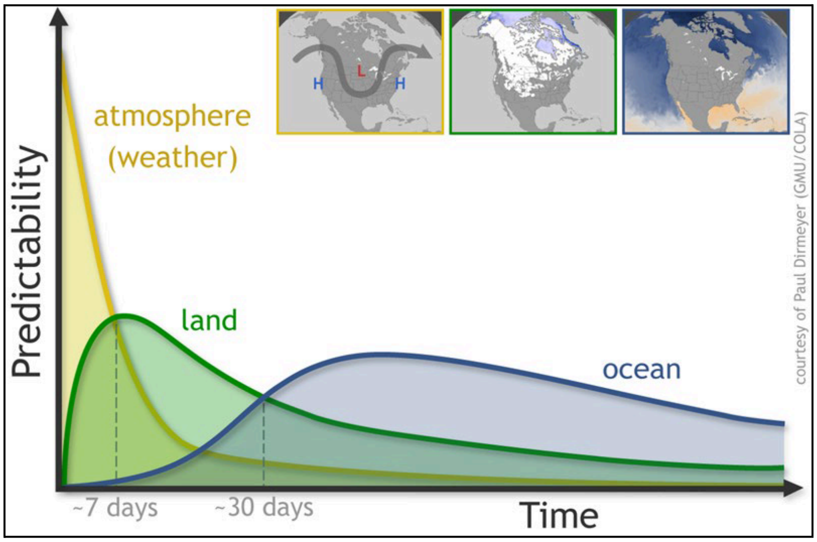

Figure 1: *Illustration of several potential sources of predictive skill (vertical axis), from the atmospheric state (yellow), the land-surface state (green), and the ocean state (blue) over various forecast lead times (horizontal axis). At shorter lead times, the initial state of the atmosphere has the greatest impact. Beyond a week, the state of the land surface (including properties like soil moisture, snow cover, and vegetation) is a significant source of predictive skill. At lead times of approximately 30 days and more, knowledge of the state of the ocean, such as variations in the sea surface temperature, are the dominant source of predictability. Credit: NOAA Climate.gov graphic, adapted from the original by Paul Dirmeyer.*

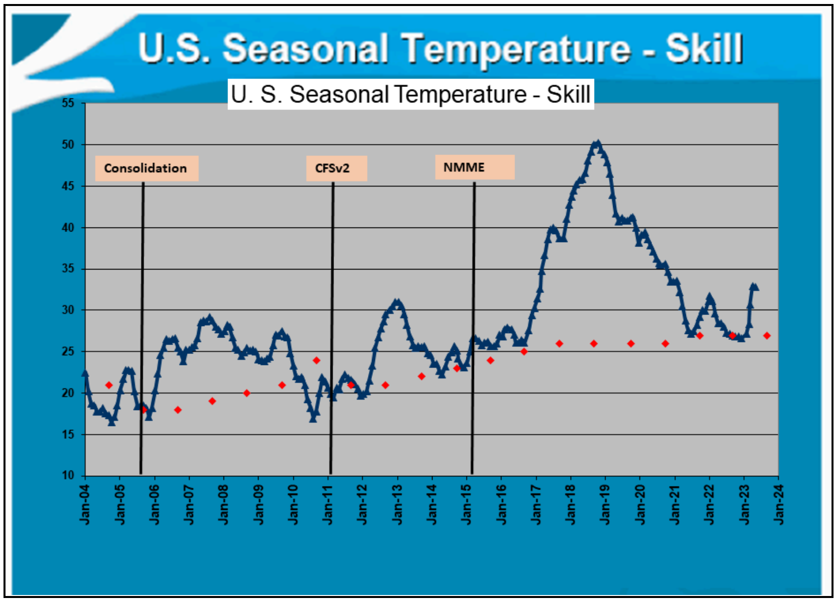

***Figure 2**: Heidke Skill Score (HSS) for U.S. seasonal temperature outlooks over the period 2004-2023. The specific calculation of the metric is a 48-month running mean of the HSS (blue line). The HSS ranges from -50 to 100, with values of 0 or less (negative) indicating no forecast skill, while positive values depict forecast value over a climatological benchmark. The greater the positive values shown, the higher the forecast skill. The red triangles are the goal for each fiscal year over the period. For example, a score of 30 means the prediction is correct 50 percent more times than a climatology forecast, which is a significant improvement. The black lines denote the introduction of major forecast system improvements which are the CPC objective tool consolidation, the CFSv2, and NMME. Credit: NWS Report to Congress (NWS, 2020)*

The CFSv2 suffers from a number of deficiencies including temporal discontinuities in ocean temperatures and soil moisture (Xue et al. 2011, 2013; Wang et al. 2011), errors in seasonal cycle of sea ice (Collow et al. 2015), slow propagation of the Madden Julian Oscillation (MJO; Wang et al., 2014), precipitation deficits during Indian monsoons due to errors in moisture flux over the western Indian Ocean (Sahana et al. 2019) and false alarm ENSO events (Tippett et al. 2020), among others. The CFSv2 is found to lag the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Navy Earth System Prediction Capability (ESPC) models in terms of its ability to predict tropical cyclone activity in weeks 1-3 timescale (Barton et al. 2021, Schreck et al. 2023).

Some of the major difficulties in operational seasonal forecasting is due to the relatively poor skill of the models in predictions beyond canonical ENSO response and transitions between severe drought and near normal conditions. Other common errors in seasonal forecasts include too frequent above-normal temperatures over the US (Becker et al. 2022), sluggish evolution in blocking, weak jets, excessive momentum in ENSO forecasts from spring and early summer causing frequent false alarms (Tippett et al. 2020), and long-term trend errors in the tropical Pacific sea surface temperature (SST; Kumar et al. 2012) accompanied by erroneous tropical precipitation anomalies (L'Heureux et al. 2020) adversely affecting prediction skill of temperature and precipitation in mid-latitudes.

2.2 Stakeholders and Customers

The demand for seasonal forecasts, beyond weather time scales, is steadily increasing as preparation and planning for climate-related risks are becoming commonplace in a wide variety of public and private sectors, including energy, water management, agriculture, financial markets, transportation, insurance and tourism, amongst others (Lemoine and Kapnick, 2024). The seasonal forecast information consists of probabilistic outlooks of monthly and seasonal temperature, precipitation, and information on drought, phenomena such as El Nino - Southern Oscillation (ENSO), Madden Julian Oscillation (MJO), teleconnection indices such as the North Atlantic Oscillation (NAO), and global monsoons, storm severity and frequency, hurricane intensity and frequency, marine heat waves, extreme heat or cold waves, extreme winds, fire severity and danger, coastal inundation, snowpack, and sea ice conditions, and other environmental factors, nationally and globally.

The NCEP Climate Prediction Center (CPC) is the organization within the NWS that issues official seasonal forecasts and therefore is the primary stakeholder of the SFS. Other NWS offices such as the Ocean Prediction Center (OPC), Office of Water Prediction (OWP) and NWS' regional offices (6 regional headquarters and 150 local offices) also utilize seasonal forecasts and products. In addition, there is a growing demand for seasonal outlooks and post-processed products from a number of agencies such as Federal Emergency Management Agency (FEMA), United States Department of Agriculture (USDA), Department of Defense (DoD), National Integrated Drought Information System (NIDIS), National Integrated Heat Health Information System (NIHHIS), and United States Agency for International Development (USAID) among others. The North American Multi-Model Ensemble (NMME; Kirtman et al. 2014) is a multi-model suite for seasonal prediction that consists of leading operational and experimental models in North America, along with NOAA's current operational seasonal forecast model, CFSv2. The NMME has been used in CPC's official seasonal outlooks since 2015 (Fig. 2) and has a growing user-base.

2.3 Toward a State-of-the-Art Operational Seasonal Forecast System

The United States Congress in Fiscal Year 2023 appropriated resources for development of a new operational Seasonal Forecast System (SFS) at NOAA's National Centers for Environmental Prediction (NCEP). In response, in October 2023, the Office of Science and Technology Integration (OSTI) Modeling Program within NOAA's National Weather Service (NWS) and the

Weather Program Office (WPO) of NOAA's Oceanic and Atmospheric Research (OAR) came together to establish a Seasonal Forecast System (SFS) Team and a Project toward building the version 1 of the next generation operational seasonal prediction system at NCEP. The SFS Team that comprises operational model developers and forecasters from NWS and researchers from OAR laboratories identified and drafted developmental priorities for this new operational system. The SFS development will follow an agile and incremental improvements approach. This document provides a high-level summary of the developmental priorities that will be addressed in the coming years in building SFS Version 1 (SFSv1) and subsequent upgrades. The SFS Project, commenced in October 2023, has laid out overarching objectives for 3-5 years.

The SFS is being developed as a new Application within the Unified Forecast System (UFS[1]), the community modeling framework that is being leveraged for the next generation operational systems as well as unification of the operational production suite at NCEP. The UFS is a community-based modeling system primarily funded by NOAA presently, with an objective of modernizing and unifying the NCEP's operational production suite. The UFS is one of the outcomes of the University Corporation for Atmospheric Research (UCAR) Community Advisory Committee for NCEP (UCACN)'s review of the NCEP operational production suite where a key recommendation was to transition toward a unified and collaborative approach to accelerate research to operations in modeling and data assimilation.

Over the years, new SFS appropriations are expected to address a number of critical gaps in the current operational system including coupled Data Assimilation (DA), better physics characterization of processes in land, oceans, sea-ice, and for aerosols and atmospheric chemistry, development of land vegetation and groundwater, sea-ice growth and melt, ocean mixing, and atmospheric ozone model that are crucial for S2S timescale. A 40+ year reanalysis for the coupled atmosphere-ocean-sea ice system must be developed and leveraged in order to provide monitoring capabilities for tracking the low frequency variability of the Earth system, providing a source of predictability on seasonal and longer time scales and the post processing calibration necessary for longer time scales. A historical reforecast for the period 1981-present is needed for model calibration and to further improve seasonal forecast outlooks. Post-processing methods need development, employing machine learning and other advanced methods for rapid and effective processing and analysis. Longer lead-time SFS predictions, and an extensive reanalysis-reforecast procedure make the representation of uncertainty and the verification process challenging and computationally intensive. Forecast products to meet the highest priorities of forecasters and stakeholders will be developed initially.

The NOAA's S2S report further points out an opportunity to use the Cloud to provide ubiquitous access to, and cost-effective use of, NOAA S2S forecast data and services. A strategic, unified use of cloud computing capabilities will help us take advantage of emerging technologies in

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[1] https://github.com/ufs-community/ufs-weather-model

cloud computing, collaborate with partners using industry best practices, and maximize portability. Transitioning to cloud services also provides an impetus and new opportunities for NOAA to modernize data storage and dissemination systems.

3. PURPOSE OF THIS DOCUMENT

This document describes NOAA's forthcoming seasonal prediction system and outlines the key development priorities that will be addressed over the next 3-5 years. The purpose of this document is to provide a high-level strategic plan for NOAA and UFS leadership and management to aid in decision-making on funding prioritization for internal and external calls for S2S modeling and product generation. Additionally, this document seeks to promote communication and collaboration with community partners, while encouraging new research and development activities to integrate with NOAA operations.

This document is organized as follows: Section 4 provides an overview of SFS design and transition to the UFS framework. Component models (Atmosphere, Land, Ocean, Waves, Sea ice, Atmospheric Composition) and their planned upgrades are described in Section 5 and prototype experiment designs are listed in Section 6. Sections 7-11 describe Coupled Ensemble Strategies, Coupled Data Assimilation Developments and Observation Processing, Reanalysis and Reforecasting, and Infrastructure and Cloud Strategy, respectively.

4. MODEL DESIGN AND COMMUNITY COMPONENTS

The SFS Version 1 (SFSv1) development will leverage significant progress made toward the first coupled ensemble system for extended-range predictions at the NCEP, the Global Ensemble Forecast System Version 13 (GEFSv13; Stefanova et al. 2022), that is being built within the UFS framework. The UFS, as mentioned in Section 2.3, is a community-based modeling system that is being used for operational model development at NOAA. Transition to the UFS framework at the NCEP began in 2019 with the adoption of GFDL's Finite-Volume Cubed-Sphere (FV3) dynamical core (Harris et al. 2021) in the Global Forecast System Version 15 (GFSv15) and thereafter in GFSv16 and in GEFSv12. Latest versions of GFS and GEFS (GFSv17, GEFSv13) are expected to be operationally implemented in late 2025.

The GEFSv13 will be the first FV3-based global coupled model for operational ensemble subseasonal forecasts at NCEP and consists of 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-Multi Parameterization Land Surface Model (Noah-MP LSM; Niu et al. 2011) for land surface processes, WAVEWATCH III (Tolman 1991; Tolman et al. 2002, WW3DG, 2019) for ocean surface waves, and Goddard Chemistry Aerosol Radiation and Transport (GOCART; Chin et al. 2002) for atmospheric composition (Fig. 3). Additional community components include Common Community Physics Package (CCPP) from the Developmental Testbed Center (DTC) and Community Mediator for Earth Prediction Systems (CMEPS) from NCAR in replacement of the NOAA Environmental Modeling System (NEMS) mediator. Table 1 lists community components in GEFSv13. Early prototypes of the SFS are being built from GEFSv13.

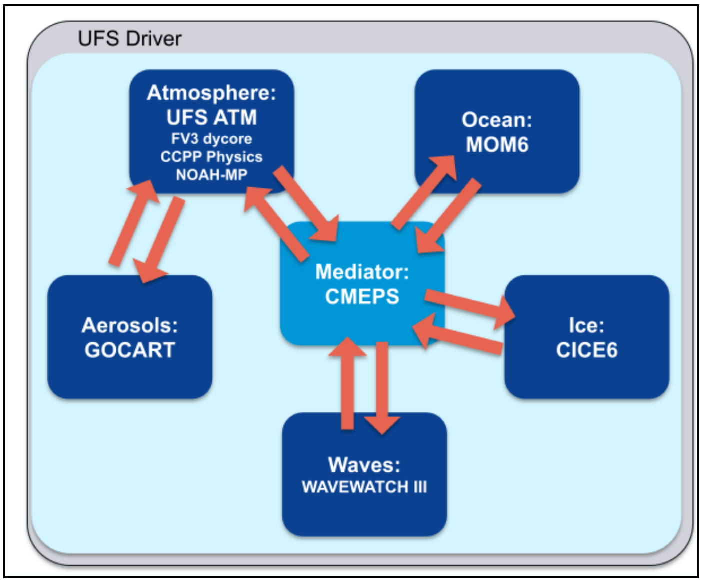

***Figure 3**: The GEFSv13 configuration with component models and Community Mediator for Earth Prediction Systems (CMEPS)*

***Table 1**: Community components in UFS*

	Community Component	**Developed/Managed by**	**Reference**
Model components	Finite Volume Cubed Sphere (FV3) dynamical core	GFDL	Harris et al. 2021
	Common Community Physics Package (CCPP)	Developmental Testbed Center (DTC) with contributions from EMC, OAR labs, NCAR, Navy and academic partners	Heinzeller et al. 2023
	Noah-Multi Parameterization Land Surface Model (Noah-MP LSM)	NCAR, EMC, DTC	Niu et al., 2011
	Modular Ocean Model (MOM),	GFDL	Adcroft et al. 2019
	Los Alamos Sea ice model (CICE)	Los Alamos National Laboratory with contributions from NCAR, Navy, UKMO, Danish Meteorological Institute	Hunke et al. 2017

	WAVEWATCH III wave model (WW3)	NOAA EMC	Tolman 1991; Tolman et al. 2002, WW3DG, 2019
	Goddard Chemistry Aerosol Radiation and Transport (GOCART)	NASA GSFC	Chin et al. 2002
Model infrastructure	Earth System Modeling Framework (ESMF)	ESMF team	Theurich et al. 2016
	Community Mediator for Earth Prediction Systems (CMEPS)	NCAR, EMC, ESMF	CMEPS github documentation
	Flexible Modeling System (FMS)	GFDL	https://noaa-gfdl.github.io/FMS/index.html
Data assimilation, post-processing, and verification	Joint Effort for Data Assimilation Integration (JEDI)	JCSDA	https://www.jcsda.org/
	Unified Post-processor (UPP)	NOAA EMC	https://upp.readthedocs.io/en/develop/
	Enhanced Model Evaluation Tools (METplus)	NCAR, NOAA GSL, NOAA EMC	https://dtcenter.org/community-code/metplus

5. COMPONENT MODELS

5.1 Atmosphere: Physics and Dynamics

The SFSv1 will be primarily built upon the GEFSv13 system, for which many physics and dynamics advancements have been made in the past few years (Bengtsson et al. 2021, 2022; Stefanova et al. 2022). To extend GEFSv13 for seasonal forecasts, additional development, testing and evaluation in physics parameterizations and dycore options are required to reduce coupled model systematic biases at long forecast lead time, to improve model representation of low-frequency dominant modes in the Earth system, and to optimize model physics and dynamics options to achieve the best computational efficiency whilst improving seasonal forecast skills. Process-level diagnostics and hierarchical testing framework are required to provide agile and timely feedback to developers and allow influencing the development process.

Activities in the Physics and Dynamic group will involve testing and evaluations and optimizations for SFS resolutions (50 and 100 km) from the GFSv17/GEFSv13 package which are currently designed for 13 and 25 km respectively, focusing on developing and optimizing the hydrostatic dynamics core option, improving representation of trace gasses in the stratosphere, reducing systematic biases in SST, air-sea fluxes, radiation, clouds, sea-ice, jet streams in both troposphere and stratosphere and monsoonal circulations.

The physics and dynamics improvement priorities include:

- Assessing the applicability of GFSv17 physics package and dynamics options for seasonal forecast and finalizing an optimal physics suite and dynamics options for seasonal timescale and resolutions.
- Improving computational stability, and scientific validity, of the current microphysics, and gravity wave drag scheme in the GFSv17 suite at coarse model resolution.
- Testing and evaluation to compare hydrostatic versus non-hydrostatic dycore
- Assessing and refining cellular automata in cumulus convection at the coarse resolution. Investigate impact of including advection of sub-grid plumes.
- Continuing development and testing of next generation cumulus convection (Community Convective Cloud - C3 - scheme), and testing its impact on seasonal forecasts.
- Reducing cloud and radiation biases in the tropics, especially over the transition zone from stratocumulus to cumulus conventions in the tropical Eastern Pacific, and the Western Pacific Warm Pool, which are critical for ENSO predictions.
- Improving air-sea coupling to reduce biases in air-sea fluxes in the tropics.
- Improving representation of tropical deep convection, tropical waves, and the teleconnections to mid-latitudes .
- Improving the phase and magnitude of the QBO in the tropics, the strength and location of polar jet streams in the upper atmosphere, and stratosphere/troposphere interactions.
- Improving the boundary layer processes and shallow cumulus.
- Improving the representation of mixed-phase clouds and radiation balance in the Arctic which are critical for sea-ice prediction.
- Improving land snow physics and snow-albedo feedback which affect the responses of North American climate to ENSO forcing.
- Improving land physics and land-atmosphere coupling to reduce the warm and dry biases in the central US which are common to coupled climate models.
- Developing aerosol-cloud interaction algorithm; improve aerosol-radiation interaction algorithm; assess aerosol-cloud-radiation interactions on meteorology forecast.
- Improving the mass and energy conservation of UFS for SFS application; Investigating the impact of various dycore damping mechanisms on conservation; Developing and evaluating innovative physics and dynamics coupling techniques to reduce sensitivity of physics tendencies to forecast time steps.
- Updating historical trace gas (e.g. CO2) and volcanic background aerosol datasets.
- Evaluating and improving O3 and water vapor predictions in the upper atmosphere.

5.2 Ocean, Waves and Sea Ice

The SFS will employ GFDL's MOM6 (Adcroft et al. 2019), Los Alamos National Laboratory's CICE6 (Hunke et al. 2017) and WAVEWATCH III (Tolman 1991; Tolman et al. 2002, WW3DG, 2019; developed at NCEP EMC) as ocean, sea ice and wave models, respectively. The activities will include optimizing component configurations for improvements in forecast skill of the El Niño and La Niña and their transitions, simulation of air-sea fluxes, seasonal variations and forecast skill of sea ice extent and sea ice thickness and reduction in systematic SST biases.

The horizontal resolution for ocean and sea ice models will be 1° for initial testing and evaluation phases, where ocean eddies will be parameterized, and ¼° in the final testing and evaluation phase, which will be eddy permitting. Ocean eddies are significant features in ocean dynamics, contributing to the transport of heat, salt, and other properties within the ocean. Since the ocean impacts atmospheric variability primarily through SST, improving SST accuracy is crucial. Additionally, as the ocean holds most of the climate system's memory, the quality of initialization for ocean components play a vital role in seasonal forecasting. The ENSO phenomenon stands out as the most influential source of variability in seasonal timescales. ENSO impacts climate not only in the tropics, but also in the mid-to-high latitudes via tele-connections. As ENSO arises from the coupled interaction between the atmosphere and ocean, accurate representation of SST, mixing layer depth, and thermocline variations in the ocean model holds significant importance in seasonal prediction. The CICE6 will be upgraded to improve its coupling with MOM6 through adoption of a common C-grid, and addition of aerosol coupling to the CICE. Deposition of light absorbing aerosols onto sea ice affects the albedo of the surface (Flanner et al. 2006, 2007), which will potentially affect seasonal prediction (Holland et al. 2012; DeRepentigny et al. 2021). Sea ice characteristics also have predictability potential at time scales much longer than the typical weather predictions due to the slow variation in sea ice thickness and its connections with the ocean's memory. As sea ice's boundaries are the atmosphere and ocean, the coupling between these components are very important for predictions. Sea ice characteristics are also related to mid to tropical latitude climate via teleconnections (Cohen et al. 2021).

The ocean, sea ice and waves improvement priorities include:

- Examining model systematic biases and their sensitivities to different ocean and sea ice initial conditions by taking advantage of available datasets such as CPC's GLobal Ocean Reanalysis (GLORe[2])

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[2] *The GLORe system for climate monitoring and predictions is configured based on MOM6 and CICE6 and with the JEDI-Sea Ice Ocean Coupled Assimilation (SOCA) 3D variational data assimilation (3DVar) scheme. The GLORe is an extension of Next Generation Global Ocean Data Assimilation System (NG-GODAS; Jong et al. 2022), but with modifications to meet the operational requirements for climate monitoring and diagnostics at CPC.*

- Examining near surface vertical resolution in the ocean model to reduce SST biases
- Examining and mitigating potential deficiencies in oceanic circulations (e.g. Atlantic Meridional Overturning Circulation (AMOC)) that impact meridional heat transport and precipitation
- Improving coupling between CICE6 and MOM6
- Improving coupling between CICE6 and FV3
- Exploring economical alternatives to the costly wave model and two-way coupling between WAVEWATCH III and CICE
- Examining and mitigating potential deficiencies in moisture and energy conservation in the whole system

5.3 Land

The memory of the Earth system components and the associated coupled processes act as sources of predictability at seasonal time scales. Land surface states change slowly in terms of moisture storage, vegetation, and snow cover, which in turn affect the atmospheric state and circulation through the transfer of heat, moisture, and momentum between the atmosphere and the surface. Studies have shown that soil moisture memory can influence weekly to seasonal variability of the Earth system. Therefore, the choices of land surface processes and their coupling with atmospheric components are critical for SFS forecast skill at various scales as shown in Fig. 1. It is important for models to capture the sensitivity, variability, and memory of the coupled land-atmosphere-ocean system for creditable prediction.

The UFS Land Workshop (Barlage et al., 2021) identified four key physical processes that would be important to capture for seasonal forecast systems, which are briefly described below.

Hydrological processes and exchanges, including plant water interactions, snow, and irrigation. Better representation in the vertical between vegetation, root-accessible soil moisture, water in the vadose zone and groundwater can be improved. As timescales lengthen, the role of deeper water stores become important for surface fluxes and the atmosphere above. Snow processes are still very simply represented - altitude variations and exposure impacts on melt in mountainous areas, differences between sublimation-dominant, radiative heating melt-dominant, and rain-on snow melt dominant regimes are not well represented in any operational center LSM. Land-management impacts on hydrology, namely through agriculture (e.g., irrigation, either tapping surface water or groundwater) and reservoir operations is another weak point with potentially large implications for forecast skill on regional scales. All have implications for turbulent energy exchanges with the atmosphere, which lay at the heart of such extended range forecasts.

Prognostic phenology and its implications for land surface characteristics, including radiative exchanges and turbulent fluxes, is another land surface element that gains importance at seasonal timescales. Simple representations of vegetation anomalies are not currently a part of weather forecasting models, in spite of their obvious impact on surface energy, momentum and water balances. Prognostic phenology should include both "natural" responses and land management impacts.

Land state initialization of prognostic variables, including slowly varying fields such as vegetation structure, frozen water at surface and in soils, soil heat storage, and groundwater levels is an obvious pathway to improved seasonal forecasts. Soil moisture, snow coverage and mass, and shallow soil temperature remain foremost priorities that can be improved with current data assimilation techniques and real-time data streams.

Extreme weather precursors that have origins or modulation from the land surface, particularly fire and fire weather precursors due to land surface moisture and dry vegetation fuel sources is another area that needs attention. The land is also a source of aerosols (dust, pollen, VOCs) contributing to atmospheric loading with radiative and human health impacts. These elements could be improved in the current LSM. Heat waves and drought also have demonstrated positive feedback drivers from the land surface that fall within seasonal timescales. Accurate prediction of the land surface's transitions from energy-limited to moisture-limited evapotranspiration regimes, and the further transition to fully moisture-stressed conditions are key to accurately representing the land surface role in many types of extreme events.

The land component of the SFS will be the Noah-MP LSM (Niu et al., 2011), which is an open source community land surface model that has improved biophysical realism (land memory processes) such as separate vegetation canopy and ground temperatures, a multi-layer snowpack, an unconfined aquifer model for groundwater dynamics, and an interactive vegetation canopy layer (Niu et al., 2011). The land model improvements will be geared toward improving land physics that contribute to water and energy memory for seasonal applications, improving interactions of land surface with atmosphere, and developing appropriate initialization strategies for seasonal-relevant land states.

The land model improvement priorities include:

- Optimizing existing land physics for seasonal timescale that include accounting for vegetation phenology model local performance, activation of agriculture modules (crop specific phenology, planting/harvest, irrigation/tile drainage), seasonal snow prediction, deeper soil configuration and explicit use of soil composition with depth including organic matter
- Developing new land physics including a more tight coupling to community Noah-MP repository (vegetation hydraulics), incorporating medium-complexity urban canopy

model and improving representation of hydrologic cycle such as groundwater, ocean inflows, runoff fraction

- Addressing topics that need interaction with other teams such as unification of surface input data (in collaboration with atmospheric composition team), ocean inflows and coupling with Planetary Boundary Layer (PBL) at seasonal scale (e.g., phenology dependence)

5.4 Atmospheric Composition

The atmospheric composition component in the SFS will the the NASA Goddard Chemistry Aerosol Radiation and Transport (GOCART) model that simulates major tropospheric aerosol components, including sulfate, dust, black carbon, organic carbon, and sea-salt aerosols (Chin et al. 2002). This section describes the design, testing and evaluation framework for prototyping and finalizing an operational ready configuration of the aerosol component for SFS. The approach is to extend GEFSv13 aerosol predictions to seasonal scales in all SFS members, include data assimilation of aerosol optical depth data in the weakly coupled DA system, and allow feedbacks of aerosols on physics processes, starting with radiation and extending to impacts on microphysics, as development of the latter matures.

One of the biggest development needs for aerosol predictions on seasonal scales is adequate representation and prediction of biomass burning emissions. This is an active area of development (e.g. Fire Forecasting Model, Sofiev et al., personal communication 2023).

The atmospheric composition model improvement priorities include:

- Extending GEFSv13 simulations with aerosols to seasonal scales
- Developing biomass burning emissions at S2S scales which include
  - generating long-term climatology (22 years) of fire emissions including aerosols, air pollutants (e.g. carbon monoxide and nitrogen dioxide), and greenhouse gases (methane and carbon dioxide) using the Global Blended Biomass Burning Emissions Product (GBBEPx) algorithm and also compile a climatology from Global Fire Assimilation System (GFAS) data available from ECMWF
  - consider using Global Fire Emissions Database (GFED) burned area products for global application.
  - conducting research to understand fire intensity (FRP) on fuel load (kgC/ha) combined with land (vegetation moisture, greening, etc.) and atmosphere conditions (winds, temperature, etc.) that influence the start of fire using historical data. This research should/could feed into the development of required inputs for ML algorithms that will forecast future fires/fire emissions.

- Developing initialization of aerosols for ensemble seasonal predictions that includes ensemble data assimilation of aerosol optical depth (AOD) observations, perturbations of aerosols in all ensemble members
- Improving representation of feedback of prognostic aerosols on atmospheric physics for seasonal predictions that include developing an aerosol-cloud interaction algorithm, improving aerosol-radiation interaction algorithm, and assessing impacts of aerosol-cloud-radiation interactions on meteorology forecast
- Improving representation of stratospheric composition, focusing on ozone and water vapor representation on seasonal scales
- Modeling and evaluating interactions between land processes, ice processes and aerosols such as interaction with fire burn area and the alteration of the land surface albedo, feedback of the fire heat and water vapor flux on weather, evolving dust source with changing of lateral cover and inland lakes/seas, and feedback and modification of snow/ice albedo from deposited aerosols

6. BASELINE EXPERIMENTS, VERIFICATION AND PRODUCT DEVELOPMENT

This section describes the design, testing and evaluation framework for prototyping and finalizing an operational-ready configuration for SFSv1. The experiments are organized into three phases in a hierarchical testing framework (Buizza et al. 2018; Table 2). It is expected that the model configuration would be frozen at the end of Phase III, following which the reanalysis and reforecasts will be produced and realtime and retrospective experiments will be performed. The SFS framework will be based on the current global coupled UFS (ufs-wm[3]).

***Table 2**: Summary of baseline experiments toward an operational version of SFSv1*

SFSv1 - Planned Baseline Experiments							
	Spatial Resolution			**Ensemble**	**Duration**		
	Atm/Land/Aerosols	**Ocn/Sea Ice**	**Waves**	**Members**	**Time period**	**Starts (Month)**	**Forecast length**
Phase I	100 kms (1 deg)	1 deg	1 deg	11	1994-2016 (2023)	2 (May, Nov)	4 months
Phase II	100 kms (1 deg)	1 deg	1 deg	21	1993-2016 (2023)	2 (May, Nov)	12 months
Phase III	50 kms (1/2 deg)	1/4 deg	1/4 deg	21	1993-2023	2 (May, Nov)	12 months

Phase I: SFS experiments in Phase I will be mainly focused on testing the system configuration and initialization with coarse model resolutions (1 deg), small ensemble sizes (11), short forecast length (3-month), and selected initialization dates. Distinct experiments will be conducted to test

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[3] https://github.com/ufs-community/ufs-weather-model

initial conditions, physics updates, component model updates, model infrastructure updates, data assimilation schemes, ensemble designs etc. to seek improvements.These experiments should help optimize complexity of SFS components with their grid resolutions and ensemble size.

Evaluation during this phase will include:

- Reasonableness of initial conditions in each component
- Drift of ocean, sea ice, and land surface state in the forecast, especially for SST, sea ice concentration, and thickness,and soil moisture
- Capability of SFS in capturing the contrast between El Nino and La Nino years
- Mean biases in SST, precipitation, surface air 2-meter temperature (T2m), soil moisture and sea ice concentration

Products that reside in CFSv2 will need to be replicated in SFSv1 for consistency of operations. The Phase I component will be to compare the output from the prototype SFS with current operational output from CFSv2, to ensure duplicate product output. Additionally, Phase I will explore user requirements for new products.

Phase II: Experiments in phase II will be more complete than Phase I with full target length (12 months) and full ensemble size (21). During this phase, METplus capability will be expanded to address top priority deficiencies found during configuration in Phase I.

The evaluation during this phase will focus on

- Drift of ocean, sea ice, and land surface state in the forecast, especially for SST, sea ice concentration and thickness, and soil moisture
- Mean biases and deterministic and probabilistic skills
- Atmospheric teleconnections
- MJO and ENSO forecast skill and associated air-sea coupling and convection/large-scale circulation interaction
- Lead-time dependent long-term (multi-decade) trends in T2m, SST, precipitation, soil moisture and sea ice concentration

Phase III: Experiments in phase III will be very close to the final version of the SFS forecast operational implementation. During this phase, METplus capability will be expanded to address top priority deficiencies found during configuration in Phases I and II. The evaluation during this phase will be similar to that in Phase II but for reforecasts carried out with high resolutions.

Product development will continue in Phase III and possibly include AI/ML components.
In addition to Phase I and Phase II metrics, evaluation will be extended to mean aspects of upper-air fields such as temperature and winds, sea-surface temperature, radiation and

precipitation. The variabilities will be evaluated with scale-dependent standard deviations together with phenomena like the MJO, ENSO, teleconnections, blocking and flow regimes.

Continued evaluation and diagnoses will be carried out for the SFS target phase experiments, reforecasts with the final configuration, and real-time forecast after the SFS implementation to assess consistency between the reforecasts and real-time forecast. The SFS performance will be evaluated against the current CFSv2 and NMME, especially for errors of the too frequent above-normal temperatures over the US, SST long-term trend errors in the tropical Pacific, and frequent false alarms in NMME, and sea ice concentration and discontinuity in tropical SST in CFSv2.

The evaluation and diagnostic priorities include:

- Assessing SFS systematic errors and providing feedback to model developers during the development phases
- Developing a SFS verification package based on METplus that will be used by model developers
- Comparing SFS biases and reforecast skills with existing operational systems to assess model performance improvement
- Evaluating the representation of climate modes and associated physical processes in SFS
- Identifying areas for continued improvement in future versions of the SFS
- Evaluating real-time forecast and assessing consistency between the reforecast and real-time forecast
- Designing ensemble-based guidance that can be generated from the SFS via gathering user and community requirements
- Exploring use of AI/ML techniques for post-processingSFS output to improve forecast skill and ensemble reliability

7. COUPLED ENSEMBLE STRATEGIES, DESIGN AND DEVELOPMENT

Forecasts beyond the weather time-scales are probabilistic in nature. In order to address the probabilistic nature of forecasts at these timescale, ensembles of forecasts are needed to sample the uncertainty. Uncertainty will be addressed by estimation of the analyzed state uncertainty at the beginning of the forecast and estimation of model physics uncertainty using stochastic parameterizations during the integration of the forecast.

NOAA has a lot of experience developing and tuning the stochastic parameterizations to produce well calibrated forecasts for the weather and subseasonal forecast (Zhou et. al 2022), but early testing for seasonal forecasts has shown excessive ensemble spread in key sources of predictability such as those associated with ENSO.

For the subseasonal forecast system, GEFSv13, initial perturbations for the 30 year reforecast are taken from ensemble perturbations in ECMWF Reanalysis v5 (ERA5) and applied to the upper-air initial conditions. The ocean initial perturbations are a combination of the differences among 3 different ocean reanalyses available from the Global Ocean Physical Multi Year product available at https://doi.org/10.48670/moi-00024 . The three reanalyses are: Ocean Reanalysis System 5 (ORAS5; Zuo et al. 2019), Global Ocean Reanalysis and Simulation (GLORYS2V4; Lellouche et al. 2013), and the Euro-Mediterranean Center for Climate Change (CMCC) Global Ocean Reanalysis System (C-GLORS05; Storto et al. 2016) sampled at the initialization date and the prior 5 and 10 days. Each reanalysis has its own climatology removed and time means over the three different times removed as well. The land and sea ice components have no perturbations. On seasonal time scales, the slower varying components of the Earth system such as ocean, sea ice and land components have memory of the initial perturbations, while initial perturbations in the atmosphere grow quickly and saturate in a few weeks, and have little impact on seasonal forecast. An open science question is the tradeoff between resolution and ensemble size. On seasonal timescales, it appears that there is only marginal benefit to run at a higher horizontal resolution, namely 0.3, as opposed to 0.8 degrees (Scaife et al. 2019). We will explore the potential of creating an ensemble of mixed resolution with a small amount from a higher-resolution model augmented with a larger ensemble from a lower-resolution model. This work will provide feedback into the overall testing and design of the SFS configuration.

In an operational setting, there is a need to balance the load on the operational computer that generates all of the forecasts in the NCEP production suite. Although it is desirable to run large ensemble forecasts from the most recent initial conditions,there are usually not enough computer resources to do so. An alternative method is referred to as the lagged ensemble, which is a simple aggregation of a series of deterministic forecasts initialized over a certain period up to the most recent initial conditions. Both methods have their benefits and drawbacks.

A burst ensemble requires that only a limited number of ensemble members can be run at a time on the operational computer. This could potentially be alleviated with running a burst ensemble on cloud computing services where computing resources can be scaled up as the demand surges.. On the other hand, a lagged ensemble fits nicely into the operational computer's schedule, but the most recent forecast is the most skillful, with older members being less skillful. This requires a tradeoff between ensemble size and degradation of the forecast skill from older members. In addition, this method does not sample the uncertainty in the initial conditions on a given day, but relies on the non-linear error growth of the Earth system to generate perturbations.

A well designed ensemble system should generate reliable forecasts in which the observed outcome falls within the spread of the individual ensemble members. The following guidelines will be adhered to in the ensemble development for SFSv1:

- Stochastic parameterizations should be included in all prototype testing
- Initial conditions should be provided by coupled DA that sample uncertainty in all components, particularly in the state estimation of the ocean, sea ice and land components
- Ensembles have an ability to test model improvement in the prototypes
- Ensembles could use coarse model resolution for prototype experiments, and the use of mixed resolution should be examined as well.
- Ensemble products should be developed, specifically for ocean, ice, aerosols
- Decisions on resolution versus ensemble size should be made based on scientific results.

8. OBSERVATION PROCESSING, DATA ASSIMILATION AND INITIALIZATION STRATEGY

In order to initialize the coupled SFSv1 system, observation processing and data assimilation capabilities will need to be developed and integrated for the components of the system. The plan for coupled data assimilation capabilities for the SFSv1 are well aligned with the plans for the coupled Global Data Assimilation System (GDAS), which is a weakly-coupled, ensemble-based hybrid assimilation for the real-time implementation of the GFSv17 and GEFSv13. It is well known that the sources of predictability on seasonal timescales reside within some of the non-atmospheric components, and elements of the SFS initialization will focus on further advancing and accelerating developments to the components of relevance for such sources of predictability (particularly ocean, sea ice, soil moisture, and snow cover/depth). Leveraging the path set forth through development of the coupled GDAS, ensemble-based coupled data assimilation capabilities will be further developed for use to initialize coupled, ensemble-based SFS predictions.

The coupled data assimilation will initialize the SFSv1 in both real-time and as part of the effort to generate reanalysis initial conditions. This will include developments toward full utilization of the next-generation unified data assimilation system through the Joint Effort for Data assimilation Integration (JEDI). The initial development target for SFSv1 is aligned with plans that have already been developed for the coupled GDAS, where key priorities are the following:

- Gridpoint Statistical Interpolation (GSI)-based hybrid 4DEnVar with expansion to include scale-dependent localization, Local Ensemble Transform Kalman Filter (LETKF) for ensemble update and possible expansion to update soil moisture and temperature, improvements to Near Sea Surface Temperatures (NSST[4]) through weak coupling;
- JEDI-based hybrid EnVar from the Sea-ice Ocean Coupled Assimilation (SOCA) project;
- JEDI-based snow assimilation through an OI-like update leveraging the LETKF;

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[4] https://dtcenter.ucar.edu/gmtb/users/ccpp/docs/sci_doc/GFS_NSST.html

- JEDI-based 3DVar for aerosols to initialize the aerosol member of GEFS.

A description of the current GDAS can be found in Kleist et al (2023). The ultimate goal is to have a single coupled GDAS for initialization of GFS, GEFS, and SFS. However, it may be necessary to have some aspects of the configuration modified and tailored to be specific to initialization of the SFS (e.g. if longer assimilation windows are needed for some of the components, for example).

The DA efforts discussed here are expected to result in more advanced initialization of some aspects of the coupled system through targeted innovations toward more strongly coupled assimilation. One example of this is advancement of the current scheme to initialization of NSST within the GDAS through radiance assimilation toward the use of coupled observation operators within the coupled system. The current scheme to produce a background of foundation temperature for performing the assimilation in the GDAS system relies on a persistence model. However, the coupled system allows for dynamic prediction of the background, laying the foundation for significantly improved assimilation of surface sensitive satellite data to analyze sea surface temperatures. Furthermore, the same satellite data can be used in a coupled observation operator to drive upper oceanic thermal analyses and remove dependence on the assimilation of retrieval-based estimates.

Efforts will be made to improve the state of initialization of important land variables of relevance to seasonal forecasts, particularly snow and soil moisture. This will be achieved through the development of advanced land assimilation capabilities, including developments toward strongly coupled land-atmospheric assimilation leveraging ensemble-based techniques.

Efforts will be made to improve the initialization of sea-ice. In addition to some of the lessons learned through the production of the 40-year, stand-alone low-resolution ocean reanalysis such as GLORe, development of next-generation sea-ice assimilation capabilities are already underway with research lab and academic partners. This project will supplement those efforts with further advancements of existing capabilities within the JEDI SOCA application, including improved representation of background errors and accelerated utilization of new types of observations of sea-ice. This will include:

- Pursuing solutions to make the initialization of the CICE model more robust and stable;
- Exploration of log and logit transforms for some of the non-gaussian variables; and
- Potential use of new observation and forward operators: sea ice surface temperature, sea ice drift.

Work is underway to develop aerosol data assimilation and initialization capabilities in preparation for GEFSv13. The JEDI-based developments will be leveraged for potential use in reanalysis and real-time initialization.

Advancements in preparing observations for assimilation in the weakly coupled JEDI-based system include developments necessary to reformat datasets into necessary conventions such as the Interface for Observation Data Access (IODA) and development of new tools for performing quality control of observations prior to assimilation. For atmospheric observations, this will largely leverage developments already underway for eventual transition of JEDI for replacing legacy observation processing and GSI-based assimilation systems. For ocean and sea-ice observations, the development, validation, and evaluation of hierarchical JEDI-based tools for quality control will be developed. Initial explorations into leveraging capabilities already developed by core collaborators for aerosol retrieval and emissions datasets will be performed to enable potential for aerosol reanalysis.

In summary, this effort will result in a fully mature, operationally ready, JEDI-based assimilation system for the coupled UFS-based SFS (in addition to GFS/GEFS). Advancements will be made in coupled assimilation technologies to improve the initialization of the components of relevance to the SFS from which there are known sources of predictability.

Specific priorities in this section are:

- **Observation processing** including staging input observations in cloud services, gathering and formatting reprocessed observations from the entire reanalysis period, evaluating and optimizing quality control for observations used in reanalysis and developing and supporting observation processing procedures for real-time extension of reanalysis
- Development and implementation of a **coupled model initialization** method to blend/optimize SST-related increments in atmospheric and oceanic components of the coupled system and testing and evaluation, improvements to NSST components within the coupled system, initial exploration of improved background error modeling for SST and exploration of potential use of AI/ML and experimentation with coupled observation operators to remove dependence on SST retrievals
- **Advancing JEDI components for coupled DA system** including development of converts for entire suite of non-atmospheric observations to create JEDI-IODA input files, optimization and calibration of background errors for marine (sea-ice, ocean, coupled analysis) application, testing and evaluation of methods for assimilation of sea-ice observations, acceleration and expansion of strongly coupled EnKF-based assimilation to constrain soil moisture and temperature using atmospheric observations

and ingest of historic observation in JEDI (e.g. the TIROS Operational Vertical Sounder (TOVS) suite of instruments)

9. REANALYSIS AND REFORECAST STRATEGY, AND PLAN FOR SFSv1

Due to model errors and small signals at timescales beyond weather, a set of retrospective forecasts (reforecasts) are necessary to bias-correct and calibrate the raw model output in order to make useful forecasts. Reforecasts are also needed to assess performance of the forecast system. Such an assessment is important for a skill estimate of the real-time forecast and its consolidation with other forecast tools. In order for the retrospective forecast to be useful for forecast calibration, the initial conditions for the retrospective forecasts need to be consistent with the operational initial conditions, with similar bias and error characteristics.

In addition to the need to provide initial conditions to reforecasts, reanalysis provides an essential climate record that provides the baseline with which anomalies in the seasonal forecast can be compared. Reanalysis provides the essential record from which the seasonal anomalies are computed.

A high quality reanalysis dataset with the coupled UFS provides a dataset which is consistent in both time and across the different components of the coupled system. Generating a high-quality reanalysis consists of collecting and preparing all of the observations that will be assimilated as well as other observations that will be used for independent verification. Since the observing system has evolved over the 40+ years, with a large increase in the number and types of satellite observations and in-situ ocean observations, there can be spurious jumps in some reanalysis fields as observing systems come and go. NOAA PSL is exploring extension of the on-line bias correction work (Chen et al. 2022) that should allow for more accurate estimation of interannual signals even in presence of changes in the historical observation system.

The configuration of the reforecast initialization frequency and ensemble size depends on how the real-time forecast will be carried out. Assuming a true (burst) ensemble of real-time forecasts will be produced each month, the SFS reforecast will be initialized from the first of each month, which match the initial dates of most of the current NMME, and other operational systems. The ensemble size will be 11 to 31, depending on available computing resources. If the real-time forecast is to be produced daily, like the current CFSv2, we would initialize the reforecast every 5 days, with 5 runs from each day.

Specific tasks for the preparation of the full-resolution SFS reanalysis include:

- producing the low resolution scout runs and evaluating them;
- increasing resolution and upgrading model components of the reanalysis suite;
- preparations of inputs for the full-resolution reanalysis for the 1979-present period.

Scout runs are a low-resolution (nominally 1-degree resolution), stripped down version of the reanalysis that is planned to be completed for a 40-year period. Scout runs will be used to prepare the observation system for full-resolution production of reanalysis and examine the impact of the changes to the observing system (e.g. new satellites, addition of Argo floats in the ocean). The scout runs will be used to initialize Phase I and Phase II reforecasts described in section 6.

Resolution increases and upgrade of the model components will be used to evaluate computation cost of the production reanalysis and configure the reanalysis candidate to be consistent with the computational resources available for this task. Additionally, the upgraded candidate will be used as the concrete prototype of the scientifically credible configuration for the reanalysis production for the period 1979-present.

Preparation for the 1979-present production period will include staging of the observations for the 1979-1994 and 2020-present period on the Amazon Web Services (AWS) NOAA Open Data Dissemination (NODD) archive. It will also include near-real time extension of the observational archive to support future near-real time reanalysis production stream. We note that the observations for the 1994-2020 are available in the public domain through cloud services[5]. In addition to the observation staging, this activity will include improved archive of river discharge and adjustments to the sea level rise over the 1979-present period.

This project will also coordinate with NOAA Global System Laboratory (GSL) with respect to production of the aerosol component of the reanalysis. At present, GSL is funded to produce a pilot 6-year long aerosol reanalysis. We can coordinate that project with this reanalysis using appropriate atmospheric forcings, such as coupled replay run produced in support of the GEFS v13 initialization. We will also develop a roadmap for an aerosol extension to the fully-coupled reanalysis that we plan to produce under this project.

In this project, we will evaluate scientific integrity of our configuration, fine tune the observing system, data assimilation, and model configurations in preparation for the reanalysis productions and finally produce the 1979-present reanalysis. Select periods of the reanalysis will be re-run with these fine tuning, and the quality of the reanalysis will be evaluated with additional reforecasts just for those select years.

Subsets of a full reanalysis need to be performed to assess the quality of the forecast system before the large investment of the full reforecast dataset is carried out. The subsets are defined in Section 4.1, and consist of 3 phases of testing. The Phase I tests will be initialized with the

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[5] https://noaa-reanalyses-pds.s3.amazonaws.com/index.html#observations/reanalysis/

30-year UFS replay that is being produced for the GEFS v13 reforecasts. Once the 1-degree scout runs are ready, the Phase I tests will be carried out using those initial conditions.

A monitoring system for reanalysis runs needs to be developed to evaluate every component of the system. The monitoring tools currently under development for the GEFS v13 replay will be expanded to include fits to observations in satellite radiance space and to the ocean/sea-ice data assimilation systems.

Given uncertainty in the computational resources that will be available for the high-resolution coupled reanalysis outlined above, the following mitigation strategy is proposed. NOAA will continue preparing for producing reanalysis-like dataset for SFS reforecast covering the period 1979-present. This includes preparing and staging observations and inputs for coupled reanalysis, conducting low-resolution scout runs to test model configurations from 1979-present, and building reanalysis evaluation capabilities. In a likely case that computational resources will be insufficient for producing a high-resolution reanalysis for the entire period of 1979-present, we will generate initial conditions for SFS reforecasts using the replay methodology, where we will replay the final SFS model configuration to the ERA5/ORAS5 reanalysis. This is similar to the methodology used to initialize GEFSv13 reforecasts. Acknowledging that the climatology of the replay will likely be different than the climatology of the GFSv17/GEFSv13 real time initial conditions, we will also conduct a shorter reanalysis using the operational configuration of the GFSv17/GEFSv13 system. The length of the reanalysis will depend on the available computational resources but notionally it will be 6 years long. This short reanalysis will allow us to reconcile the climatology of the long (1979-present) replay dataset and the climatology of the operational GFSv17/GEFSv13 initial conditions.

For the operational SFS forecasts, the land states will be initialized from the operational GFSv17/GEFSv13 initial conditions. These land initial conditions should be reasonably consistent with the SFS model physics, while also with improved representation of land surface anomalies gained from the GFSv17/GEFSv13 DA system. However, the operational GFSv17/GEFSv13 initial conditions will not be available for the time period of the SFS reforecasts (1979-present). For the reforecast, the land initial conditions will be generated with an offline (land-only) version of the Noah-MP model, forced with ERA5 atmospheric fields that have been bias-corrected to match the climatology of the operational GFSv17/GEFSv13 atmospheric initial conditions. This bias correction will focus on precipitation, since it is the main driver of soil moisture, and will be based on comparison between a shorter reanalysis based on the operational configuration of the GFSv17/GEFSv13 DA system with a notional period of about 6 years and ERA5.

Specific priorities in the reanalysis and reforecast activities include:

- Preparation and testing of high-quality observations and inputs for native reanalysis.

- Delivery and scientific validation of the reforecast initial conditions (through a combination of replay and reanalysis) from 1979 to present
- Reconciling differences between forecasts initialized with operational initial conditions and forecasts initialized from the historic archive of initial conditions prepared above.

10. INFRASTRUCTURE AND CLOUD STRATEGY

The infrastructure activities include improving the coupled model infrastructure framework as well as building a common model workflow to help facilitate various experimental runs. Efforts are also being made to leverage commercial cloud computing resources for experimental runs and potentially for future operational forecast runs.

Coupled model infrastructure: The SFS infrastructure will build upon the model infrastructure being developed for GFSv17 and GEFSv13, the next generation UFS-based weather and subseasonal applications, respectively. The UFS model infrastructure relies heavily on the Earth System Modeling Framework (ESMF; Theurich et al. 2016 and references therein) and utilities built within that framework that provide data structures, interfaces, grid remapping, time management, model documentation and data communications. The ESMF is a community software package for building and coupling component Earth system models. The implementation of ESMF is simplified through the addition of the National Unified Operational Prediction Capability (NUOPC) layer, which is a software infrastructure cap built on the top of each model component. Through the NUOPC cap, each model component is connected to the Community Mediator for Earth Prediction Systems (CMEPS) through which the interactions between the model components are handled. As a mediator, CMEPS transfers field information from one model component to another such as mapping of fields between component grids, merging of fields between different components and time-averaging of fields over varying coupling periods. In addition, the Community Data Models for Earth Predictive Systems (CDEPS) are built where component models interact with data models, which is a useful coupled model development tool used in diagnosing errors in individual model components by intentionally removing active interactions between component models. In CDEPS, the data component models perform the basic function of reading external data files, modifying those data, and then sending the data back to the CMEPS mediator.

Priorities in coupled model infrastructure development include:

- Expanding the capability of UFS data component models to include data-land, data-ice and data-ocean components within the CDEPS framework. This will allow validation of the coupling schemes, isolating coupling feedback among component models and conducting hierarchical component testing.

- Expanding the diagnostic capabilities in the CMEPS mediator for testing and evaluation of global energy conservation in the UFS coupled model. This includes identifying and resolving potential issues with current flux computation and adding a capability to calculate fluxes in the CMEPS mediator.
- Implementing the exchange grid capability for calculating fluxes between the atmosphere and ocean model in the UFS Weather Model.
- Testing the Noah-MP land model as a NUOPC component (In GEFSv13, Noah-MP is a module inside the CCPP) and incorporating river routing capability
- Developing a more sophisticated intra-step coupling by allowing for multiple run phases/sequences of the different components.
- Improving efficiency in output at required temporal and spatial resolutions and efficient ingest of fixed (climatological) files within the atmosphere.
- Potentially developing a generalized write grid component to allow asynchronous I/O for all components where needed.
- Exploring cloud native tools for I/O performance and new compression algorithms to optimize data processing on the cloud.

Workflow Infrastructure: The SFS experiments will be run with the global workflow, which is the workflow that is under development for GFSv17 and GEFSv13. Building the global workflow for SFSv1 includes three main development areas: 1) enabling hierarchical testing and development for the SFS prototypes, 2) meeting requirements for testing and development of coupled data assimilation and reanalysis, and 3) developing a configuration management system for SFS experiments. The global workflow development will include a hierarchical testing framework which will involve creating a number of low resolution configurations of coupled models working with Physics and DA teams as well as supporting running data component models, e.g. data atmosphere with MOM6/CICE6 and data ocean/sea Ice with atmosphere). The workflow development will also focus on supporting replay runs, hybrid Enar cycled experiments with a staged ensemble and flexibility to allow for variable assimilation windows and update cadence. For reanalysis production, the workflow will be modified to work with the curated observational database being created for decadal reanalysis, have an ability to change the DA configuration (e.g. seasonal static background error covariance, observing system characteristics, etc.) during the reanalysis period, have an ability to specify historic inputs to the model during the reanalysis period (CO2, river discharge etc) and have an ability to work with observation database for real time, retrospectives and reanalysis. Also planned is the development of a configuration management system that can meet the needs of the experiments that need to be conducted by the global workflow.

Cloud Strategy: The NOAA’s Cloud Strategy (NOAA, 2020) and the Cloud Action Plan (NOAA, 2022) emphasize the importance and urgency in leveraging the fast growing commercially available cloud computing resources for research and development as well as for operational requirements. The Priorities in Weather Research (PWR; NOAA Science Advisory Board, 2021) Report recommends NOAA to leverage and invest in cloud computing. An assessment on NWS's computing resources and current needs conducted by the OSTI Modeling Program (Gasbarro et al. 2023) underlines the value in exploring scalable, on-demand cloud resources for NWS's model development and operational requirements. Seasonal forecasting is especially identified as a suitable candidate for the cloud, considering the reduced cadence of the initialization and longer forecast runs, making it ideal for surge computing applications.

With this background and due to limited resources available on NOAA's on-premise High Performance Computing (HPC) systems, scalable cloud resources will be leveraged during the SFS experimental phases as well as potentially during future operational real-time seasonal forecast runs. The SFS experiments will consist of several 20+ year runs (Table 2) to test initial conditions, physics, grid resolutions, components' performance, data assimilation and ensemble design, which will require large amounts of HPC resources. In addition, the scalable cloud resources will be explored to speed up the production of the reanalysis and reforecast, an effort that requires large amounts of computing and storage resources.

In partnership with EPIC, progress is being made in ensuring that operational configurations of UFS Applications are effectively run across the on-premise and cloud platforms. The SFS infrastructure team will work with EPIC to deploy initial configurations of the global workflow for SFSv1 on the cloud. The team will also work with EPIC to ensure that the configurations can run as efficiently as possible on the cloud. Development will be made such that the global workflow will be able to run on both on-premise and cloud environments. The team will work with ensemble and DA testing teams to ensure that these configurations meet their testing requirements.

11. SUMMARY OF PRIORITIES

A summary of key priorities for SFSv1 and following version(s) are provided in Table 3 below. The priorities as stated in Table 3 are being implemented by the SFS AT in the work plan in FY24 and FY25. However, the development path will be adaptable to changes that are required due to changes in science and technology requirements as well as the availability of both human and computing resources. To enhance communication with the broad S2S community, the NWS OSTI is organizing a series of annual workshops where the community can have an in-depth discussion with the SFS AT and provide comments and suggestions on SFS priorities that can have impacts on the development path of SFSv1 and following versions. The first workshop[6], referred to as "*NOAA's Subseasonal and Seasonal Applications Workshop: Toward Increasing Collaborations among Users, Modelers and Researchers*", will be held at College Park, Maryland on September 4-6, 2024. The workshop will not only discuss NOAA's S2S

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[6] https://vlab.noaa.gov/web/osti-modeling/workshops/2024/s2s-workshop

Applications (GEFS and SFS), but also include sharing experience/insights in improving operational S2S systems from NMME and other modeling centers around the world. This is a workshop where inputs from the broad community will be heard, and used to advance NOAA's S2S applications, S2S forecast products and decision support.

Table 3: Summary of SFS development priorities

Focus Area	**Must-do's (SFSv1)**	**Should-do's (SFSv1)**	**Should-do's (SFSv2 and beyond)**
Physics & Dynamics	Decide on hydrostatic versus non-hydrostatic dycore to use in SFSv1 Ensure physics configuration in the initial GFSv17 physics suite is optimized for the coarser SFS resolution Improve computational stability, and scientific validity, of the current microphysics in the GFSv17 suite at the coarse model resolution Assess and refine cellular automata in cumulus convection at the coarse resolution. Investigate impact of including advection of sub-grid plumes	Improve air-sea coupling in tropical deep convection, tropical waves, and the teleconnections to mid-latitudes Improve representation of mixed-phase clouds and radiation balance in the Arctic Improve land snow physics and snow-albedo feedback Improve land-atmosphere coupling and reduce the warm and dry biases in the central US	Test next generation cumulus convection (Community Convective Cloud - C3 - scheme), and test in parallel its impact on seasonal forecasts Develop aerosol-cloud interaction algorithm; assess aerosol-cloud-radiation interactions and their impacts on meteorology forecasts Update historical trace gas (e.g. CO2) and volcanic background aerosol datasets Improve O3 and water vapor predictions in the upper atmosphere
Land Model	Activate and tune vegetation phenology module Increase number and depth of soil levels	Implement updates to snow module Activate crop module with relevant agriculture datasets	Assimilation of vegetation and albedo Implement urban canopy model Better represent hydrologic cycle: groundwater, ocean inflows, runoff fraction Unify surface input with atmospheric composition team Increase use of human-influenced surface characteristics (e.g., burned area, land cover change)
Ocean, Sea-Ice, Waves	Examine model biases when using different ocean and sea ice initial conditions Increase near surface vertical resolution in the ocean model to reduce SST biases	Examine and mitigate potential deficiencies in oceanic circulations (e.g. AMOC) Check moisture and energy conservation in the whole system Adopt the C-grid CICE to replace the current B-grid CICE	Reduce long-standing shortcomings in the feedback between cold ocean currents and stratus clouds Search for economical alternatives to the costly wave model Add the ability to couple aerosols to CICE Include two-way coupling between WW3 and CICE Test different melt-pond schemes in CICE

Focus Area	**Must-do’s (SFSv1)**	**Should-do’s (SFSv1)**	**Should-do’s (SFSv2 and beyond)**
Atmospheric Composition	Ensure Aerosol emissions and processes are configured properly and workflow/codes updated for seasonal prediction Activate and tune smoke emissions by region Include weather impacts on smoke emissions (eg: RH, precip modulation). For Tune dust emissions by desert region Update Anthropogenic emissions to latest available inventory Include AOD DA from polar orbiting satellites	Activate nitrate chemistry Include aerosol perturbations for ensemble members Include hourly global smoke emissions where available Increase PBL vertical resolution to improve dust emissions and plume rise	Add simple stratospheric/tropospheric Tungas phase chemistry Couple sea salt emissions to ocean model Include updated smoke plume rise Assimilare geostationary satellite AOD where available
Ensemble Development	Develop an ensemble initialization strategy for reforecasts that is compatible with the operational analysis that will be used to initialize the real-time forecasts	Quicker access to ensemble initial conditions from the coupled data assimilation system for ensemble tuning	Incorporate stochastic schemes in the rest of the model components (sea-ice, coupler)
Coupled DA & Obs	Complete curated observation database for coupled reanalysis Complete development and testing of weakly coupled assimilation system for use in coupled reanalysis and real-time cycling (both reanalysis extension and coupled GDAS for GFS/GEFS/SFS) Investigate solutions to improve SST initialization within context of weakly coupled system (evolution from current NSST-based system) Production of subsets of high resolution coupled initial conditions for model development	Acceleration of full JEDI-based assimilation system for future coupled reanalysis development and production	Support for follow-on reanalysis development activities for further, continued improvement Continues support, integration, and updating of observation archive including real-time extension/continuation
Reanalysis & Reforecast	Produce initial conditions for SFS reforecasts from 1979-present using either native reanalysis or replay. Verify validity of the produced reanalysis. Complete 40-years of retrospect ensemble reforecasts that cover the same initialization and ensemble strategy as the real-time forecasts.	Produce shorter reanalysis with operational GFSv17/GEFSv13 system to account for differences in the 40 year record of I.C. and operational I.C. Produce a larger ensemble reforecasts. Shorten the time needed for reforecasts by using the surge capability of the Cloud to augment on-prem	SFSv2 will use native reanalysis for the entire period. Reduce the time necessary for reforecasts by running reforecasts “on the fly”

Focus Area	Must-do's (SFSv1)	Should-do's (SFSv1)	Should-do's (SFSv2 and beyond)
		compute.	
Infrastructure and Cloud	Develop Earth modeling component testing framework Create a workflow to carry out seasonal ensemble forecasts on the cloud and on-prem	Develop exchange grid coupling capability	Develop a generic write gridded component for all component models
Product Development & Verification	Develop a METplus based package for evaluation of SFSv1 and its comparison with existing forecast systems. Improve ENSO prediction skill in SFSv1, especially for the removal of temporal jumps due to initialization in CFSv2 Improve sea ice extent prediction in SFSv1 of long-term trend and interannual anomalies, which are erroneous in CFSv2 due to unrealistic sea ice initial conditions.	Reduce positive long-term SST trend errors in the tropical Pacific in the current dynamical forecast models (NMME) Reduce too frequent above-normal temperature forecast over US in the current dynamical forecast models (NMME) Reduce excessive momentum in ENSO forecast and false alarms	Improve predictions of tropical SST outside central Pacific at longer lead times (>3 month) Predict atmospheric variability beyond canonical ENSO response

LIST OF ACRONYMS

AI/ML	Artificial Intelligence/Machine Learning
AMOC	Atlantic Meridional Overturning Circulation
AOD	Aerosol Optical Depth
AWS	Amazon Web Services
CCPP	Common Community Physics Package
CDEPS	Community Data Models for Earth Predictive Systems
CFS	Climate Forecast System
CICE	Los Alamos Sea ice model
CMEPS	Community Mediator for Earth Prediction Systems
CPC	Climate Prediction Center
DA	Data Assimilation
DoD	Department of Defense
DTC	Developmental Testbed Center
ECMWF	European Centre for Medium Range Weather Forecasts
EMC	Environmental Modeling Center
ENSO	El Nino - Southern Oscillation
EPIC	Earth Prediction Innovation Center
ESMF	Earth System Modeling Framework
ESPC	Earth System Prediction Capability
FEMA	Federal Emergency Management Agency
FV3	Finite-Volume Cubed-Sphere
GBBEPx	Global Blended Biomass Burning Emissions Product
GCMs	General Circulation Models
GDAS	Global Data Assimilation System
GEFS	Global Ensemble Forecast System
GFAS	Global Fire Assimilation System
GFDL	Geophysical Fluid Dynamics Laboratory
GFED	Global Fire Emissions Database
GFS	Global Forecast System
GLORe	GLobal Ocean Reanalysis
GLORYS	Global Ocean reanalysis and Simulation
GOCART	Goddard Chemistry Aerosol Radiation and Transport
GSI	Gridpoint Statistical Interpolation
GSL	Global System Laboratory
HPC	High Performance Computing
HSS	Heidke Skill Score
IODA	Interface for Observation Data Access
JCSDA	Joint Center for Satellite Data Assimilation
JEDI	Joint Effort for Data assimilation Integration
LETKF	Local Ensemble Transform Kalman Filter
LSM	Land Surface Model
MJO	Madden Julian Oscillation
ML	Machine Learning
MOM4	Modular Ocean Model version 4
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NEMS	NOAA Environmental Modeling System
NIDIS	National Integrated Drought Information System
NIHHIS	National Integrated Heat Health Information System
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
Noah-MP	Noah-Multi Parameterization
NODD	NOAA Open Data Dissemination Program
NSST	Near Sea Surface Temperatures
NUOPC	National Unified Operational Prediction Capability
NWP	Numerical Weather Prediction
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OPC	Ocean Prediction Center
ORAS	Ocean Reanalysis System
OSTI	Office of Science and Technology Integration
OWP	Office of Water Prediction
PBL	Planetary Boundary Layer

PSL	Physical Sciences Laboratory	TROPOMI	TROPOspheric Monitoring Instrument
PWR	Priorities for Weather Research	UCACN	UCAR Community Advisory Committee for NCEP
QBO	Quasi Biennial Oscillation	UCAR	University Corporation for Atmospheric Research
S2S	Subseasonal to Seasonal (also, Subseasonal and Seasonal)	UFS	Unified Forecast System
SFS	Seasonal Forecast System	USAID	United States Agency for International Development
SOCA	Sea-ice Ocean Coupled Assimilation	USDA	United States Department of Agriculture
SST	Sea Surface Temperature	WCRP	World Climate Research Program
T2m	2-meter Temperature	WMO	World Meteorological Organization
TOVS	TIROS Operational Vertical Sounder	WPO	Weather Program Office

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