Community-Supported Research Initiatives For Improvement of Subseasonal to Seasonal (S2S) Prediction

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PREFACE

The research initiatives in this document were derived from two leading S2S community activities/working groups, 1) the international WWRP-WCRP S2S Prediction Project and 2) the S2S Working Group under the (now defunct) interagency IWRCC under OFCM, and cultivated into its present form by National ESPC program leadership. Thus the input and synthesis represents contributions from international and national interagency S2S leadership.

An important consideration moving forward with ICAMS is how to maintain the bridges that were built through these discussions and this activity between the international and national S2S programs.

Inputs and Synthesis During Fall 2019-Spring 2020

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INTRODUCTION

This document is a summary of suggested research initiatives for improving S2S prediction, designed as a bottom-up survey for input on short-term, easily achieved improvements vs. longer-term, more sweeping efforts. The input was collected from researchers through meetings and written documents; then participants were invited to collaboratively refine their suggestions during a series of four virtual panel discussions that took place from August through October, 2020. While it is based on broad community input, it does not attempt to represent all important S2S research, but to reflect what a broad segment of the S2S community perceives as important at this time.

The long-term goal is to develop fully coupled ensemble S2S prediction systems with state-of-the-art initial and model uncertainty representations as well as consolidated databases which are used to disseminate a wide array of S2S data. This document breaks this main goal into achievable short-, medium- and long-term tasks identified by the community and focused towards this overarching goal.

- **Short-term tasks** are those estimated to be achievable within one year, scientifically and technically straightforward, and may leverage existing funded activities.
- **Medium-term tasks** should fit within a standard proposal or award lifecycle. They are achievable within approximately three years, and may be scientifically or technically difficult.
- **Long-term tasks** are major initiatives with a time frame for benefits of five or more years. These tasks may require multiple award cycles, be scientifically and technically challenging, and are expected to highly leverage international activities and resources.

We acknowledge that there are some short- and medium-term tasks that won't be necessary in the long-term, e.g. as coupled models improve, the need for lead-time dependent de-biasing of S2S forecasts will hopefully no longer be needed.

This document encompasses both research initiatives and supporting activities such as programmatics, research support, and enterprise improvements. Due to the cross-disciplinary nature of Earth system modeling, some tasks are cross referenced in multiple categories.

One broad goal submitted through this process was to establish a single, international effort, run in the cloud, with contributions from every WMO member state. While such a goal is outside the scope of this document, it remains a useful framework to build toward. A first step toward this goal would be the coordination of intra- and interagency efforts within the US.

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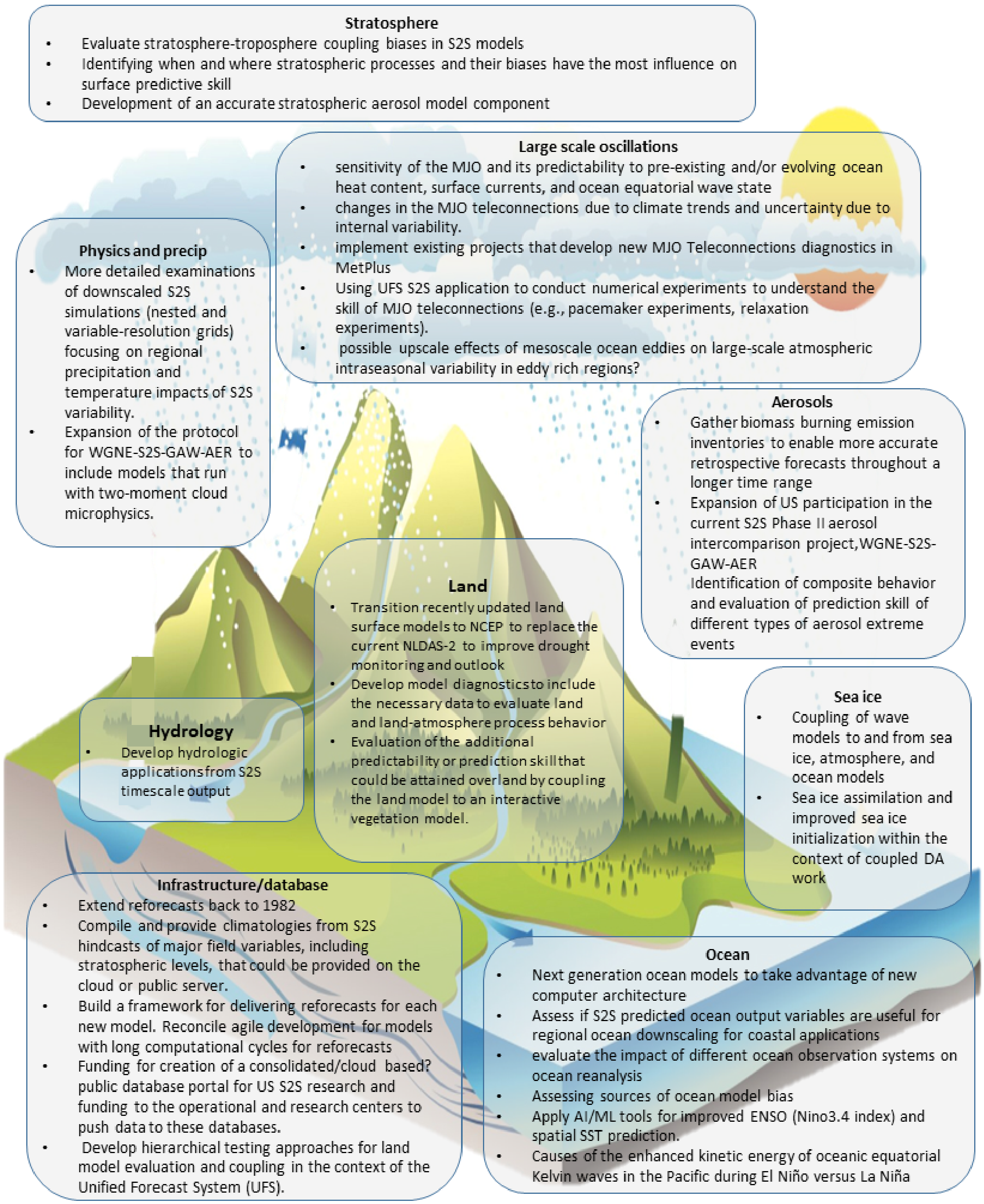
Stratosphere
- Evaluate stratosphere-troposphere coupling biases in S2S models
- Identifying when and where stratospheric processes and their biases have the most influence on surface predictive skill
- Development of an accurate stratospheric aerosol model component
Large scale oscillations
- sensitivity of the MJO and its predictability to pre-existing and/or evolving ocean heat content, surface currents, and ocean equatorial wave state
- changes in the MJO teleconnections due to climate trends and uncertainty due to internal variability.
- implement existing projects that develop new MJO Teleconnections diagnostics in MetPlus
- Using UFS S2S application to conduct numerical experiments to understand the skill of MJO teleconnections (e.g., pacemaker experiments, relaxation experiments).
- possible upscale effects of mesoscale ocean eddies on large-scale atmospheric intraseasonal variability in eddy rich regions?
Physics and precip
- More detailed examinations of downscaled S2S simulations (nested and variable-resolution grids) focusing on regional precipitation and temperature impacts of S2S variability.
- Expansion of the protocol for WGNE-S2S-GAW-AER to include models that run with two-moment cloud microphysics.
Aerosols
- Gather biomass burning emission inventories to enable more accurate retrospective forecasts throughout a longer time range
- Expansion of US participation in the current S2S Phase II aerosol intercomparison project,WGNE-S2S-GAW-AER
Identification of composite behavior and evaluation of prediction skill of different types of aerosol extreme events
Land
- Transition recently updated land surface models to NCEP to replace the current NLDAS-2 to improve drought monitoring and outlook
- Develop model diagnostics to include the necessary data to evaluate land and land-atmosphere process behavior
- Evaluation of the additional predictability or prediction skill that could be attained over land by coupling the land model to an interactive vegetation model.
Hydrology
- Develop hydrologic applications from S2S timescale output
Sea ice
- Coupling of wave models to and from sea ice, atmosphere, and ocean models
- Sea ice assimilation and improved sea ice initialization within the context of coupled DA work
Infrastructure/database
- Extend reforecasts back to 1982
- Compile and provide climatologies from S2S hindcasts of major field variables, including stratospheric levels, that could be provided on the cloud or public server.
- Build a framework for delivering reforecasts for each new model. Reconcile agile development for models with long computational cycles for reforecasts
- Funding for creation of a consolidated/cloud based? public database portal for US S2S research and funding to the operational and research centers to push data to these databases.
- Develop hierarchical testing approaches for land model evaluation and coupling in the context of the Unified Forecast System (UFS).
Ocean
- Next generation ocean models to take advantage of new computer architecture
- Assess if S2S predicted ocean output variables are useful for regional ocean downscaling for coastal applications
- evaluate the impact of different ocean observation systems on ocean reanalysis
- Assessing sources of ocean model bias
- Apply AI/ML tools for improved ENSO (Nino3.4 index) and spatial SST prediction.
- Causes of the enhanced kinetic energy of oceanic equatorial Kelvin waves in the Pacific during El Niño versus La Niña

RECOMMENDATIONS:

I. Research Initiatives

A. Atmosphere

1. **Short-term** - Evaluate stratosphere-troposphere coupling biases in S2S models (note: The Stratosphere sub-project has plans underway to do an internationally collaborative project on this topic, though currently the effort is largely from voluntary contributions).
2. **Medium-term** - Develop predictive biomass burning emission schemes linked with vegetation and Meteorology.
3. **Medium-term** - Identify composite behavior and evaluate prediction skill of different types of aerosol extreme events such as dust storms, intense transport of aerosol across long range, and episodic transport of aerosol into pristine geographic regions.
4. **Medium-term** - Evaluate the impact of aerosol direct and indirect effect on sub/seasonal forecast skill of meteorological/oceanographic fields. This includes both mean skill and identification of forecasts of opportunity related to specific extreme events.
5. **Medium-term** - Develop an accurate stratospheric aerosol model component and assess additional prediction skill or predictability that can result from improved stratospheric aerosol, including the identification of and assessment of skill during forecasts of opportunity (such as may occur after a major volcanic event).
6. **Long-term** - Identify when and where stratospheric processes and their biases have the most influence on surface predictive skill, involving further prediction system simulations. Example projects could be evaluating the extent to which interactive stratospheric ozone chemistry and/or radiatively active stratospheric aerosols affect predictive skill, stratospheric nudging experiments in S2S prediction systems, or observing system simulation experiments (OSSEs) for stratosphere-troposphere coupling.

B. Ocean and Sea Ice

1. **Short-term** - Identify seasonality and regionality of ocean model drift for a variety of S2S relevant variables, and their prediction skill among forecast models: SST (cloud feedbacks, ocean fronts); 0-300 m ocean heat content (marine heat waves, hurricane intensification, ENSO dynamics); sea surface height (ocean equatorial waves; coastal flooding); surface salinity and mixed layer depth (upper ocean stabilization, upwelling); surface currents (surface flux regulation, industrial operations); sea ice coverage (cloud feedbacks; biological activity; shipping operations). Study the impact on ocean prediction skill by model resolution, coupling frequency, and initialization strategy.

2. **Short-term** - Assess ocean prediction skill on S2S timescales using the recently available ocean output variables in the S2S database.
3. **Medium-term** - Identify causes of the enhanced kinetic energy of oceanic equatorial Kelvin waves in the Pacific during El Niño versus La Niña, and whether they act as a self-reinforcing mechanism for persistent El Niño periods.
4. **Medium-term** - Assess if S2S predicted ocean output variables are useful for regional ocean downscaling for coastal applications.
5. **Medium-term** - Conduct OSE experiments to evaluate the impact of different ocean observation systems on ocean reanalysis and their value for S2S forecasts, with a focus on TPOS, IndOOS, AtlantOS.
6. **Medium-term** - Conduct large-eddy simulations of the ocean mixed layer to characterize turbulence in the upper ocean.Identify how accurately we need to represent this turbulence to account for ocean uptake/sequestration of heat, gases, nutrients, etc.
7. **Medium-term** - Evaluate the benefits of representing uncertainty in ocean models with stochastic parameterization, stochastic perturbations of existing parameters, etc.
8. **Medium-term** - Assess sources of ocean model bias.
    a) **Medium-term** - Identify the sources of bias for ocean heat content, ocean equatorial waves, surface fluxes, sea ice, upwelling.
    b) **Medium-term** - Examine how biases in upper ocean heat content affect tropical cyclone prediction.
    c) **Medium-term** - Advance understanding of how ocean processes and their biases affect the atmosphere.
9. **Long-term** - Understand ocean turbulence and improve its representation in models. This will likely require iterative analyses of a hierarchy of models (LES, regional, global) to guide sensor design, deployment, and sampling strategies; analysis of data collected by those sensors; translating observations into model improvements; and evaluating their impact on S2S forecasts. Regimes that reliably exhibit strong ocean mixing and turbulent processes may be well-suited for such an interactive approach, such as tropical diurnal warm layers, eastern Pacific tropical instability waves (and their potential links to atmospheric convection), and ocean eddy regimes.

C. Land and Hydrology

1. **Short-term** - Transition recently updated land surface models (LSMs) to NCEP to replace the current NLDAS-2 to improve drought monitoring and outlook. Coordinate between Federal Agencies to reinvigorate R2O partnerships for LSMs.
2. **Short-term** - Enable longer-term progress by taking stock of the current state of knowledge of land influences on S2S, and capabilities for forecast applications. Such a detailed assay would be a starting point to target the

3- and 5- year progress on important and tractable processes, phenomena and regions of particular importance.

3. **Short-term** - Create and explore Hydrologic applications from S2S timescale model output. Earth system model outputs tailored to support the hydrologic component modeling and hydrologic model outputs for both application and feedback into other modeling components will only become more valuable in many future simulations.
4. **Medium-term** - Evaluate the additional predictability or prediction skill that could be attained over land by coupling the land model to an interactive vegetation model.

D. Models

1. Construction and Diagnostics

a) **Short-term** - Develop dynamical attribution system to understand processes contributing observed S2S anomalies based on pacemaker experiments.

b) **Short-term** - Use long, uninitialized model runs to understand real-time predictions as a way to overcome sample limitations. Generate advanced analog and pattern matching methods to inform forecasts of opportunity.

c) **Short-term** - Using S2S data bases, develop a baseline assessment of the current generation of S2S prediction systems to assess influence of future model updates. This would include baseline skill for 500-mb height, surface temperature, precipitation etc. including their seasonality, for societally relevant extremes (e.g., heat waves, heavy precipitation), baseline estimate of signal-to-noise for different variables, and assessment of spread-skill relationship for S2S timescale.

d) **Short-term** - Run C-UFS out to 9 months to expose model biases such as sea ice coverage; mitigation of these biases will further improve the forecast at shorter timescales.

e) **Medium-term** - Conduct sensitivity studies and multi-model comparisons to develop strategies for coupled model ensembles (e.g., resolution vs. ensemble size tradeoffs, model uncertainty and spread in ocean, sea ice, and land models).

f) **Medium-term** - Establish the trade space to be explored for initialization and ensemble design for coupled models (ensemble size/resolution, burst and lagged membership, ocean/land/coupled perturbations and ties to coupled DA).

g) **Medium-term** - Improve model-error representation. Systematics and random model error should be represented using multi-model, multi-parameter or stochastic approaches. They should be employed consistently (“end-to-end”) on the short, medium and S2S-timescale and be included in the data assimilation step. The representation of model uncertainty/error should be introduced in all components (e.g., atmosphere, ocean, sea-ice, land surface) of coupled systems, and the impact of this uncertainty should be evaluated in the full system.

h) **Medium-term** - Develop strategies for "seamless" verification and calibration across various timescales.
i) **Long-term** - Develop next generation ocean models to take advantage of new computer architecture.
j) **Long-term** - Develop next generation sea ice models to take advantage of new computer architecture, including discrete element models.
k) **Long-term** - Lay the groundwork for community model development of S2S prediction systems (physics, data assimilation, communication between different components of the earth system).
l) **Long-term** - Support process-oriented diagnostics of atmospheric, oceanic, and coupled processes. This effort should provide sustained support for the research community to develop new diagnostic methods, and for programmers to integrate diagnostics into an easy-to-use user interface to maximize return on investment of diagnostic development and to accelerate model improvement cycles.
m) **Long-term** - Develop a community effort for a periodic assessment of biases and performance of S2S prediction systems (along the lines of CMIP paradigm). A more detailed discussion on this can be found in the 2nd report of the Tropical Pacific Observing System 2020 (TPOS 2020) project.
n) **Long-term** - Establish or enhance the ability of cross-organizational plug-and-play of NUOPC compliant models.
o) **Long-term** - Assess the operational feasibility of seamless weather to seasonal prediction systems

2. Post-processing and Forecast Products

a) **Short-term** - Fully transition validated research about expanding multiple linear regression to include stratospheric predictors. Many prediction tools will employ regression models, but there is an incomplete exploration of which predictors may result in appropriate predictions. Increase skill by finalizing work to add predictors that also have validated physical pathways.
b) **Short-term** - Work with the coupled UFS Project to develop post processing software for the UFS, including novel algorithms and methods for model bias correction and calibration such as machine learning and artificial intelligence, software optimization and compression techniques, visualization techniques.
c) **Short-term** - Improve bias correction methods or model output statistics to ensure that land and land-atmosphere model

predictions at the S2S time scale can be used for operational decision-making (drought, heat wave, hydrologic forecasts). Particularly, extension of multi-model ensembles (including SubX and NMME) forecasts in the S2S range for hydrological and agricultural prediction that can better inform decision support. In the West, this includes snowpack, which critically depends on model resolution in mountain areas. Bias correction / MOS requires a nimble system to recalibrate whenever models are updated, added or removed.

d) **Short-term** - Expand seasonal calibration methods to subseasonal timescales. Certain methods to make seasonal outlooks rely on calibration statistics conditioned on background conditions. Given that a certain portion of skill in the S2S timeframe will come from boundary conditions, there could be an enhancement to skill and/or attribution by applying similar methods to the subseasonal outlooks.

e) **Short-term** - Develop methods to explore spatial downscaling of S2S precipitation outlooks. Precipitation observations are made at increasingly fine resolution, and exploiting that every growing record to downscale and create outlooks at spatial scales that approach observational resolution could prove useful to many communities.

f) **Medium-term** - Develop post-processing methods utilizing stratospheric information, which would be informed by observed stratosphere-troposphere coupling processes that are lacking in S2S prediction systems. Test to see which post-processing methods improve forecast skill. For example, prediction systems often fail to simulate correctly the persistence of the North Atlantic Oscillation (NAO), which could impact surface temperature and precipitation forecasts over the eastern United States on S2S timescales.

g) **Medium-term** - Develop machine learning techniques that take advantage of stratospheric information. This could include identifying forecast windows of opportunity based on stratospheric events; analyzing relationships between stratospheric processes and surface skill in dynamical models; making improved statistical forecasts; or generating forecast ensembles to best maximize ensemble spread and match observed signal to noise ratios. Investigate machine learning techniques including Linear Inverse Modeling (LIM) and causal networks to see if there are less resource-intensive methods of making S2S predictions which could complement dynamical forecasting methods.

h) **Medium-term** - Develop S2S forecasting products that better take advantage of stratospheric information and identify periods of stratosphere-troposphere coupling. NWS does have some stratospheric forecasting products, but more products could be developed to forecast stratosphere-troposphere coupling. These products could inform S2S operational forecasts, at least during windows of opportunity such as anomalous states of the stratospheric polar vortex; testing should be done to evaluate whether incorporating these products into forecasts improves outcomes, and in what regions and lead times.

i) **Medium-term** - Test the use of Machine Learning to post-process ocean S2S forecasts to improve skill, and to affordably represent the effects of ill-constrained or unresolved ocean physics.

j) **Medium-term** - Investigate relative merits of methods for combining and calibrating S2S forecasts.

k) **Medium-term** - Improve probabilistic prediction on S2S time scales. This could include current and new (e.g., machine-learning) methods for state-dependent bias correction, ensemble calibration, and downscaling or mapping model output to sensible weather parameters of concern (e.g. solar insolation, near-surface winds).

l) **Long-term** - Apply artificial intelligence / machine learning techniques. First apply non-physically constrained AI/ML directly to the S2S problem, including the key land-atmosphere processes that are poorly represented in numerical prediction models. The analogy is to statistical forecasts of yore, but as with statistical forecasts, AI/ML forecasts should inform the improvement of physically based models, as only they can deal with the accelerating change in climate that moves us outside the envelope of historical training data. Thus, the ultimate goal is to use AI/ML to improve physical models, as components within parameterizations or illuminating the complexities that are poorly represented but crucial in today’s coupled land-atmosphere models.

3. Coupling

a) **Short-term** - Implement ESMF interpolation on non-structure grids with mismatches in the land/sea mask between components. Strengthened communication between NRL and the ESMF team should facilitate short-term completion of this goal.

b) **Short-term** - Develop hierarchical testing approaches for land model evaluation and coupling in the context of the Unified Forecast System (UFS). The land models of interest include but are not limited to the current land component in the UFS, but should be ready to run with the UFS by the end of the project. Projects on developing and implementing land-only reanalysis and reforest datasets and metrics for evaluating the fidelity of UFS in capturing key land processes and land-atmospheric coupling, isolating and quantifying the impacts of the land component on coupled system particularly in terms of surface temperature and precipitation forecasts from weather to S2S scales, and assimilating land-relevant observations to improve land initiate states, are strongly encouraged.

c) **Medium-term** - Develop mediators for consistent flux calculations between models/components.

d) **Medium-term** - Improve coupling of wave models to and from sea ice, atmosphere, and ocean models that includes the appropriate physics in each that respond to wave interactions.

4. Ensembles

a) **Short-term** - Investigate ensemble reliability: Ensemble forecasts are typically under-dispersive and over-confident due to inadequate error growth properties of the underlying model caused in part by numerical truncation and inadequate parameterization of moist processes. Recent work claims that certain large-scale processes, in particular the North Atlantic Oscillation, are over-dispersive. The reliability of S2S ensemble should be quantified rigorously using process-based and probabilistic metrics and accounting for observational uncertainty.

b) **Medium-term** - Optimize ensemble configuration for S2S-forecasts in the context of limited computer resources. Experiments including lagged ensembles as well as bursts approaches may provide additional skill and should be used together with the optimal number of ensemble members. The trade-space between number of ensemble members and model resolution should also be investigated.

E. Observations and Data Assimilation

1. General or Crosscutting Obs/DA

a) **Short-term** - Survey available metrics for assessing observing systems (e.g. kriging error, 4dVar cost function, decorrelation scale, minimizing variance) to better understand how different algorithms perform, and which ones best quantify the value of additional observing systems. This assessment should be made with an eye toward the planned TPOS redesign.

b) **Long-term** - Develop joint assimilation systems using vegetation and fire observations

2. Coupled DA

a) **Medium-term** - Improve coupled data assimilation. This includes proposals on uses of observations across the interface and for tools/techniques needed for coupled DA.

b) **Long-term** - Develop coupled model initialization methods.Represent the uncertainty in the initial state of the land, ice and ocean components using analyses derived via data assimilation (weakly coupled, pseudo-strongly coupled or strongly coupled) or other initialization strategies (anomaly initialization, nudging).

(1) **Short-term** - Improve sea ice initialization within the context of coupled DA work, for example with observational retrieval of sea ice thickness for dynamical forecasts.

(2) **Medium-term** - Improve sea ice assimilation. For example, sea ice thickness, sea ice temperature and drift, and coupled data assimilation with the sea ice and atmosphere and ocean.

c) **Long-term** - Develop strongly coupled data assimilation in S2S forecast systems. Leverage these efforts to improve ocean reanalyses. Ocean data assimilation and reanalyses should reasonably assimilate all available ocean observations with state-of-the-art ocean models with the goal of producing acceptably small budget residuals of heat, salinity, and momentum to enable process diagnosis of observed events. Analysis increment tendencies should be provided to enable researchers and model developers to identify likely sources of model error.

(1) **Short-term** - Explore how “strongly” to couple components for coupled DA (and which components). Determine which algorithms are most appropriate for coupled DA and how to deal with different temporal/spatial scales across components. Topics include: Utilizing field observations to improve DA in S2S case studies, and testing levels of DA strength on one component

(2) **Medium-term** - Test strongly coupled data assimilation for S2S forecasts

d) **Long-term** - Investigate coupled model drift,a source of systematic bias and thus systematic errors in S2S-forecasts. It should be investigated using DA (analysis increments, model-error term in weakly coupled DA) and other methods, possibly using a simple perfect model framework first and/or a hierarchy of models of increasing complexity.

3. Land Obs/DA

a) **Short-term** - Gather biomass burning emission inventories to enable more accurate retrospective forecasts throughout a longer time range.

b) **Long-term** - Enhance and improve the robustness of essential observations of key states and fluxes. For in situ measurements, that means bringing soil moisture (and temperature) observations into the realm of coordinated, operational, real-time reporting like atmospheric measurements. Currently there is an overlapping mixof state, regional and national networks of varying quality and levels of support. Some, like SCAN and SNOTEL at the national level and the Oklahoma Mesonet at the state level are functionally operational but not guaranteed to continue indefinitely, uncoordinated, and due to different instrument technologies, often not comparable. Such networks would be essential for forecast initialization and satellite calibration.

    c) **Long-term** - Make satellite observations of heat and momentum fluxes. This is a major observational requirement with significant implications for model development.

4. Ocean/Ice Obs/DA
    a) **Short-term** - Improve sea ice initialization within the context of coupled DA work, for example with observational retrieval of sea ice thickness for dynamical forecasts.
    b) **Medium-term** - Improve sea ice assimilation. For example, sea ice thickness, sea ice temperature and drift, and coupled data assimilation with the sea ice and atmosphere and ocean.
    c) **Long-term** - Develop a coordinated international initiative to observe and model MJO initiation events in the western Indian Ocean. The current gap of concomitant ocean and atmosphere observations prevents a detailed understanding of mass and energy transfers at their interface and limits our understanding of how the atmospheric boundary layer humidifies in the region prior to convective onset.
5. Atmospheric Obs/DA
    a) **Long-term** - Examine the objectives of the decadal survey relating to Aerosols and Clouds, Convection and Precipitation (ACCP), and apply to the S2S time scale as appropriate.. Any additional objectives or needed observations that would be targeted specifically for seasonal scales should be incorporated into the plans/white paper set down by ACCP and other groups planning future observing Systems.

F. Large-scale Oscillations and Cross-Scale Interactions

1. **Short-term** - Augment projects that are focused exclusively on evaluating MJO and teleconnections using SubX data to include S2S models in their analysis
2. **Short-term** - Explore seasonal extremes in NMME, SubX, UFS, and GEFSv12. Quantities such as days above excessive heat thresholds or below extreme cold thresholds on S2S timescales can greatly aid in resource planning. Explore methods to diagnose rare events. This would support heat-health concerns.
3. **Short-term** - Study Week 3/4 predictability and explore prediction skill sources. The physical phenomena, and their interactions, that control

predictability in the Week 3/4 time period are not yet fully explored. More fully understanding the predictability, skill, and the gap would help target improvement strategies.

4. **Short-term** - Implement existing projects that develop new MJO Teleconnections diagnostics in MetPlus or create community diagnostics packages.
5. **Short-term** - Include case studies of extreme events strongly influenced by MJO and teleconnections in projects focused on evaluating deterministic and probabilistic skill of subseasonal forecast systems.
6. **Short-term** - Apply AI/ML tools for improved ENSO (Nino3.4 index) and spatial SST prediction. A few methods have been developed to predict Nino3.4 using different ML methods and varying training data. Some of those methods are comparable to the state-of-the-art dynamical models and could provide a complementary datastream.
7. **Medium-term** - Determine the sensitivity of the MJO and its predictability to pre-existing and/or evolving ocean heat content, surface currents, and ocean equatorial wave state.
8. **Medium-term** - Investigate the changes in the MJO teleconnections due to climate trends and uncertainty due to internal variability.
9. **Medium-term** - Examine downscaled S2S simulations (nested and variable-resolution grids) focused on regional precipitation and temperature impacts of S2S variability.
10. **Medium-term** - Use UFS S2S application to understand the skill of MJO teleconnections in this model (e.g., pacemaker experiments, relaxation experiments).
11. **Medium-term** - Investigate possible upscale effects of mesoscale ocean eddies on large-scale atmospheric intraseasonal variability in eddy rich regions. Determine if fine spatial details of the ocean surface are important to the atmosphere on S2S timescales.
12. **Medium-term** - Use a hierarchy of methods (dynamical models, ML/AI, observations) that exploit the potential predictability of teleconnections for improving the forecast skill on S2S time scale.

G. Synthesis and Societal Applications

1. **Short-term** - Establish connections with the stakeholder community to assess the need/desire for near-real time sub/seasonal air quality forecasts using aerosol load (PM 1.0, PM 2.5). This includes clarifying to such a community what is possible in terms of skill and reliability based on current forecast models.
2. **Medium-term** - Develop user-oriented evaluation of S2S forecasts (metrics and their communication).
3. **Medium-term** - Support efforts on the value assessment of S2S forecasts and products.
4. **Medium-term** - Develop sector specific forecasts, e.g., probabilistic forecasts of rainy season onset, wet/dry spells, heat/cold waves).

5. **Long-term** - Conduct virtual field campaigns to understand the role of atmospheric teleconnections in making subseasonal forecasts for: Agricultural related applications (e.g., Uncertainty Analytics Toolbox CSIRO/Digiscape); Public health related applications; Water management related applications. The big challenge would be to convince other agencies on the potential value of the S2S forecasts.
6. **Long-term** - Focus one or more activities geographically rather than phenomenologically. While the laws of physics are universal, the balance of processes and states that determine the evolution and predictability of phenomena on subseasonal time scales varies from region to region. Geographically focused calls for proposals, and associated task forces of sponsored PIs can bridge modeling vs observations, land vs atmosphere, physics vs dynamics... a range of factors that contribute to local weather and climate. It would foster interaction between communities that otherwise interact sporadically. It would also resonate with the GEWEX Hydroclimatology Panel, which has a long history of fostering such regional science campaigns.

II. Programmatic Activities, Research Support and Enterprise Improvements

A. **Short-term** - Expand US participation in the current S2S Phase II aerosol intercomparison project, WGNE-S2S-GAW-AER. Encourage production of forecasts "with" and "without" interactive aerosol.
B. **Short-term** - Expand the protocol for WGNE-S2S-GAW-AER to include models that run with two-moment cloud microphysics. At present, a modeling group that wishes to participate in this way must determine on their own how to run the "without interactive aerosol" experiment. A protocol would be useful for intercomparison among other modeling centers who wished to contribute experiments that could be used to examine the impact of aerosol-cloud interactions and aerosol indirect effects.
C. **Short-term** - Gather biomass burning emission inventories to enable more accurate retrospective forecasts throughout a longer time range.
D. **Short-term** - Ensure forecast model diagnostics include the necessary data to evaluate land and land-atmosphere process behavior, so that model development can be accelerated ensuring models get the right answers for the right reasons. This can take two forms: (1) updating default model output so that existing metrics packages like ILAMB (https://www.ilamb.org/) can easily ingest necessary data; (2) including code to calculate some of the more data-intensive metrics internally (e.g., http://www.coupling-metrics.com/). Outreach to modelers could be through SubX and the international S2S Prediction Project.
E. **Short-term** - Compile and provide climatologies from S2S hindcasts (including different model system versions) of major field variables (i.e., temperature, winds), including stratospheric levels, that could be provided on the cloud or

public server. Downloading the S2S hindcasts to calculate the model climatology for bias correction is resource intensive and a barrier to wider analysis. Computer resources are needed to store/host the data.

F. **Short-term** - Make more types of output available Encourage output on stratospheric levels from S2S modeling initiatives (SubX, NMME, and any future S2S modeling efforts), for example additional stratospheric levels. Resources might be needed to process and store additional data, but this would greatly expand the amount of data available to evaluate stratosphere-troposphere processes in S2S forecasts. Our community could contribute to the coordination of what variables and levels would be of most value.
G. **Short-term** - Increase vertical resolution of the UFS in the stratosphere. GFSv16 is the first major increase in the vertical resolution in the stratosphere in many years. Stratospheric components have been shown to benefit S2S outlooks in statistical models, and via some studies with dynamical models, specifically “high top” models.
H. **Short-term** - Perform a limited hindcast of a fully coupled, convective allowing model, out to 35 days, exploring the resolution of each component as well as initialization techniques
I. **Short-term** - Extend reforecasts back to 1982.
J. **Short-term** - Create a consolidated/cloud based public database portal for US S2S research and funding to the operational and research centers to push data to these databases.
K. **Short-term** - Make data from existing projects that have processed data from S2S and/or SubX databases (anomalies for each model) available to the community to prevent duplication of research efforts.
L. **Short-term** - Increase ouputs of SubX variables in order to facilitate analysis of critical parameters for subseasonal forecasting.
M. **Medium-term** - Build a framework for delivering reforecasts for each new model. Reconcile agile development for models with long computational cycles for reforecasts.
N. **Medium-term** - Expand participation in seasonal prediction efforts with models in use or under development in many centers that include the aerosol direct and indirect effects.
O. **Long-term** - Create a nationwide soil-moisture monitoring system, used to monitor conditions, and validate LDAS results.

DISCUSSION & CONCLUSIONS

Prediction skill at timescales beyond traditional weather forecasts, especially in the subseasonal to seasonal range, can assist decision making in sectors from natural resource management to public health. This document was generated with input across federal agencies and academic partners to address the goal of improving earth system prediction at S2S timescales. Many of the research initiatives presented here align with the strategies and goals of federal agencies including NOAA, NASA, NSF, DOE, as well as the Department of Defense. Agencies could leverage each others' strengths to streamline major research efforts into the forcing components of the S2S forecast. The short- and medium-term projects may be suitable for funding from within individual programs; however the long-term projects represent major investments that can benefit from full agency support and interagency partnerships. Some of the initiatives listed in this document explicitly call for this approach, such as establishing or enhancing cross-organizational plug-and-play of NUOPC compliant models. Others may be applicable to multiple agencies, such as assessing the operational feasibility of seamless weather to seasonal prediction systems. Such an effort could benefit from cross-agency communication to share best practices and prevent duplicative efforts. Several of the long-term projects may have a scope which exceeds the mission of any single agency. Aligning projects and areas with various agencies, and identifying interagency partnerships to tackle longer term projects could best be accomplished by a multi-agency coordinating group.

Appendix: Acronyms and Abbreviations

ACCP	Aerosols and Clouds, Convection and Precipitation
AI	Artificial Intelligence
AtlantOS	Atlantic Observing System
CMIP	Coupled Model Intercomparison Project
CPC	Climate Prediction Center
CSIRO	Commonwealth Scientific and Industrial Research Organization
DA	Data Assimilation
DOE	Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
ESMF	Earth System Modeling Framework
ESPC	Earth System Prediction Capability
GEFS	Global Ensemble Forecast System
GEWEX	Global Energy and Water Exchanges
GFS	Global Forecast System
GSFC	Goddard Space Flight Center
GSL	Global System Laboratory
ICAMS	Interagency Council for Advancing Meteorological Services
ILAMB	International Land Model Benchmarking System
IndOOS	Indian Ocean Observing System
INPE	Institute Nacional de Pesquisas Espaciais, Brazil
IRI	International Research Institute for Climate and Society
IWRCC	Interagency Weather Research Coordination Committee
JPL	Jet Propulsion Laboratory
L-A	Land-Atmosphere
LDAS	Land Data Assimilation System
LES	Large Eddy Simulation
LIM	Linear Inverse Model
LSM	Land Surface Model
MJO	Madden-Julian Oscillation
ML	Machine Learning
MOS	Model Output Statistics
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NLDAS	North American Land Data Assimilation System
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSF	National Science Foundation
NUOPC	National Unified Operational Prediction Capability

NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OFCM	Office of the Federal Coordinator for Meteorology
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PI	Principal Investigator
R2O	Research to Operations
S2S	Subseasonal to Seasonal
SCAN	Soil Climate Analysis Network
SMAP	Soil Moisture Active Passive Radar
SNOTEL	Snow Telemetry
SST	Sea Surface Temperature
SubX	Subseasonal Experiment
SUNY	State University of New York
TPOS	Tropical Pacific Observing System
UFS	Unified Forecast System
US	United States
WCRP	World Climate Research Programme
WGNE-S2S-GAW-AER	S2S Phase II aerosol intercomparison project
WMO	World Meteorological Organization
WWRP	World Weather Research Programme