SubX Current and Potential Users Forum Report

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Executive Summary

The Weather Research and Forecasting Innovation Act of 2017, enacted in April 2017, aims to improve the NOAA weather research through a focused program of investment on affordable and attainable advances in observational, computing, and modeling capabilities to support substantial improvement in weather forecasting and prediction of high impact weather events, to expand commercial opportunities for the provision of weather data, and for other purposes. Despite enormous progress in medium-range weather forecasts and seasonal climate predictions, a prediction gap still exists at the subseasonal to seasonal (S2S) time scale. A recent report to congress discussed this gap, noting that NOAA has outlined two goals in regards to S2S forecasting and prediction: 1) improve skill of S2S forecasts and 2) enhance the value of S2S products for stakeholders and NWS core partners.

The Subseasonal Experiment (SubX), launched in 2016, is a multi-model ensemble project using both research and operations components; it addresses both the need for real-time prediction guidance as well as a means to answer pressing research questions at the subseasonal (2 weeks to 3 months) time scale. SubX provides identical real-time and retrospective systems, a re-forecast period spanning 1999-2015, and daily data on a uniform 1x1 grid. Real-time forecasts are made available to NOAA's National Center for Environmental Prediction center and Climate Prediction Center by 6 am ET Thursdays. Following its initial launch, SubX was extended for an additional two years and transferred to the NOAA Weather Program Office (WPO) S2S program in FY18. SubX continues to benefit research partners with case studies and model intercomparisons as well as occasional/situational U.S. forecast use. A 2019 review determined that SubX should continue, ideally under interagency governance.

In late August 2021, the NOAA WPO convened the SubX Current and Potential Users Forum. The primary goals of this virtual workshop were to 1) investigate ways SubX is being used, in research, product development and decision support and 2) identify barriers to new user adoption. The workshop brought together 105 registrants from international organizations, federal and state government agencies, academia, and private enterprise. Each day of the workshop featured plenary sessions addressing SubX features and current uses in five different areas: 1) agriculture, water resources, and energy; 2) modeling and operational forecasters; 3) public health and insurance; 4) defense and maritime; and 5) research community. Following each session, participants were invited to discuss how SubX can better serve user needs as well as how forecasts are best communicated to stakeholders and decision makers.

The outcomes from workshop presentations and discussions are broadly categorized into one of two categories: 1) improving SubX skill to meet user needs and 2) connecting data and products with stakeholders. Participants identified two major strengths of SubX. First, because SubX includes 11 hindcast and 31 real-time members, it lends itself to tracking and evaluating model updates and may act as a proving ground for updates. Second, models initialize weekly, with some initializing daily. Models do not initialize synchronously, however, introducing challenges for product development of error. Moreover, participants noted the need to improve our estimates of the initial state of the ocean, land surface, and polar ice conditions.

Much of the discussion centered on whether future improvements to SubX should target achieving operational-level skill or instead expanding its capability to address a wide range of research and user needs (**Table 1**). Participants emphasized that website usage data might better inform where SubX is of most use but that currently there are no resources allocated to collecting this data. Participants concluded that in order to maximize SubX utility, changes in how the components of the S2S enterprise (operational, research, and private sectors) work together are needed.

The workshop discussion revealed a wider range of sectors actively relying on data from subseasonal ensembles than was originally recognized. Users from public health, agriculture, water resource management, defense, energy, sea ice and navigation, fisheries and ecosystem modeling, and research/model verification are using subseasonal data for situational awareness, resource planning and, in some cases, decision support. As noted, with no current usage data collected on the SubX website, we may miss valuable insights into individual model use, or potential user groups. Perhaps most importantly, participants emphasized a critical need to distill technical data into information to partners and stakeholders without meteorology or atmospheric science degrees.

Challenges and Recommendations

SubX serves a broad spectrum of sectors within the public, private, and academic weather enterprise, and is the only live-updating data stream for the World Meteorological Organization (WMO) S2S Project; however, there is no commitment for long-term support. Gaps in user needs will likely emerge should SubX be discontinued. This instability prevents adoption by new users that require long-term confidence in their ability to access data and forecasts. Workshop participants strongly recommended that future SubX development and protocols should be conducted in close coordination with users. Therefore, the workshop resulted in several recommendations to consider as next steps are formulated.

1) Participants agreed that the present ensemble is an excellent start; however, they noted the urgent need for interagency coordination and commitment for SubX's sustained existence and updates; frequent additions of various model output data, increased consistency and synchronization in model initialization, and consistent output timing and formats.

2) Participants suggested that verification and validation focus more on specific user needs such as probabilistic prediction; object-oriented verification that could incorporate both temporal and spatial variations; user value or return-on-investment; and more user engagement in the development of tailored products.

3) Participants inquired as to whether federal agencies should be responsible for the continuation of SubX. Potential advantages to this arrangement might include the following:
    a) Provide the opportunity to increase user product development, utility, and decision support services;

b) Continue the high-quality research dataset without sacrificing resources for decision support; and
c) Increase opportunities for work between private sector, community resource managers and decision-makers for product development.

4) Participants emphasized that significant multi-sector need calls for user-driven products that consider four pillars of subseasonal services:
    a) Generate: run models
    b) Translate: useful output data
    c) Transfer: provide to users
    d) Use: incorporate into decisions

5) Participants agreed on the need to shift communication strategy as well as dedicate funding that includes communication specialists.Social and behavioral science research is critical for better understanding the needs of decision makers and how best to deliver information to them.

To summarize, SubX contributes to our effort to improve accuracy, precision, and efficiency of forecasts and predictions to save lives and property and support a vibrant economy. SubX fills a critical capability gap in seamless forecasts at extended weather and subseasonal time scales for public, private, and academic sectors; it contributes to the weather enterprise's goals to improve the skill of S2S forecasts while also enhancing the value of S2S products for a wide range of stakeholders. Finally, the workshop also illuminated the critical need for improved decision support services to beco-designed with stakeholders and decision-makers to minimize the impact of heat waves, extreme cold, flooding rains, flash drought, or other weather hazards as far as 4 weeks into the future.

Table 1. Identified User Needs Not Currently Met with SubX
Model Components
• Air quality • BGC
Model Initialization Timing
• Early-week SubX Outlooks to accommodate early week decision makers
Model/Output/Data Configurations
• Combine multi-model mean • 2 ensemble models in interactive MME • Ability to download SubX data in .netdcf format • Downscale of SubX data • Higher temporal frequency (e.g., diurnal cycle of the Maritime Continent) • Longer hindcast period (e.g., QBO-MJO connection)
Operational Needs
• Configuration for robust post-processing • Optimal configuration for MME • Research-to-operations options
Variables
Agricultural
• SST • Ocean salinity anomalies • Soil moisture
General
• Maximum and minimum temperatures • Estimates of heat indices • Soil moisture • Prevailing wind directions • Relative humidity • 850mb, 700mb, and 200m wind • Buoyancy parameter (CAPE for severe weather)

Tropical forecasting
• Average vertical wind shear (850-200mb) • 200 mb velocity potential • 700mb relative RH anomalies • Tropical cyclone tracks • 3D MJO structure
Winter Forecasting
• QBO • Snowpack forecasting
Visualizations
• Regional maps • Dynamic maps w/ ability to zoom • Consistency in height anomalies from negative (cool colors) to positive (warm colors) • Apply smoothness of static maps to interactive maps

Session 1: Workshop Welcome and Opening Remarks

Welcome, Workshop Logistics, Goals, and Expected Outcomes | Dr. Jessie Carman

Dr. Jessie Carman (NOAA WPO) welcomed all the attendees and opened the workshop with an overview of the workshop's goals and agenda for the next three days. The goal of this workshop is to encourage sharing practices among current SubX users as well as to identify barriers to adoption by new users. Each session of the workshop featured plenary sessions highlighting the features of SubX and how it is currently informing operations, applications, and research. The workshop also aimed to address whether SubX is currently optimally balanced between research and user needs. Each session was followed by a discussion session to allow for more detailed conversations about current and potential future SubX use. Dr. Carman also introduced the NOAA WPO's S2S Program and its activities in support of the 2017 Weather Research and Forecast Improvement Act (P.L. 115-25), authorizing NOAA to improve capabilities for extended range prediction across a spectrum of decision-making activities: for personal and property protection; health; infrastructure; transportation and shipping; agriculture and water management; and national security.

SubX Overview | Dr. Kathy Pegion

Dr. Kathy Pegion (George Mason University) provided an introduction to the SubX, which targets forecasting between weather and seasonal outlooks (10-14 days to a month). Dr. Pegion notes that forecasting in this space is especially challenging because it is beyond the time scale where initial atmospheric conditions play a large role but before the ocean and ENSO plays a large role. In other words, subseasonal to seasonal processes are influenced by a combination of atmospheric, oceanic, and land processes and data provides lower resolution information where detailed information is not available but situational information may still be communicated to users. Our ability to forecast at the S2S timescale is important for planning and resource management, in particular to allow for the mobilization and efficient allocation of local, regional, and national resources in response to potential hazards and threats. However, Dr. Pegion noted that some of the greatest challenges to achieving sufficient skill in S2S forecasts beyond two weeks include location, initial condition/flow regime, and season. SubX addresses much of the uncertainty at this time scale by 1) running ensembles to account for initial condition uncertainty and 2) using multi-model ensembles to account for model uncertainty (i.e., improving the sampling of forecast uncertainty).

The SubX Protocol includes prediction system details up to the provider, identical real-time and retrospective systems, re-forecast period spanning 1999-2015, a minimum of 3 ensemble members, a minimum length of 32 days, daily data on a uniform 1x1 grid, and real-time forecasts made available to the NOAA's NCEP and CPC every Thursday by 6 am EST every week. SubX submodels include ocean, ice, and land groups whereas others only include land and ocean. Moreover, Dr. Pegion noted that grid point by grid point, the SubX multi-model ensembles do better than individual models and can help us better take advantage of forecasts of opportunity. SubX also offers the option to access weekly maps for different variables and data, forecasts and hindcasts, and maps are made publicly available. Dr. Pegion concluded that SubX is useful for research questions (e.g., understanding sources of predictability, evaluating

model biases and calibration and post-processing) and has been applied to providing guidance to NCEP and CPC operational outlooks, tropical cyclone precipitation outlooks, coastal flooding outlooks, and estuarine forecasts.

Session 1 Discussion | Dr. Jessie Carman

Dr. Carman opened a discussion considering the current strengths of SubX and future directions for growth. Participants commented that one of the major strengths of SubX is that it readily lends itself to tracking and evaluating model updates because its ensemble includes eleven members in the hindcast and 31 real-time members. Most of the models provide daily data and initialize weekly, though some (e.g., NCEP) initialize daily. One challenge, however, is that models are not initializing on the same date, which likely introduces additional uncertainties in forecast products. Forum participants also questioned the reach of SubX to potential user groups. Dr. Pegion noted that SubX currently does not have the capacity (funding or personnel) to collect or analyze user data from the website. Participants commented that this usage data could prove valuable in tracking which data and models are utilized most frequently. Moreover, usage data could help identify potential users who may not be leveraging SubX as a resource. Participants also noted that it may be beneficial to establish some form of regular communication with current and potential user groups to inform on updates and relevant information. Much like tracking usage data, supporting sustained communication efforts would require additional funding and personnel resources.

Session 2: Agriculture, Water Resources, & Energy (Part I)

Forecasting across time scales for water management in a changing climate | Dr. Mike Anderson

In the first presentation, Dr. Mike Anderson (California Department of Water Resources) discussed the need to improve forecasts between weather and climate scales to better inform water management decisions in drought-prone regions of the western United States. Dr. Anderson noted that atmospheric rivers are one of the key phenomena affecting California water supply and flooding and that their size, number, and strength result from the alignment of key processes operating on different spatial and temporal scales, including subseasonal to seasonal scales. While the spatial and temporal fidelity of forecasts decrease with increased lead time, decision makers can nonetheless accommodate for less detailed information. Dr. Anderson indicated that over the past decade, the California Department of Water Resources has invested significantly in observations and collaborations to improve forecasts from the event to seasonal time scales. He added that decision support services must accompany such investments in order to optimize their societal benefit.

Subseasonal to Seasonal forecasts for improved climate services | Dr. Andrew Robertson

Dr. Andrew Robertson (International Research Institute for Climate and Society) presented on the need for improved subseasonal to seasonal forecasting within the climate services context. He posited that for subseasonal to seasonal forecasts products to maximize their potential as a decision-making tool, forecast products must be co-developed with users

and embedded with the four pillars of climate services: Generate, translate, transfer, and use. Dr. Robertson highlighted the need for user-oriented subseasonal to seasonal forecasts that are calibrated, validated, real-time, flexible, and tailored to user needs. He also stated that, depending on the user or sector needs, both deterministic and probabilistic formats may be useful, though it is imperative to include information surrounding forecast uncertainties. Dr. Robertson presented results of a stakeholder survey identifying four primary barriers to subseasonal to seasonal forecast uptake: 1) lack of accuracy or poor skill, 2) lack of post-processing, 3) lack of forecast verification, and 4) lack of stability in the forecast model output.Dr. Robertson added that there is added value on using the International Research Institute's (IRI)/NextGen's flexible format approach, which uses the entire probability density function. He outlined several cases where IRI is working with partners to develop forecasts of variables such as acute undernutrition, mosquito abundances, and rice yield as a means of providing holistic climate services at subseasonal timescales. Finally, he highlighted work from the WMO's S2S Real Time Pilot Initiative, which seeks to identify what is needed to make subseasonal to seasonal forecasts accessible, how that varies by sector/organization/experiences, and to develop a set of best practices.

Session 2 Discussion | Dr. Mark Olsen

Dr. Mark Olsen (NOAA WPO) led the discussion following the second session, which primarily focused on effective communication of SubX data products to water managers and other stakeholder groups. Participants highlighted a critical communication gap and urgent need to distill technical data and information to partners and stakeholders that do not necessarily hold meteorology or atmospheric science degrees. Dr. Anderson noted that one communication pathway is to work through existing partnerships between NWS Regional and Weather Forecast Offices and local/state partners. Dr. Robertson noted that communication efforts must also include demonstrable success of how community managers have successfully implemented S2S from SubX in their decision-making processes. He added that effective communication efforts often require dedicated funding that includes communication specialists. Participants also noted, however, that data and science are only part of the decision-making process and that in many cases, societal and political considerations outweigh technical advice.

Session 3: Agriculture, Water Resources, & Energy (Part II)

Applied Subseasonal to Seasonal Forecasting: Digital Farming at BASF | Sonya Miller

Ms. Sonya Miller (BASF) presented digital farming techniques developed by BASF. These techniques apply precision location methods and decision quality agronomic information to illuminate, predict, and affect the continuum of cultivation issues across farms at micro-, field-, and meso- scales. Ms. Miller indicated that subseasonal to seasonal forecasting is infused into these digital farming techniques to provide agricultural stakeholders with information on subseasonal weather trends by 1) producing 10-day to 9-month forecasts that inform growth stage yield forecasts, 2) developing seasonal maps and in conjunction with federal partners like the NWS that are used by BASF sales teams, and 3) generating point-based forecasts that enable better prediction of crop production in agronomic models. Ms. Miller noted that BASF

does not currently utilize the SubX model, primarily because they require more variables and model stability to be able to reliably use SubX for operations. She indicated that the additional variables needed include frost/heat stress, disease risk, precipitation frequency, and solar irradiation.

SubX Forecasting and the Private Sector | Bob Smerbeck

Mr. Bob Smerbeck (Accuweather) detailed the use of SubX re-forecast and real-time forecasts available at the IRI Data Library, Columbia University (COLA) for subseasonal to seasonal forecasting. Mr. Smerbeck indicated that commodity trading, energy, construction, and travel industry stakeholders largely require extreme temperature and precipitation forecasts and confidence measures of SubX forecasts. He also outlined Accurweather's suite of subseasonal to seasonal products that include a 15-30 day forecast blog, 90-day temperature and precipitation outlook, 1-4 week temperature and precipitation outlook tailored to agriculturalists and commodity traders, a general weeks 3-4 outlook that supports energy and retail customers, and a video format long-range outlook. Mr. Smerbeck concluded with several logistical and aesthetic modifications to the COLA SubX forecasts that would enhance their S2S capabilities: 1) a Sunday/Monday (early) version of the Week 3-4 forecast of the multi-model ensemble (MME) that is initialized over the weekend to accommodate customers making early week decisions, 2) output guidance for two interactive SubX MME, 3) cool colors for negative height anomalies warm colors for to positive anomalies, 4) user choosing their own anomalies, 5) contour smoothness of the static maps applied to the interactive maps, 6) skill scores for COLA SubX MMEs, 7) more tropical forecasting parameters: average vertical wind shear 850-200 mb, 200 mb velocity potential, 700 mb relative humidity anomalies, 10 m and 200 mb wind speed/vector anomalies, and 8) additional agricultural forecasting parameters such as sea surface temperature, sea salinity, and soil moisture anomalies.

Session 3 Discussion | Dr. Jessie Carman

Dr. Carman opened the third discussion session asking whether this session's presenters would find SubX applicable for predicting extreme events. Presenters answered that extreme height anomalies, extreme rainfall anomalies, velocity potential for previous two weeks, the time of frost events, soil moisture at 4-week time frame, and stronger historical measurements would all be useful data for predicting extreme events. They also noted that SubX could have been useful for forecasting the Texas Cold Air Outbreak in 2021. Moreover, predicting early snowfall means would also require cold anomaly forecasting. Participants also conveyed interest in downloading NCEP data via a netcdf file so that they can develop their own variables as well as the ability to use SubX directly as opposed to via COLA, as well as the need to revisit the timing of COLA forecasts. Additional needs moving forward include coupling land and ocean models as well as strengthening snowpack and fire forecasting. Participants also discussed the potential to obtain SubX on Columbia IRI, which currently hosts an archive of all model forecasts as well as methods for making maps. One participant shared that the U.S. Air Force uses IRI to download post-processed files via ftp server but added that they have experienced trouble with downloading IRI data directly.

Session 4: Agriculture, Water Resources, & Energy (Part III)

Predicting climate shocks to get ahead of humanitarian crises | Dr. Josée Poirier

Dr. Josée Poirier (United Nations Office for the Coordination of Humanitarian Affairs) opened the final agriculture, water resources, and energy session with a discussion on how the humanitarian aid community is increasingly proactive with addressing climate disasters through predictive analytics. Dr. Poirier posited that such work begins with an anticipatory action, which is prearranged financing, an established plan of actions, and robust forecasting of climate disasters and threats. She noted that this action reduces the humanitarian impact and the cost of response. Dr. Poirier provided numerous examples of the Office for the Coordination of Humanitarian Affairs (OCHA) initiatives in which this anticipatory framework is currently in use or under development throughout Sub-Saharan and Eastern Africa, as well as in Southeast Asia. Throughout these initiatives, significant pre-emptive work is done to identify potential shocks such as droughts, floods, and infectious disease. Identifying these shocks includes assembling ground truth datasets of historical shocks, determining early signs of high risks for shocks, and establishing methods for mitigating humanitarian crises from shocks. She detailed an early success in using this framework to assess and predict potential food insecurity in Ethiopia 5-6 months prior to severe drought using signals of the ENSO. Dr. Poirier challenged that while early initiatives demonstrate great promise, limitations that must still be addressed include obtaining a more robust set of historical data, expert evaluation of model skill, uncertainty, error and subseasonal to seasonal production, increasing the frequency of forecast publication to reduce delays in acting based on fresher data, and downscaling of model simulations. She concluded that overcoming such challenges will increase the skill in predicting and responding to slow- or sudden-onset climate shocks such as a recent dry spell in Malawi.

Weather forecasting: Enel's point of view | Dr. Marco Formenton

Dr. Marco Formenton (The Enel Group) demonstrated the uses of subseasonal to seasonal forecasting within The Enel Group, a global energy development and production company with a capacity of 49 Gigawatts and 74 million end users. Dr. Formenton stated that the company uses weather variables such as temperature, precipitation, wind speed, and solar irradiation to make reliable forecasts that determine power demand. This forecasted is then used to establish a supply and demand ration, which is followed by setting power prices that ultimately drive Enel's revenue. Dr. Formenton noted that an example of this approach is currently in use with hydroelectric power production in Italy, where rainfall and temperature variables are used in a non-linear seasonal function and compared to historical data to predict the hydroelectric output. The Enel Group expands on this approach by also including subseasonal forecasting (which Enel defines as 15 days to one month) and seasonal (beyond one months to several months) in their power output estimates. The seasonal forecasts are supported by Seasonal Climate Forecasting for Integrated Risk Assessment (SECLI-FIRM), a European Union funded project from SEAS5, the German Weather Service (DWD), MeteoFrance, and UK MetOffices. Dr. Formenton posits that this approach has benefited The Enel Group since the goal of SECLI-FIRM is to assess how climate forecasts can add practical and economic value. He concluded that building a seasonal forecasting framework is ongoing

and that an experimental tool has been introduced for seasonal forecasting that ingests GFS and North American Multi-model Ensemble (NMME) data.

Session 4 Discussion | Dr. Kathy Pegion

Dr. Pegion opened the final discussion period on agriculture, water resources, and energy. Participants inquired about the amount of skill needed from subseasonal forecasts, to which Dr. Poirier responded that climatological averages could be sufficient. She was also asked if OCHA utilized a 30-day ensemble from the European Centre for Medium-Range Weather Forecasts (ECMWF). She noted that while they do utilize ECMWF 30-day forecasts, they are delivered twice a week. Participants also asked if OCHA consults with climate scientists to interpret forecast products. Dr. Poirier stated that they use Columbia's IRI but would like to engage more with climate scientists to ensure proper interpretation. In this session, participants also discussed that probabilistic forecasts may provide more granularity but also noted that many of the applications require a longitudinal perspective and may not require that level of detail.

Session 5: Modeling Centers and Operational Forecasters

SubX use at CPC | Matthew Rosencrans

Mr. Matthew Rosencrans (NOAA CPC) outlined the uses of SubX at the NOAA's CPC. Mr. Rosencrans shared that at CPC, SubX is primarily used for testing and development. CPC international desk is also using SubX for research on MME for week 3-4 probabilities. He noted that internationally, not everyone has access to the same suite of models as CPC so SubX is a way of distributing multi-model data to the international community. Mr. Rosencrans stated that SubX is not directly used computationally in the forecast, namely because it did not score as well as available operational models. He suggests that some possible reasons explaining this are 1) bias corrections, 2) individual ensemble models, and 3) differing initial conditions. He also suggested that one challenge with SubX is that the models are not initialized on the same day, introducing additional uncertainties. CPC also used hindcasts from SubX models in the development phase of an ensemble subsampling project and found that temperature and precipitation skill increased 5-15% when using an objectively determined subset of ensemble forecast members. Nonetheless, CPC only uses operational models (e.g., GEFS, CFSv2) in the testing phase of the project. Mr. Rosencrans concluded with consideration for next steps for SubX and whether or not SubX should be operationalized or research-focused only.

ESPC SubX use at the U.S. National Ice Center | Alexandra Darden

Ms. Alexandra Darden (U.S. National Ice Center) presented on the uses of subseasonal to seasonal forecasting at the U.S. National Ice Center (USNIC). Ms. Darden shared that USNIC uses five models and is experimenting with 2 additional models, though only one model is long-range. She noted that the Navy's Earth System Prediction Capability (ESPC) ensemble, which became operational in August 2020, provides information on sea ice thickness, concentration, and sea ice drift from individual ensemble members. The U.S. Navy also provided support for the U.S. Government IceX Project in 2020, providing data for situational

awareness and position tracking for multi-year ice flows and a 45-day outlook used for Ice Camp planning from September 2019 to February 2020. She noted, however, that the model only accounts for ice thickness and not ice age (i.e. first-year vs. multi-year ice). Ms. Darden also stated that the USNIC is also using the Navy ESPC subseasonal model to produce a Ross Sea Outlook for resupply missions to McMurdo Station, Antarctica. She concluded that the USNIC will continue to incorporate the Navy ESPC into tailored support and outlooks and will likely pursue future statistical validation efforts.

Session 5 Discussion | Dr. Scott S.Sandgathe

Dr. Sandgathe opened the fifth discussion session. Participants inquired as to whether CPC uses ensemble means, deterministic forecasts, and probabilistic forecasts. Mr. Rosencrans responded that for operational models, CPC creates ensemble means but also uses ensemble members to create a probability spread. There was also discussion as to why SubX underperforms operational models, determining that it could likely be that one of the ensemble members is not at an optimal ensemble size or a probability initialization lag because SubX's initial conditions are older than three days. Moreover, SubX members initialize on different dates, likely increasing error margins. Participants also noted that SubX may be at a decision point, where coming close to meeting initial conditions and ensemble size will require significant resources. They questioned if this is the best path forward or if resources could be better leveraged by focusing on value-added products to meet increasing user needs. Participants noted that operational forecasters are looking for the highest skill for 3-4 week outlooks. Because SubX ranks lower in skill than other tools, it may be most useful to concentrate next steps on strengthening SubX's unique characteristics (e.g., different models have different hindcasts but SubX's multi-model ensemble provides additional opportunities for post-processing that perhaps other operational models do not.

Session 6: Public Health & Insurance Industry

Applications of SubX for air quality, fire, and smoke | Dr. Samantha Kramer

Dr. Samantha Kramer (Sonoma Technology) presented the applications of SubX for forecasting air quality, fire, and smoke in the Western United States. She stated that common air quality forecasts currently represent current- and next-day forecasts, as extended day air quality forecasts are computationally expensive. Forecasters look at other common weather indicators for air quality such as high atmospheric pressure, high air temperature, mixing height, and wind speed. Wildfire incidents also contribute significantly to poor air quality. High wildfire risk conditions are forecasted with numerous indicators including: air temperature, wind speed, soil moisture, precipitation, drought, and the first 3-day precipitation period in autumn. Additionally, the U.S. Forest Service developed a hot-dry-windy index based on wind speed and vapor pressure deficit that indicates how difficult a fire may be to manage. Dr. Kramer emphasized that forecasting potential fire scenarios is indispensable for seasonal planning that allows for more efficient allocation of resources as well as planning for prescribed burns to combat wildfire threats. However, she noted that conditions for prescribed burns must be optimal in order to introduce smoke into a dispersive atmosphere, keep burns controlled, and limit air quality impacts based on preferable wind direction and dispersive conditions. Dr. Kramer stated that the

potential benefits of using SubX include extended forecasts of air quality weather indicators, fire weather forecasts,and prescribed fire prescription forecasts. However, she also indicated that private companies are hesitant to invest resources to operationalize products without being able to ensure their existence long-term.

Impact-based decision support services in human health | Dr. Wassila Thiaw

Dr. Wassila Thiaw (NOAA CPC) highlighted how subseasonal to seasonal forecasts can aid impact-based decision support services in human health applications. He emphasized that climate change is a major threat to society and contributes to an increase in the prevalence of numerous public health threats such as infectious diseases and heat-related illnesses. These threats demonstrate the need for early warning systems with actionable forecasts to help mitigate their impacts. Dr. Thiaw drew on an example of an early heat warning in Africa, where many communities are at highest exposure and vulnerability to extreme weather. This project 1) evaluated the ability of NOAA's NCEP to depict and predict heat waves and 2) developed tools for forecasting heatwaves and ensuring National Meteorological Services (NMS) are able to access these tools. This effort not only worked to characterize, predict, and translate forecasts for early planning, it also sought to bring about awareness of heat waves and impacts on health and other socioeconomic activities such as power generation, transportation, and food production. Dr. Thiaw noted that the demand for actionable weather and climate information far exceeds the weather enterprise's current capacity and that there is a need to better understand both climate variables and thresholds that trigger disease.

SubX and Health Equity: The path to Collaboration | Dr. John Balbus

Dr. John Balbus (National Institute of Health) discussed an overview of the Office of Climate Change and Health Equity (OCCHE) and its role in facilitating collaborations between public health experts and physical scientists. The OCCHE was mandated by Executive Order 14008, which mandates the establishment of the office as well as an interagency working group to decrease risk of climate change to children, the elderly, people with disabilities, and other vulnerable groups, as well as the establishment of a biennial Health Care System Readiness Advisory Council. Some of the objectives of the OCCHE include to identify communities with disproportionate exposure, address health disparities exacerbated by climate impacts, promote and translate research on public health benefits of multi-sectoral climate actions, support regulatory efforts to reduce greenhouse gas emissions in the health care sector, and foster innovation in climate adaptation. Dr. Balbus emphasized the need of physical scientists to work with public health experts to build climate forecasts and products that are understandable beyond the physical science community, highlighting the increasing number of billion-dollar weather and climate disasters that also impact public health. Those impacts range from injuries and fatalities to increased exposure to malnutrition and diseases resulting from changes in vector ecology. Dr. Bablus emphasized that SubX could prove particularly useful in providing information on patterns and timing of precipitation and extreme heat, heat indices, soil moisture integration with drought forecasts, air quality, heat parameters, prevailing wind directions/smoke plume prediction, and extreme weather and storm risks.

Session 6 Discussion | Matthew Rosencrans

Mr. Rosencrans opened the discussion asking speakers what changes to SubX would better support their operations and decision-making. Dr. Kramer responded that she would like to see a combined multi-model mean for fire weather applications while Dr. Thiaw answered temperature maxima and minima, relative humidity, and pressure data at 200 mb, 700mb, and 850mb. Participants also commented that there is a need to downscale and improve event forecasting and probabilities of reaching extreme variables. Dr. Balbus noted the need for improved and sustained collaboration between public health experts and physical scientists that would foster cross-disciplinary problem solving. Participants also emphasized the need to support co-design of forecast and model products with intended end users to ensure that products meet stakeholder needs and that stakeholders better understand the current limitations of forecasting and modeling. Participants also argued that effective co-design is another area where dedicated and sustained funding is required.

Session 7: Defense and Maritime

14 Weather Squadron use of SubX for optimizing military planning and intelligence assessments | Mr. Justyn Jackson

Mr. Justyn Jackson (U.S. Air Force) presented the use of SubX within the U.S. Air Force's 14 Weather Squadron, whose primary duty is to collect, protect, and exploit authoritative climate data to optimize military and intelligence operations. Mr. Jackson shared that the CMAP group within the squadron uses SubX forecasts for week 3-4 predictions. CMAP uses these forecasts to equip military planners and the intelligence community with hazards risks and information for situational awareness. These risk assessments primarily consider four parameters: 1) the event that is occuring, 2) the overall impact of the event, 3) whether conditions will get worse, persist, or improve, and 4) the necessary parameters for various forecasts. He enumerated various examples where the 14th Weather Squadron has applied this approach, including real-time scenarios such as water security in East African countries and precipitation amounts and anomalies in the Western United States and Mexico. Mr. Jackson concluded that while the current SubX infrastructure is sufficient, additional products such as MME forecast probability, probability of exceedance of temperatures and precipitation in netcdf format, and operationally supported data sources would improve the usability of SubX in the 14th Weather Squadron.

Navy ESPC system overview and products | Dr. Matthew Janiga

Dr. Matthew Janiga (Naval Research Laboratory) presented the Navy ESPC, a 16-member coupled atmosphere-ocean-sea ice ensemble which is used for probabilistic forecasting on subseasonal timescales. The U.S. Navy uses this model to broaden its forecasting of large-scale climate phenomena such as the Madden Julian Oscillation and El Niño Southern Oscillation. Version 1 of Navy ESPC is run at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and provides a $1/12^{th}$-degree ocean resolution as well as the ability to forecast ocean salinity and ice thickness. Dr. Janiga shared that Naval Research Laboratory (NRL) is currently developing its second version of Navy ESPC that will include an

increased number of atmospheric vertical levels and doubling of horizontal resolution, high-altitude atmospheric prediction, one-way ocean wave coupling using WaveWatch3, and stochastic kinetic energy backscatter (SKEB). He also noted that Navy ESPC is deemed comparable to other models (i.e. ECMWF, NCEP, and UKMO) based on several model verification tests of its MJO prediction skill. The third version of Navy ESPC is also under development, slated for release in FY26, with a new atmospheric dynamical core that supports cloud-permitting resolution and multi-resolution grids.

Session 7 Discussion | David McCarren

Mr. McCarren moderated the seventh discussion session. Participants inquired as to whether the U.S. Air Force is verifying their week 3 forecasts. Mr. Jackson responded that they currently or not for the hazards predictions but agreed they need to more aggressively pursue this, noting that some would be easier to do (e.g., temperature, precipitation, tropical cyclone). Another participant noted that NOAA CPC is also working on verifying hazards and suggested that a NOAA-U.S. Air Force collaboration may make sense to pursue. Participants also wonder how the U.S. Air Force decided to use SubX rather than NOAA operational products, to which Mr. Jackson responded that SubX is easy to download and has a multi-model ensemble from individual members. He added that they do use other operational ensembles to produce products and that because they serve as an operational center for both the U.S. Air Force and Department of Defense, they need a more stable data source that is not going to shut down at the end of a grant cycle. Participants also discussed whether or not the U.S. Navy Global Environmental Model (NAVGEM) was considering hindcasts for v1 and v2. Dr. Janiga responded that ideally they would like to eventually move to an on-the-fly system and do hindcasts but it is dependent on available computing resources. Additional SubX variables that could support U.S. Navy operations include variables related to snowfall anomalies and buoyancy parameters like CAPE for severe weather conditions and tropical cyclones.

Session 8: Research Community Use

Advance subseasonal predictability research using SubX database | Dr. Hyemi Kim

Dr. Hyemi Kim (Stony Brook University) discussed how SubX products are used to predict the Madden Julian Oscillation. Dr. Kim outlined ways in which SubX products are applied. The first is a process-oriented evaluation of MJO forecasts, which involves assessing the key physical processes and biases related to MJO forecasts in SubX models. She emphasized the robustness of the moisture advection processes in the model and link the process with SubX model's . Dr. Kim also used SubX forecasts to examine the MJO and QBO relationships and biases in models. She also used machine learning for bias correction of the MJO forecasts in SubX models and demonstrated improved forecast skill after nonlinear bias correction compared to original forecasts.

S2S Prediction of Extreme Air Quality Events | Dr. Daniel Tong

Dr. Daniel Tong (George Mason University) discussed the applications of subseasonal to seasonal forecasting to extreme air quality events such as dust events. Dr. Tong stated that data from ground observation networks show that the frequency of dust events in the United States have increased by 12% per year over the past 30 years, demonstrating the importance of better understanding these events. The increased presence of dust particles originate from rain water calcium, dust deposition from snow, fine soil, and agricultural expansion. Dr. Tong emphasized that these phenomena have significant impacts on public health and the U.S. economy. Public health impacts include higher rates of Valley Fever in the Western U.S., which results from the suspension of soil-dwelling fungi coccidioides in the air that cause lung infections, inflammation, and skin lesions. Moreover, dust can also damage and reduce power generation efficiency and induce traffic accidents with reduced visibility and road traction. Dr. Tong closed his presentation discussing the collaborative effort by George Mason University, the Center for Disease Control, University of Tulsa, the Arizona Department of Environmental Quality and the NOAA Environmental Modeling Center (EMC) to improve dust forecasting by enhancing the FENGSHA dust emissions model parameterization within SubX models.

Session 8 Discussion | Dr. Kathy Pegion

Dr. Pegion moderated the eighth discussion session, where participants discussed next steps in expanding SubX capabilities. Participants enumerated several additional variables such as specific humidity to better see 3D MJO structure, higher resolution local and global spatial scale and temporal frequencies (e.g., diurnal cycles over the Maritime Continent), and a longer hindcast period. Participants also wondered whether SubX might eventually provide real-time MJO forecasts and Dr. Pegion confirmed that it is already slated for development.There was also discussion around what else besides QBO might drive the need of a longer retrospective period. Participants stated that a longer retrospective would support more samples, resulting in greater skill and allowing researchers to test MJO in various ENSO modes. Towards the end of the discussion, participants also noted that SubX is much easier to use than other products, especially with Python and GrADS tools.

Session 9: Feasibility vs User Needs

S2S forecasts for US west coast oceanography and fisheries applications | Dr. Michael Jacox

Dr. Michael Jacox (NOAA Southwest Fisheries Science Center) opened the ninth session with an overview of potential SubX applications for coastal ocean and ecosystem modeling. He noted that while forecasting for fisheries has typically been on the seasonal scale, they are increasingly moving towards subseasonal. Dr. Jacox stated that there are two primary groups of key processes and mechanisms that are important for fisheries and ecosystem forecasting: physical and biological. Key physical processes include coastal waves, persistence, sea-ice processes, re-emergence, baroclinic rossby waves, advection, and tropical-extratropical connections. Important biological processes include biogeochemical responses to physical forcing, species responses to environmental changes, and species life history. Dr. Jacox highlighted three examples where subseasonal forecasts could inform fisheries management

practices. WhaleWatch uses real-time analysis to address the issue of ship strikes of blue whales, EcoCoast builds species distribution models to help address bycatch, and climate-informed harvest guidelines incorporate sea surface temperature forecasts to inform fluctuations in fish populations. Finally, Dr. Jacox introduced a newer project in collaboration with NOAA's Climate Program Office (CPO) that aims to improve the utility of global climate forecasts for regional fisheries applications by incorporating influences from MJO and ENSO.

Subseasonal forecasts for coastal oceans and ecosystems | Dr. Andrew Ross

Dr. Andrew Ross (NOAA GFDL) discussed how subseasonal to seasonal forecasting could provide useful applications for coastal oceanography and fisheries. He noted that while the NOAA GFDL does not use SubX directly, it is used as inputs to other empirical, statistical, and numerical forecast models, and he highlighted that this use of global model data as inputs to other models is common in the coastal ocean modeling and forecasting community. Dr. Ross outlined numerous examples in which salinity and air/water temperature forecasts are important in fisheries planning, including the impact of catch-and-release practices in warmer water, the temperature and salinity dependence of toxic algal and bacterial species, and aquaculture planning. The advance warning of optimal conditions for rapid growth of harmful algal blooms and bacteria would allow for the adaptive implementation of safe practices, harvest restrictions, and recreational closures. He also highlighted the role of storms, storm surges, and flooding in influencing local salinity and water quality conditions, especially in response to large terrestrial freshwater discharges. Dr. Ross provided two examples of current subseasonal ocean forecast systems, the George Mason iFLOOD and Coral Reef Watch, but noted that other skill in subseasonal forecasts may be possible for other applications . Dr. Ross concluded that SubX provides easy data access and processing for numerous variables relevant to coastal processes but enumerated several user needs that would increase the value of SubX in coastal forecasts: 1) Resolving coastal oceans with resolutions higher than 1°; 2) empirical-statistical bias correction and downscaling algorithms; including lead-dependent bias correction and downscaling; 3) increased frequency of forecast initialization; and 4) accessibility for users at sea with sporadic or low-bandwidth internet access.

Session 9 Discussion | Matthew Rosencrans

Mr. Rosencrans opened the ninth discussion session and inquired as to whether ecological modeling has verified the skill of biomass, to which Mr. Jacox responded that they have done some cross-validation across years. Participants considered SubX variables that support ecological forecasting and modeling and determined that SubX provides many of the needed variables. However, bottom temperature, mix-layer depth, biogeochemical data (e.g., dissolved oxygen, pH, dissolved inorganic carbon, etc.) and some measure of upper ocean stratification would also be valuable. Participants also acknowledged that it is particularly difficult to find verification datasets of more specialized variables, especially biogeochemical data. In such cases, ecological forecasters and modelers invest considerable effort into 2-step processes that provide confidence they are using quality observations. Participants concluded the discussion by considering how to best connect ecological forecasts and models with fishery

managers, determining that similar gaps between forecasters/modelers and stakeholders exist as do other potential SubX users.

Session 10: Recommendations For Moving Forward

Discussion, Summary, and Looking Forward | Organizing Committee

Dr. Ben Kirtman opened the last session with a summary of discussion from workshop sessions. He also stated that SubX has achieved great success but is at a developmental crossroads where a decision needs to be made as to whether it will be pushed to operational skill, provide value-added products to meet increasing user needs, or if SubX can realistically sustain both with available resources. Dr. Kirtman emphasized that while the S2S community envisions numerous improvements for SubX, resources are not without limit and so further SubX development in the immediate future should focus on more easily attainable changes while subsequent funding is sought to sustain and develop SubX further. He noted that once SubX has a commitment for further funding, the focus can shift to larger development projects.

Participants suggested numerous modifications that could be made to SubX with minimal investment such as changes to visualizations, adding downloadable data under each image, providing derived variables (e.g., TRMM, shear), and providing a robust assessment of MME forecasts. Participants also noted the need to make products more user-friendly, particularly given the array of users external to federal and academic partners. One participant suggested that operational limits have not been reached and so it might make sense to evaluate how well models perform under specific conditions and scenarios to guide decisions on which models to use under which conditions. Another participant shared that work is currently underway at CPC to address this challenge. Some also suggested that machine learning could provide opportunities with post-processing the MME and that there is already a commitment to achieve this with the real-time component. Finally, participants acknowledged that the best solution may be to continue using SubX as a research tool that can be used as a platform for testing and allow CPC to provide products for users with needs requiring operational skill.

Upon considering long-term development of SubX, participants noted that the focus can shift to model configuration and improving our ability to estimate the initial state of the ocean, land surface, and polar ice conditions. SubX only runs one ocean model and model perturbations are in the atmospheric component. Coupling processes and feedback would greatly improve predictability. Moreover, restructuring SubX could allow enough flexibility to initialize on certain days, thereby further reducing forecast uncertainty. Participants concluded that SubX has enormous flexibility and potential but that it will need a sustained commitment of funding and personnel to move forward.

Appendix A: Acronyms

BGC	Biogeochemistry
CAPE	Convective Available Potential Energy
CFS	Climate Forecast System
CPC	Climate Prediction Center
CPO	Climate Program Office
COLA	IRI Data Library, Columbia University
CMAP	Climate Prediction Center Merged Analysis of Precipitation
DWD	German Weather Service (*Deutscher Wetterdienst*)
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center
ENSO	El Niño-Southern Oscillation
ESPC	Earth System Prediction Capability
FENGSHA	Wind-blown dust emission model
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GEFS	Global Ensemble Forecast System
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
IRI	International Research Institute, Columbia University
MJO	Madden-Julian Oscillation
MME	Multi-Model Ensemble
NAVGEM	Navy Global Environmental Model
NCEP	National Center for Environmental Prediction
NMME	North American Multi-model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NMS	National Meteorological Services
NWS	National Weather Service
OCCHE	Office of Climate Change and Health Equity
OCHA	Office for the Coordination of Humanitarian Affairs
QBO	Quasi-biennial oscillation
RH	Relative Humidity
S2S	Subseasonal-to-seasonal
SEAS5	ECMWF Seasonal Prediction System
SECLI-FIRM	Seasonal Climate Forecasting for Integrated Risk Assessment
SKEB	Stochastic Kinetic Energy Backscatter
SST	Sea surface temperature
SubX	Subseasonal Experiment
TRMM	Tropical Rainfall Measuring Mission
UKMO	United Kingdom Meteorological Office
USNIC	U.S. National Ice Center
WMO	World Meteorological Organization
WPO	Weather Program Office

Appendix B: Agenda

Day 1: Tuesday, August 24

11:00 am Session 1: Workshop Welcome and Opening Remarks

Welcome, Workshop Logistics, Goals, and Expected Outcomes | 15 min.
Jessie Carman, Ph.D., NOAA WPO
SubX Overview | 30 min.
Kathy Pegion, Ph.D., GMU
Discussion | 15 min.
Moderator: Jessie Carman, Ph.D., NOAA WPO

12:00 pm Session 2 : Agriculture, Water Resources, & Energy (Part I)

Forecasting across time scales for water management in a changing climate | 15 min.
Mike Anderson, Ph.D., California Department of Water Resources
Subseasonal to Seasonal forecasts for improved climate services | 15 min.
Andrew Robertson, Ph.D., Int'l Research Institute for Climate & Society
Discussion | 30 min.
Moderator: Mark Olsen, Ph.D., NOAA WPO

Break (1:00 - 3:00 pm)

3:00 pm Session 3: Agriculture, Water Resources, & Energy (Part II)

Applied Subseasonal to Seasonal Forecasting: Digital Farming at BASF | 15 min.
Sonya Miller, BASF
SubX Forecasting and the Private Sector | 15 min.
Bob Smerbeck, Accuweather
Discussion | 30 min.
Moderator: Jessie Carman, Ph.D., NOAA WPO

4:00 pm Session 4: Agriculture, Water Resources, & Energy (Part III)

Predicting climate shocks to get ahead of humanitarian crises | 15 min.
Josée Poirier, Ph.D., U.N. Office for the Coordination of Humanitarian Affairs
Weather forecasting: Enel's point of view | 15 min.
Marco Formenton, Ph.D., The Enel Group
Discussion | 30 min.
Moderator: Kathy Pegion, Ph.D., GMU

5:00 pm ADJOURN

Day 2: Wednesday, August 25

11:00 am Session 5: Modeling Centers and Operational Forecasters

SubX use at CPC | 15 min.
Matt Rosencrans, NOAA CPC
ESPC SubX use at the U.S. National Ice Center | 15 min.
Alexandra Darden, U.S. National Ice Center
Discussion | 30 min.
Moderator: Scott.S.Sandgathe, Ph.D., APL/UW

12:00 pm Session 6: Public Health & Insurance Industry

Applications of SubX for air quality, fire, and smoke | 12 min.
Samantha Kramer, Ph.D., Sonoma Technology
Impact-based decision support services in human health | 12 min.
Wassila Thiaw, Ph.D., NOAA Climate Prediction Center
Presentation Title TBD | 12 min.
John Balbus, M.D., M.P.H., National Institute of Health
Discussion | 24 min.
Moderator: Matt Rosencrans, NOAA CPC

Break (1:00 - 3:00 pm)

3:00 pm Session 7: Defense and Maritime

14 Weather Squadron use of SubX for optimizing military planning and intelligence assessments | 15 min.
Justyn Jackson, U.S. Air Force
Navy ESPC system overview and products | 15 min.
Matthew Janiga, Ph.D., U.S. Navy
Discussion | 30 min.
Moderator: David McCarren, U.S. Navy

4:00 pm Session 8: Research Community Use

Advance subseasonal predictability research using SubX database | 15 min.
Hyemi Kim, Ph.D., Stony Brook University
S2S prediction of extreme air quality events (dust storms and wildfires) | 15 min.
Daniel Tong, Ph.D., George Mason University
Discussion | 30 min.
Moderator: Kathy Pegion, Ph.D., GMU

5:00 pm ADJOURN

Day 3: Thursday, August 26

11:00 am Session 9: Feasibility vs User Needs

S2S forecasts for US west coast oceanography and fisheries applications | 15 min.
Michael Jacox, Ph.D., NOAA Southwest Fisheries Science Center
Subseasonal forecasts for coastal oceans and ecosystems | 15 min.
Andrew Ross, Ph.D., NOAA Geophysical Fluid Dynamics Laboratory
Discussion | 1 hour 30 min
Moderator: Matt Rosencrans, NOAA CPC

Break (1:00 - 3:00 pm)

3:00 pm Session 10: Recommendations For Moving Forward

Summary and Looking Forward | 15 min.
Organizing Committee
Discussion | 1 hour 30 min.
Moderator: Ben Kirtman, Ph.D., University of Miami
Wrap-up | 15 min.

5:00 pm ADJOURN