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Advances in Sub-seasonal to Seasonal Prediction Relevant to Water Management in the Western United States

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VIRTUAL WORKSHOP ON SUB-SEASONAL TO SEASONAL CLIMATE FORECASTING FOR WATER MANAGEMENT IN THE WESTERN U.S.

What: Scientists and stakeholders came together to discuss forecast priorities for western U.S. water resource management and to review existing and emerging methodologies that can improve prediction of precipitation, circulation regimes, and atmospheric rivers at lead times of weeks to months.

When: 15–17 March 2022

Where: Virtual; hosted by IRI, Columbia Climate School

Water management in the semi-arid western United States (U.S.) is a challenging endeavor that evolves from year to year based on large-scale atmospheric and oceanic conditions. This region has frequently experienced prolonged periods of drought with substantial socioeconomic impacts; the most recent instance involves California entering its third consecutive drought year. As context for the economic implications of drought, California's enacted state budget for the Fiscal Year 2021-22 authorizes more than $600 million for the California Department of Water Resources for providing immediate drought support to local water agencies (CA State Budget 2021a); this amount is part of a package of more than $5 billion over four years for water resilience and drought preparedness (CA State Budget 2021b). For drought preparedness, state and local water managers would like to rely on skillful forecasts on timescales that span the spectrum between weather forecasts and climate predictions. Despite recent improvements in developing sub-seasonal (2- to 6-weeks lead) and seasonal (2- to 6-months lead) prediction systems that compete with and/or outperform existing dynamical and statistical models (e.g., Gibson et al. 2021, Switanek et al. 2020, DeFlorio et al. 2019), forecasting limitations have hindered crucial management decisions for western U.S. water managers, especially related to longer-lead planning, budgeting, resource allocation, and better preparedness for wet and dry extremes (DeFlorio et al. 2021). Improved understanding of physical phenomena and processes governing weather and climate extremes and utilization of emerging forecast methodologies are critical to developing skillful S2S forecast products relevant to water management.

To provide a platform for cross-community dialog between researchers and water managers and review the latest scientific advancements in sub-seasonal to seasonal (S2S) prediction, a workshop was organized in March 2022, jointly by the Columbia University Climate School's International Research Institute for Climate and Society (IRI), Jet

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Propulsion Laboratory (JPL), University of Arizona (UArizona), and Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography with support from the California Department of Water Resources (CDWR). The workshop was motivated by the increasing demand for more accurate S2S predictions with the potential of providing water managers with adequate lead time for mitigation and response planning. The specific objectives were to:

- Connect climate researchers and forecasters with stakeholders to facilitate and promote applied science research;
- Learn from state and local water managers regarding their forecast product priorities for informed decision-making;
- Gain insights into the challenges associated with skillful S2S prediction in the western U.S.;
- Provide an up-to-date assessment of our current capabilities for simulating processes governing S2S predictability in the U.S. West;
- Introduce new forecasting methodologies, including empirical, dynamical, hybrid, and machine learning approaches; and
- Discuss future research directions for developing S2S forecast products tailored for the water management community.

The workshop was organized into three half-day sessions, each with a specific focus. About 80 participants, including climate researchers and forecasters, hydrologists, and water managers, attended this workshop, with participation from several federal agencies (e.g., National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), Department of the Interior, U.S. Army Corps of Engineers), state agencies (e.g., CDWR, Western States Water Council), research centers, and international institutes and universities. The workshop began with an invited session on "*Meeting Stakeholder Needs*", with invited speakers from the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, NOAA River Forecasting Center, CDWR, and the Salt River Project. The second day focused on "*Predictability Assessments*" to understand the potential sources

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of skill and their limits of predictability on S2S timescales. The third day's theme was "*New Forecasting Methodologies*", which included empirical, dynamical, hybrid, and machine learning approaches for developing forecast products (probabilistic and deterministic) that can aid in more efficient water management.

A summary of the main findings and discussions from the workshop is presented below. The complete program and recordings of talks from all three sessions can be accessed online at https://iri.columbia.edu/s2s-water-workshop-2022/.

Stakeholder Forecast Needs for Efficient Water Management

The invited stakeholder talks highlighted the needs and potential value of reliable prediction of precipitation (J. Jones, CDWR), snowpack, and streamflow (B. Svoma, SRP; J. Lhotak, NOAA CBRFC), and their associated impacts on both short-term and long-term horizons for operational decisions (Figure 1). Efficient management of water resources involves political and socio-economic considerations, namely, public health and safety, minimum supply requirements during extreme drought conditions, and prioritization of water use for balancing consumption in fisheries, agriculture, municipalities, etc. The talk by J. Jones (CDWR) highlighted that important policy decisions, like initial water supply allocations for the California State Water Project, must be made at the beginning of the wet season in the western U.S. which receives ~75% of its annual precipitation from November through March. In spring, snowmelt runoff forecasts during the snowmelt season (March through July) help water managers in planning strategies to meet the state's water supply needs. Skillful forecasts, including those of heatwaves and warm rains, can greatly improve water managers' ability to handle challenges related to capturing and storing runoff induced by spring flows in systems with significant snowmelt runoff.

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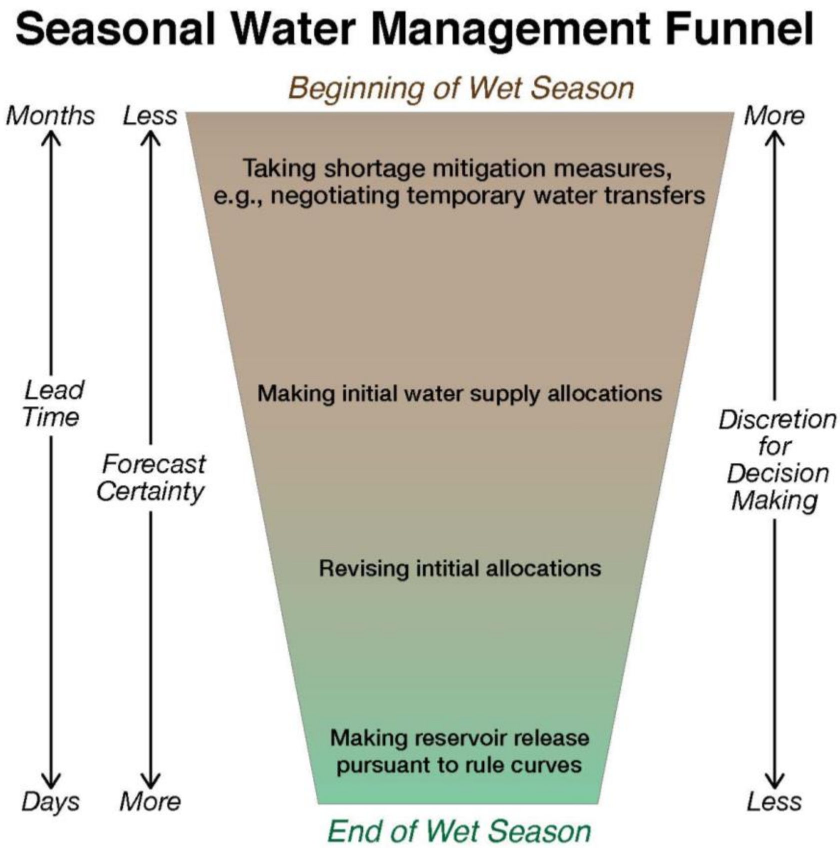

Fig. 1. (from J. Jones's workshop talk) Lead times necessary for different drought preparedness and response measures vary over daily to monthly timescales during the climatological wet season (winter), demonstrated here as a function of forecast certainty and discretion that water managers have in decision making. Note that initial water allocations must be made several months in advance when forecast uncertainty is the greatest.

Emerging research-and-operations partnerships and related success stories were highlighted which provide promising pathways moving forward. One such collaboration involves the CDWR, NASA-JPL, and academic institutions including CW3E/Scripps, IRI, and UArizona. This multi-university project led by NASA-JPL seeks to provide water resource managers in the western U.S. with innovative experimental tools for S2S precipitation forecasting (talk given by M. DeFlorio, UCSD; DeFlorio et al. 2021). It is the sole project in the World Weather Programme/World Climate Research Programme S2S Prediction Project's (Vitart et al. 2012) Real-Time Pilot Initiative (Robbins, 2020) (http://s2sprediction.net/xwiki/bin/view/dtbs/RealtimePilot) that focuses on water in the western United States; White et al. (2017, 2022) survey S2S forecast applications across various socioeconomic sectors. The talk by C. Talbot (USACE) drew attention to the Forecast Informed Reservoir Operations (FIRO) initiative, which is another important western U.S. collaboration (Jasperse et al. 2015, 2020; Talbot et al. 2019). FIRO involves the

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incorporation of weather and hydrological forecast information into water control manuals and water management decisions of retaining or releasing water at reservoir sites in the western U.S. after careful viability assessments, e.g., at the Russian River Basin (Lake Mendocino), the Santa Ana River Basin (Prado Dam), and the Yuba-Feather River Basins (New Bullards Bar and Oroville Dams).

In addition to the above applied scientific research partnerships, the concept of crowdsourcing competitions to improve S2S forecasts for water management was presented by K. Nowak (USBR). The U.S. Bureau of Reclamation has partnered with the U.S. National Integrated Drought Information System (NIDIS) to organize two real-time S2S Climate Forecast Rodeo competitions (https://www.usbr.gov/research/challenges/forecastrodeo.html), which spanned over 13 months each during 2017-18 (Rodeo I) and 2019-20 (Rodeo II). Their goal was to identify forecast tools that enhance S2S forecasting at lead times ranging from 15-42 days that would allow water managers to better prepare for hydrologic regime shifts, e.g., the onset of dry or wet weather extremes.

Workshop recommendations included continued support for research that bridges science and applications and guides the development of decision support tools at S2S lead times, which has historically received less research funding in comparison to weather and climate scales.

Sub-seasonal to Seasonal Predictability Assessments

Forecasting at lead times of weeks to months remains a challenging scientific problem. The success in predicting the state of the major driver of interannual variability—El Niño Southern Oscillation (ENSO), most notably for the 1997-98 El Niño and 1998-99 La Niña episodes, has often led to heightened expectations for skillful forecasts of precipitation at longer lead times (noted by D. DeWitt, NOAA CPC). But ENSO explains only a fraction of the interannual variation in precipitation over California, and its signal-to-noise ratio is such that unexpected outcomes can often occur (Wang et al. 2017, Cash et al. 2019). This was evident during the major El Niño event of 2015-16, which failed to provide the expected hydrologic relief to the Southwest, and a devastating drought continued instead. The skill of available precipitation forecasts degrades beyond a 2-week lead time, rendering them sub-optimal for decision-making. S2S forecasting, thus, remains far from being a solved problem.

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Research on better understanding and representing influential atmospheric, oceanic, and land-surface processes in our Earth system that give rise to predictability remains fundamental for generating seamless forecasts that connect weather and climate scales. This session covered various key physical phenomena, from landfalling atmospheric rivers (ARs) to the tropical-extratropical teleconnections associated with the Madden-Julian Oscillation (MJO), interactions between the stratosphere and the troposphere, teleconnections tied to the state of the tropical oceans, along with land-atmosphere interactions governing predictability.

ARs, which are long and narrow plumes of enhanced horizontal water vapor transport in the lower troposphere, were shown to be influential for winter precipitation in the U.S. West with a multitude of hydrometeorological impacts. These storms often act as "drought busters" alleviating existing drought conditions and replenishing reservoir levels. Recent progress in the domain of AR research was presented at the workshop (Z. Zhang, UCSD; D. Nash, UCSB), including assessments of sub-seasonal skill in hindcast systems of state-of-the-art dynamic models. Encouraging results indicate useful model skills in predicting AR occurrences up to 2-3 weeks in advance. For sub-seasonal forecasts, the MJO—the dominant component of tropical intraseasonal variability— provides a source for extended range predictability in the U.S. West in the boreal winter by exciting atmospheric Rossby wave trains giving rise to extratropical teleconnections. While recent investigations have shown that forecast models can skillfully predict the MJO up to 3-4 weeks ahead, specific advances were presented in this session related to changes in intensity and frequency of extremes over this region under different phases of MJO (J. Wang, UCSD). For example, during phases 6 and 7 of the MJO associated with enhanced convection over the western Pacific, there is substantially more AR activity in the earlier part of the wet season (October−December) compared to the latter half (January−March). MJO impacts are also strongly modulated by the stratospheric Quasi-Biennial Oscillation (QBO). Under the easterly phase of the QBO, an eastward-extended trough tends to be found over the West Coast, facilitating more organized moisture transport and a higher frequency of landfalling ARs. In this regard, the role of the stratosphere and, in particular, sudden stratospheric warming events (SSW) of the Northern Hemisphere winter, which have lagged influence on North American hydroclimate, is increasingly being recognized. More research is needed to better understand the mechanistic processes governing the stratosphere-troposphere coupling and the causes and variability of SSW events. Similarly, the modulation of wet/dry extremes by different phase combinations

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of the MJO and QBO has not been explored fully with the potential for extending predictability out to months.

On seasonal timescales, the climate system derives predictability from slowly varying, influential components with large thermal inertia, e.g., sea surface temperatures (SSTs). Anomalous SST conditions exert remote influences through a variety of teleconnections associated with changes in the atmospheric circulation patterns, as well as by inducing low-level temperature and moisture advection by climatological winds. In recent years, the marginal success in predicting the deviations of winter seasonal rainfall over California has primarily been associated with the success in predicting the state of the ENSO. In addition, the role of the Indian Ocean in mediating the ENSO-related precipitation teleconnection to North America has also been noted. E. LaJoie (NOAA CPC) presented an experimental water year outlook tool conditioned on the Oceanic Niño Index and demonstrated the value of capturing forecast skill as a function of the direction of the forecasted anomalies relative to the observed. Yet as was highlighted in this workshop by X. Jiang, UCLA, even a skillful ENSO prediction would only lead to an explanation of about 25% of California's precipitation variability. The low prediction skill of winter precipitation is attributed largely to model shortcomings in simulating the ENSO-independent, anomalous Pacific circulation, which is an important driver of year-to-year California precipitation variability. Promising results are nonetheless starting to emerge from a variety of methodologies, including nudging experiments (W.-T. Hsiao, CSU) that correct tropical and high latitude fields toward the observed state. A more comprehensive understanding of the processes driving the anomalous atmospheric circulation patterns associated with California precipitation needs to be obtained, and related investigations into the precursors and their detection are warranted. Workshop recommendations emphasized the development of forecast tools that consider cross-timescale interactions among different climate drivers (also noted in the talk by Á. Muñoz, IRI). The need to develop consistent process-oriented diagnostics/metrics that target the underlying physical mechanisms was also endorsed.

Emerging Forecast Methodologies

Another focus of the workshop was on the emerging technical methods, including empirical, dynamical, hybrid, and machine learning approaches. This session highlighted a suite of experimental sub-seasonal and seasonal forecast products (both probabilistic and

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deterministic) with potential for uptake as decision support tools by the applications community.

Probabilistic forecasts derived from dynamical models are based on the spread of the ensemble members, which relate to the small perturbations in model initializations that grow rapidly with time. Dynamical forecasting talks included IRI's calibrated sub-seasonal forecasts based on the Subseasonal Experiment (SubX; Pegion et al. 2019) and calibrated seasonal forecasts based on the North American Multi-Model Experiment (NMME; Kirtman et al. 2014) which provide seamless prediction capabilities starting from 1 day to 6 months in advance. In addition, weather regimes that seek to capture the recurrent patterns of atmospheric circulation (dominant ridges/troughs) provide further temporal context and daily guidance with opportunities for action based on seamless days (talks given by B. Singh and Á. Muñoz, IRI). On the other hand, statistical forecasts have historically relied on linear relationships between lagged spatial fields of predictors and the predictand. Presentations highlighted advances in statistical forecasting beyond the canonical methods, including approaches that attempt to capture the recurrent patterns, including lower-frequency sources, governing predictability in space and time (via the use of extended-empirical orthogonal function analysis, A. Sengupta, UCSD). Innovative hybrid techniques (dynamical models combined with empirical strategies) were also presented. One project, led by P. Gibson (NIWA), focused on the viability of training various machine learning algorithms, including deep neural networks, on large ensembles of climate models to circumvent the issue of limited data record length and then to test the model (trained in model space) on historical observed data for predicting widespread spatial clusters of precipitation. Another talk, given by W. Scheftic (UArizona), presented a two-stage hybrid post-processing system for combining seasonal climate model data with empirical climate relationships (oceanic and atmospheric teleconnection patterns) to create ensemble forecasts of snow mass, temperature, and precipitation. A machine learning framework was also proposed by A. Altinok (NASA JPL) for localized processing of precipitation data to train models at the individual grid cells and consider the effect of local topography.

Many of the forecast tools discussed at this workshop (developed using hindcast skill assessments) routinely generate and communicate winter precipitation outlooks at the beginning and midway through each wet season (at venues like CDWR's late fall Winter

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Outlook Workshop) and support decisions on efforts needed for statewide water conservation campaigns and drought preparedness activities.

Concluding Remarks

As the weather and climate across the western U.S. become more variable and droughts more frequent and widespread, water managers will increasingly need longer-lead time information on potential future water supply conditions to better prepare for S2S extremes. The S2S timescale represents a frontier that shows promise for providing reliable outlooks weeks to months in advance for supporting efficient water management. The workshop offered the opportunity for climate forecasters and researchers to interact directly with water management professionals, identify forecast priorities, and collaboratively take stock of the challenges associated with improving predictions. Together with success stories of science-based research and operations partnerships highlighted at the workshop, the new forecasting approaches will hopefully foster further investigation of underlying processes using Earth science data and ultimately culminate in the development of decision support tools.

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