Sub-seasonal to seasonal climate products for hydrology and water management
Final Report
PIs: Andy Wood and Balaji Rajagopalan
September 28, 2020

1. General Information

Project Title: Sub-seasonal to seasonal climate products for hydrology and water management
PI/co-PI names and institutions:

- NCAR PI: Dr. Andy Wood - National Center for Atmospheric Research
- UCB PI: Dr. Rajagopalan Balaji - Civil, Envir. and Architectural Engr. University of Colorado Boulder
- NOAA Co-PI: Dr. Peitao Peng - NOAA/NWS/NCEP/CPC Development Branch
- NOAA Co-I: Yu Zhang - NOAA/NWS/National Water Center

Progress Report Fiscal Year: FY 2020 (NCE)
NOAA Award: NA16OAR4310144

2. Main goals of the project, as outlined in the funded proposal

The proposed project will develop sub-seasonal to seasonal (S2S) climate forecasts products for spatial units that have greater relevance to decisionmakers and users in the water sector. It will focus first on Climate Forecast System version 2 (CFSv2) reforecasts and real-time forecasts to apply various post-processing approaches to enhance the skill and reliability of the raw CFSv2 climate outputs. The project will also investigate use of the North American Multi-Model Ensemble (NMME) data in this capacity if time permits. This objective will be pursued through four objectives:

1. The implementation of time-averaged S2S precipitation and temperature forecast products for USGS HUC4 spatial units over the CONUS domain based on two primary approaches: (a) use of bias-correction and statistical ensemble calibration to generate precipitation and temperature prediction products with enhanced skill; and (b) for benchmarking, simple mapping of raw model forecast precipitation and temperature outputs to HUC units.
2. The development and implementation of probabilistic forecasts of the probability of extreme events within the S2S forecast periods using extreme value methods.
3. Verification of the prediction skill of products implemented through (1) and (2) to raise product awareness and enhance users' understanding of product suitability for follow-on modeling or decision support.
4. Research to operations transition of the approaches and results to Climate Prediction Center (CPC), requiring implementation, evaluation, dissemination and review by end users, validation and finally deployment of scripts and codes in the operational CPC setting.

3. Results and accomplishments

Work in prior reporting periods focused on the development of real-time and retrospective analyses based on both raw and bias-corrected CFSv2 and NMME reforecasts, as well as the initial work to apply a component-based regression post-processing (via a technique called Partial Least Squares Regression, PLSR) to add skill to the climate forecasts at the watershed scale.

In the current reporting period, we have continued the PLSR-based work and submitted a paper (which is nearing publication) to JHM. The PLSR method uses concurrent CFSv2 climate and land surface forecast fields as predictors to condition the raw forecast climate predictions. PLSR forecasts showed promising results in which climate forecast skill is increased above a usability threshold in many watersheds over the four seasons analyzed, but skill improvements were not general to the entire domain

or all forecast initialization times.

An example of the results is shown in Figure 6 for the week 3-4 precipitation forecast. PLSR was simulated with concurrent CFSv2 fields of precipitation and sea surface temperatures (SST). The raw CFSv2 anomaly correlation (ACC) is very low with little to no skill for the 3-4 week precipitation forecasts for most watersheds and seasons. The raw CFSv2 forecasts are lowest during MAM and JJA over the CONUS domain. The post-processed PLSR ACC is higher than the raw CFSv2 forecast for many watersheds and seasons, especially during JJA. The post-processed results do show increases in skill exceeding 0.3 in some watersheds. Specifically, a few watersheds in Texas, New Mexico, and North Dakota during DJF show large increases in ACC where watershed PLSR forecasts become usable. Other watersheds show large increases in skill, but very few have an ACC increase to a usable level.

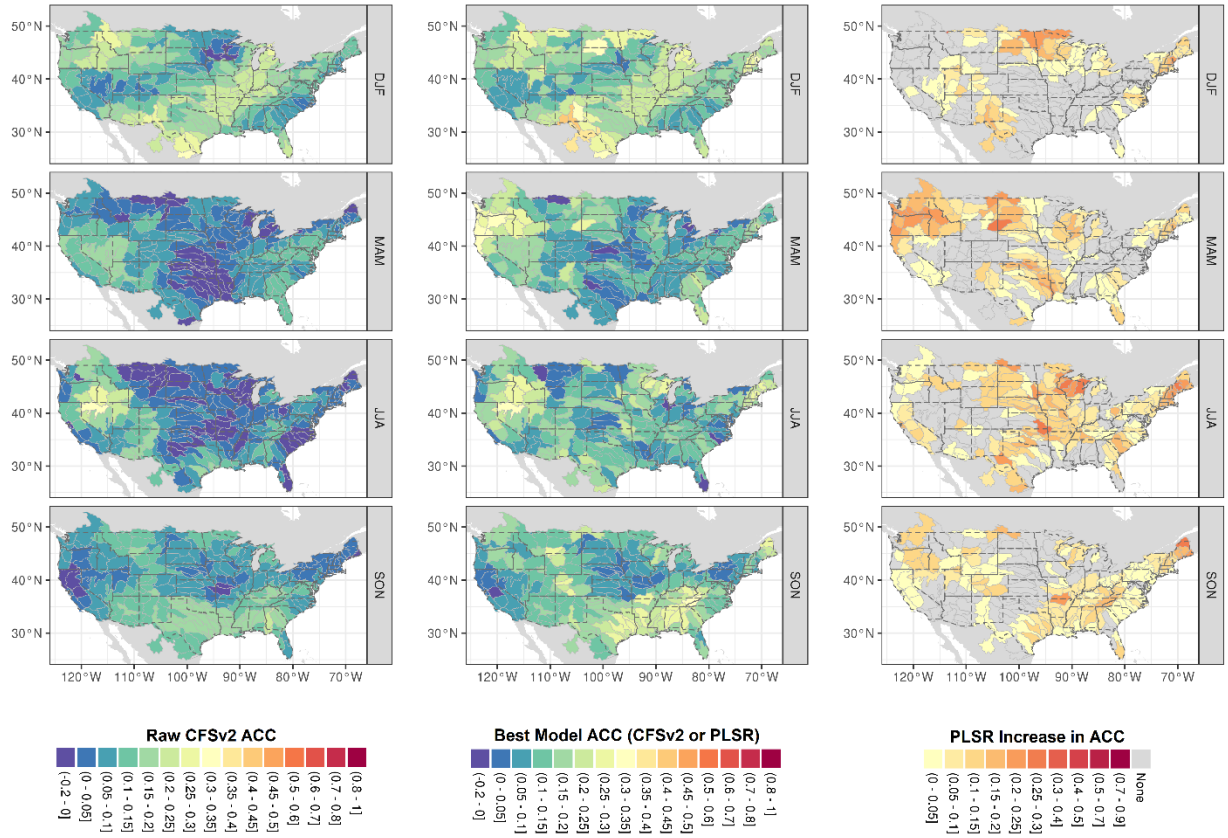

Figure 1. Skill (ACC) results for 3-4 week precipitation forecasts on a seasonal basis. The raw CFSv2 ACC is presented in the left column, the best model (either PLSR or raw CFSv2) ACC is shown in the center column, and the increase in ACC from PLSR is shown in the right column. The watersheds that are not colored (visible as gray) in the right column are where the raw CFSv2 forecast performed better than the PLSR forecast.

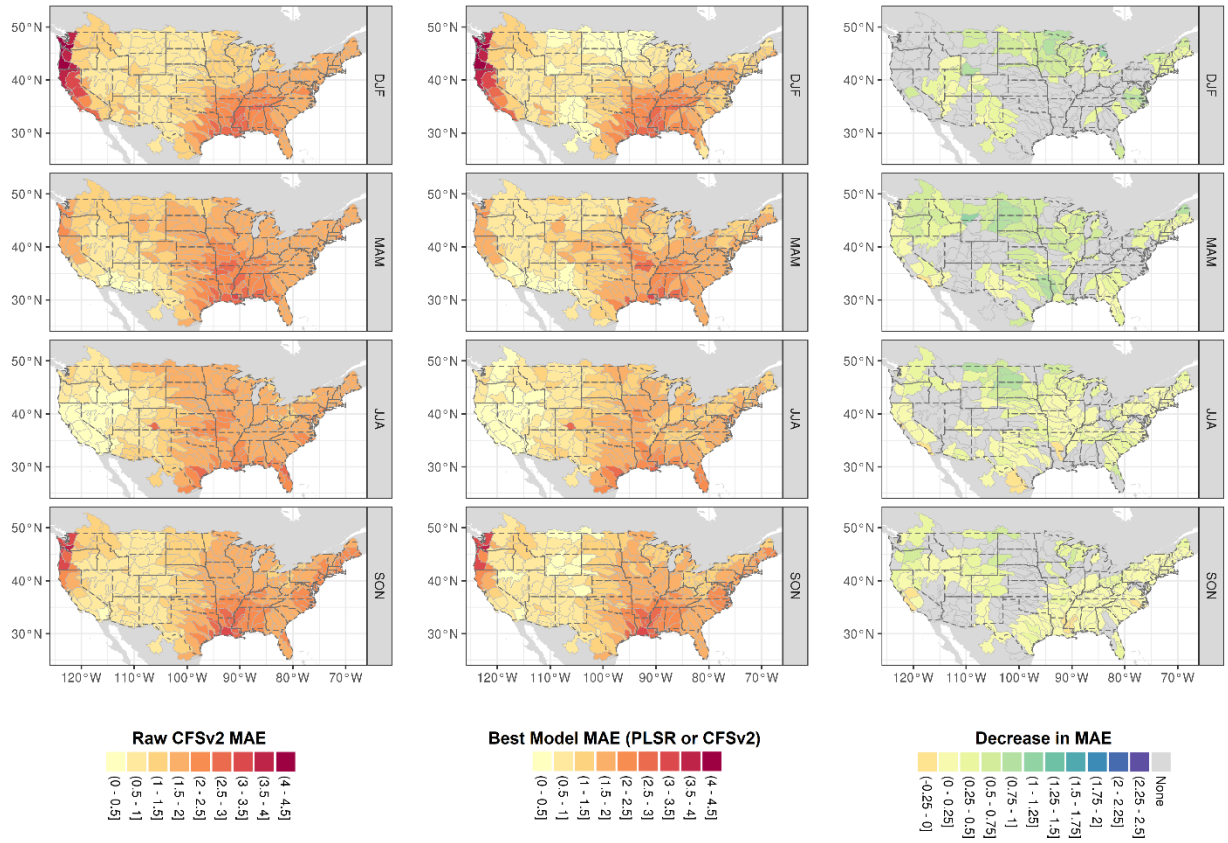

Figure 2. MAE results for 3-4 week precipitation forecasts on a seasonal basis. The format is the same as Figure 1.

A paper detailing these results is currently in review:

- Baker, SA, B Rajagopalan, AW Wood, 2020, Enhancing sub-seasonal climate forecast skill through post-processing at the scales of water management, *AMS J. Hydromet.* (in review).

This effort also progressed toward the application of the climate forecasts in water management, focusing on the upper Colorado River basin. The work had two thrusts. First, it applied climate conditioning to enhance ensemble streamflow inputs for key reservoir inflow locations that are input to a Reclamation reservoir systems model (built in Riverware). Second, the climate-conditioned streamflow inputs were used to assess the benefits of climate forecasting for water management, as measured by the accuracy of reservoir pool storage and release predictions made using the Reclamation management system. Related to the first objective, the study showed evidence of marginal gains for prediction skill when precipitation and temperature forecasts from the NMME were used to weight ensemble members from the ESP technique, which is commonly used in seasonal water management.

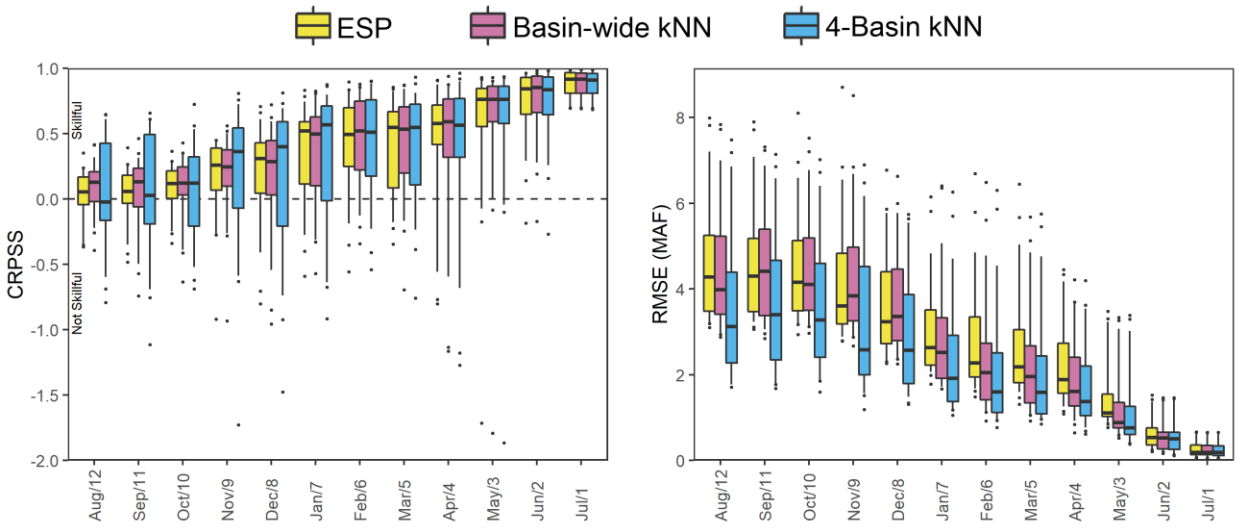

Figure 3. CRPSS and RMSE for runoff season streamflow forecasts of Lake Powell unregulated inflow volumes (April-July), made at monthly lead times of up to 9 months. The streamflow forecasts based on ESP, Basin-wide kNN, and 4-Basin kNN are compared at leads of 12- to 1-month. The two kNN forecasts include NMME-based climate conditioning.

4. Highlights

Below is a list of accomplishment highlights thus far in the project:

- We completed a baseline skill assessment on CFSv2 and NMME climate forecasts at a HUC4 watershed scale on the S2S time scales.
- We developed and applied initial strategies for post-processing (bias-correction) for CFSv2 on the bi-weekly scale, using quantile mapping, removing bias at all leads, while preserving forecast correlations.
- As the first part of the transition plan, we created a real-time system to create the watershed-based climate forecast products, and also web-based tool to display S2S forecasts in real time. CFSv2 forecasts are updated daily with real-time bi-weekly forecasts and NMME forecasts are updated monthly.

In the current reporting period:

- We have completed post-processing of bi-weekly CFSv2 forecasts using PLSR. PLSR forecasts show promising results in which climate forecast skill is increased above a usability threshold in many watersheds over the four seasons analyzed, but skill improvements come with issues associated forecasting extreme events and narrowing of the forecast range.
- A paper has been published describing the PLSR-based forecast calibrations.
- Operational streamflow hindcasts for the upper Colorado River basin were obtained from CBRFC and weighted by climate predictions, leading to improvements in skill. A paper on these results has been submitted.
- These hindcasts were run through the Reclamation water management decision support system to assess how climate forecasts could lead to improvements in reservoir system storage and release forecasting, and potentially on decision-making. A paper on this aspect is underway as of the end of the project period, and is expected to be submitted in Q1 FY21.

5. Transitions to Applications

Over the course of the project, the project team (NCAR/CU) took a number of steps to initiate the transition part of the project. In particular, the project implemented a real-time demonstration prototype system that runs at NCAR and provides an operational proof of concept that represents one step along a progression of technical readiness that is required to read a level appropriate for operational testing in the target environment (ie, CPC). This system and a website to display products has been running for nearly a year with an initial forecast product set, and the next step is to transfer the scripts and other software to CPC for a rudimentary product set while further development continued.

In the prior period, PIs Wood and Rajagopalan met with the CPC point of contact (Dave DeWitt) several times to request starting the transfer stage. Because the project is related to water management, however, CPC suggested that a better target for operationalizing the work would be the National Water Center (which seemed reasonable, but also challenging given the NWC's resource limitations and pressure to prioritize water forecasts). PI Wood contacted personnel at the NWC on several occasions to further this discussion, but without success. Transition efforts stalled out and it does not appear that transition will end up being possible in this project without new capacity being available at the target operational center (CPC or NWC).

6. Publications from the Project

The first and seconds paper from this work have been published. The third paper has been submitted to a journal, and a fourth paper (on the use of NMME-weighted streamflow forecasts for reservoir management in the Upper Colorado River Basin, is in preparation, to be submitted after this grant ends.

- Baker, S.A., A.W. Wood, and B. Rajagopalan. 2019. "Developing Subseasonal to Seasonal Climate Forecast Products for Hydrology and Water Management." Journal of the American Water Resources Association 1–14. https://doi.org/10.1111/1752-1688.12746.
- Baker, S. A., A. W. Wood, and B. Rajagopalan, 2020: Application of Postprocessing to Watershed-Scale Subseasonal Climate Forecasts over the Contiguous United States. J. Hydrometeor., 21, 971–987, https://doi.org/10.1175/JHM-D-19-0155.1.
- Baker, SA, B Rajagopalan, AW Wood, 2020, Enhancing Ensemble Seasonal Streamflow Forecasts in The Upper Colorado River Basin Using Multi-Model Climate Forecasts, submitted, *J. Amer. Water Res. Assn*.

A number of presentations have been given on the project: AGU 2018 (presentation); EGU 2019 (presentation); International S2S/S2D conference in Boulder CO; AMS; 2018 CU Boulder Hydrologic Symposium; AGU 2017 (poster); NMME/S2S meeting in Washington DC; HEPEX/BOM/CSIRO meeting in Australia; and to stakeholders and federal agencies (ie, a symposium for water users at the Southern Nevada Water Authority; and a western US-wide Reclamation Reservoir System Operations meeting); AGU 2019 and AMS 2020.

7. PI Contact Information

NCAR PI: Dr. Andy Wood – andywood@ucar.edu
UCB PI: Dr. Rajagopalan Balaji – balajir@colorado.edu

8. Budget Status

Funds Remaining at NCAR: Yr2: ~$0

Funds Remaining at CU:	Yr2: ~$0
Funds Requested by NOAA/NWS/NCEP/CPC:	Yr2: $0
Funds Requested by NOAA/NWS/NWC:	Yr2: $0

9. Ongoing Work

The majority of the planned project effort has been completed, and the budgets at NCAR and CU have been spent to within a fraction of an hour of work. The PhD student supported under the project completed her studies July 2019, and the remaining funds have supported continued experimentation on post-processing, improvements and extended operation of the real-time demonstration website at NCAR, paper writing and submission, and proposal writing to extend the effort. A second proposal by the PIs in collaboration with CPC to extend the project using OWAQ funding was not successful, although the real-time website is still running at NCAR. Work to further explore the techniques and datasets investigated in this project are continuing, funded internally by Reclamation (where the former student, Sarah Baker, now works full time) and supported where possible through synergistic activities by PIs Wood and Rajagopalan.

Tasks 5-7 were ultimately not achievable due to resource and capacity constraints at NOAA CPC, which did not allow for the transition of the new experimental products to a NOAA operational center. Despite this outcome, the climate forecast products are supporting other federally funded research (by Reclamation) to incorporate S2S climate predictions into operational statistical and model-based water supply forecasts. In particular, the NMME-based forecasts have been applied for conditional weighting of ensemble streamflow prediction from CBRFC, illustrating potential benefits a key Reclamation reservoir management system (a Riverware model) for the Colorado River basin. With further refinement, it is possible that this strategy will be adopted by several Reclamation field offices in the context of real-world reservoir management. PI Wood also has a current grant with Reclamation's office (AAO) that manages the Rio Grande River, which contains development tasks to this effect. There remains a strong interest within the federal water management community toward making better use of climate forecasts in streamflow prediction and water management, and this project is viewed as having highlighted both opportunities worth pursuing as well as still unresolved challenges in this endeavor.

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1 – NMME hindcast download & processing								
2a – Postprocessing HUC S2S P & T forecasts								
2b – Probabilistic Extremes Products								
3 – Skill assessment (verification)								
4 – Real-time Implementation (NCAR & CPC)								
5 – User Engagement and Review from CPC								
6 – Operational Demonstration at CPC								
7 – Operational Testing and Evaluation at CPC								