Final Report

Towards an Enhanced Probabilistic National Drought Forecasting

To the

National Oceanic and Atmospheric Administration

Modeling, Analysis, Predictions, and Projections (MAPP)

Award Number: NA17OAR4310079

Principle Investigator: Hamid Moradkhani

7/29/2018

Preface:
The original award (NOA Grant No. NA14OAR4310234) was terminated as of 9/30/2016 and a portion of the remaining funds was reissued as a new grant with an anticipated period of performance of 5/1/2017-4/30/2018. Prior to NA14OAR4310234 being terminated, Task 1 was completed, and Tasks 2, 3, and 4 were partially completed. As of the termination date of the original award, work on this project continued, and tasks 3 and 4 were partially completed during the interim period of 10/1/16-4/30/17 while PSU awaited NOAA to reissue the transferred award.
The revised work plan, which includes pre-award work completed since 10/1/16 and relates to original Tasks 3, 4 and 7, is as follows:

- Implement the ensemble data assimilation to characterize the land state initial condition uncertainty used for Drought Monitoring
- Implement the probabilistic drought forecast, using the multivariate statistical approach. The sensitivities of the forecast model to different predictors and Copula functions will be evaluated. Forecasts are generated for different lead times.
- Conduct retrospective assessment on drought prediction skills and compare with experienced drought events across the CONUS. In this process both deterministic and probabilistic verification measures are employed

We completed all the above tasks and we even went beyond the project commitments by extending our work to the following:

a. Post-processing of NMME precipitation data, which can be used by the community as a refined forcing data to land surface models for drought monitoring and forecasting and beyond (published work by Khajehei et al., 2017)
b. Assessment of uncertainty of ensemble-based gridded observations in land surface simulations and drought assessment
c. A comparative assessment of projected meteorological and hydrological droughts: Elucidating the role of temperature

Since we provided a final report on the earlier results and achievements of the original project, in this final report we only present the project accomplishments for the period of performance of 5/1/2017-4/30/2018. However, all the publications and presentations reflect all delivered material for both original and amended projects.

1 Results and Accomplishments

1.1 Post-processing of the North American multi-model ensemble (NMME) precipitation forecasts over the continental US

The North American multi-model ensemble (NMME) forecast system provides valuable information for climate variables at different lead times over the globe. A Bayesian ensemble post-processing approach based on Copula functions (COP-EPP) is employed to bias-correct the NMME precipitation forecast from 11 models (totaling 128 ensemble members). The study is conducted over the Continental United States (CONUS) for the hindcast period of 1982–2010 at lead-0, and the forecast period of 2012–2015 at four different lead times of lead-0 to lead-3 and the results are verified using deterministic and probabilistic measures. COP-EPP is compared with a widely-used bias-correction technique, the Quantile Mapping (QM). Although the NMME forecasts show to be more accurate across the eastern United States, large bias is found over the great plains of the central US. However, QM and COP-EPP present significant improvements over the NMME forecasts, with COP-EPP proving to be more reliable and accurate across the CONUS. In addition, COP-EPP substantially improves the temporal and spatial variability of the intra-seasonal NMME forecasts, even at lead-3.

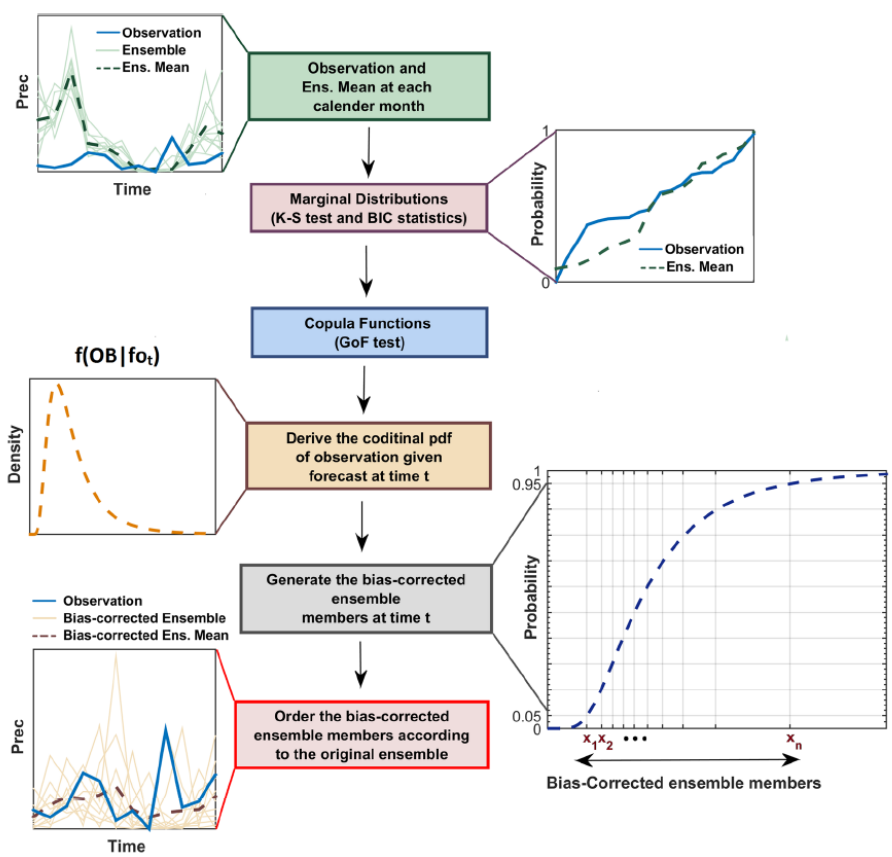

Fig. 1 Schematic procedure of the Copula ensemble post-processing (COP-EPP) used in this study

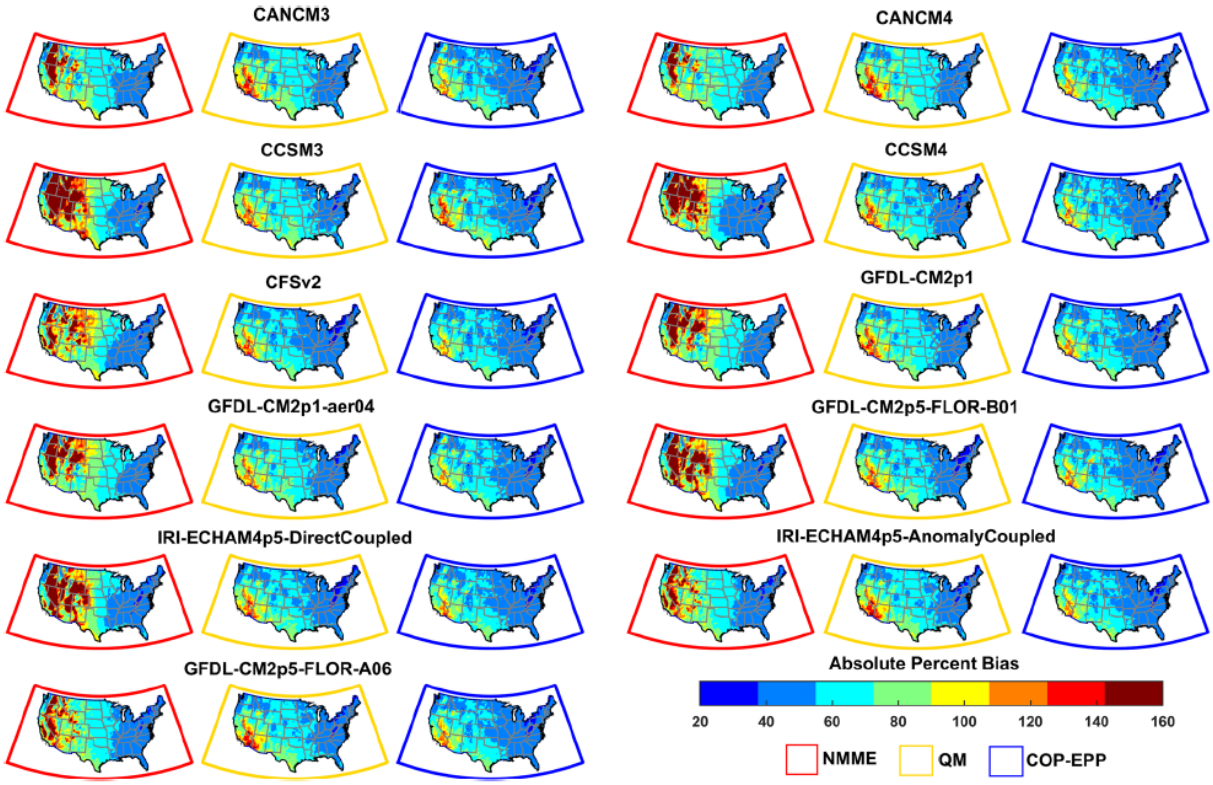

Fig. 2. Absolute percent bias of monthly precipitation calculated for the validation period of 2001–2010 The NMME model and bias-corrected precipitation by QM and COP-EPP methods are presented in red, yellow, and blue boxes, respectively

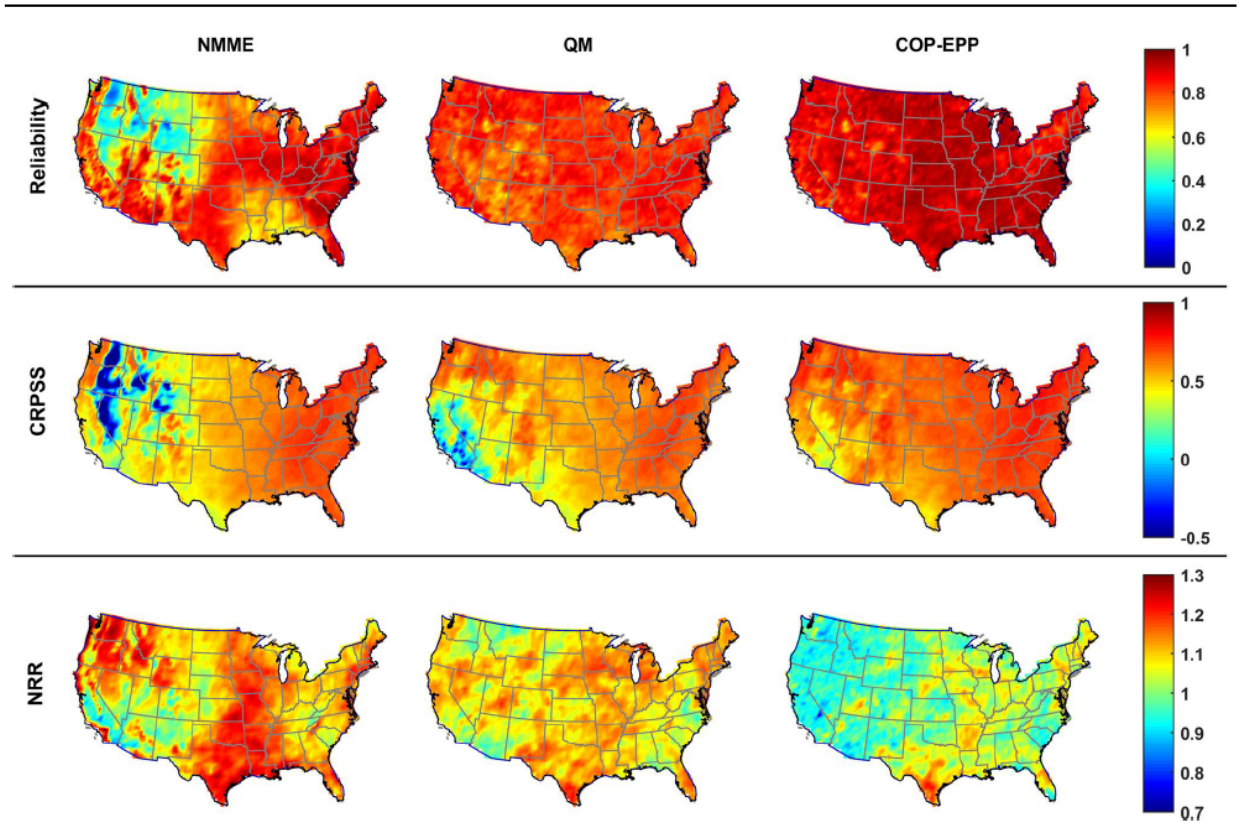

Fig. 3. Probabilistic forecast verification of the NMME (128 ensemble members), QM, and COP-EPP for the validation period of 2001–2010

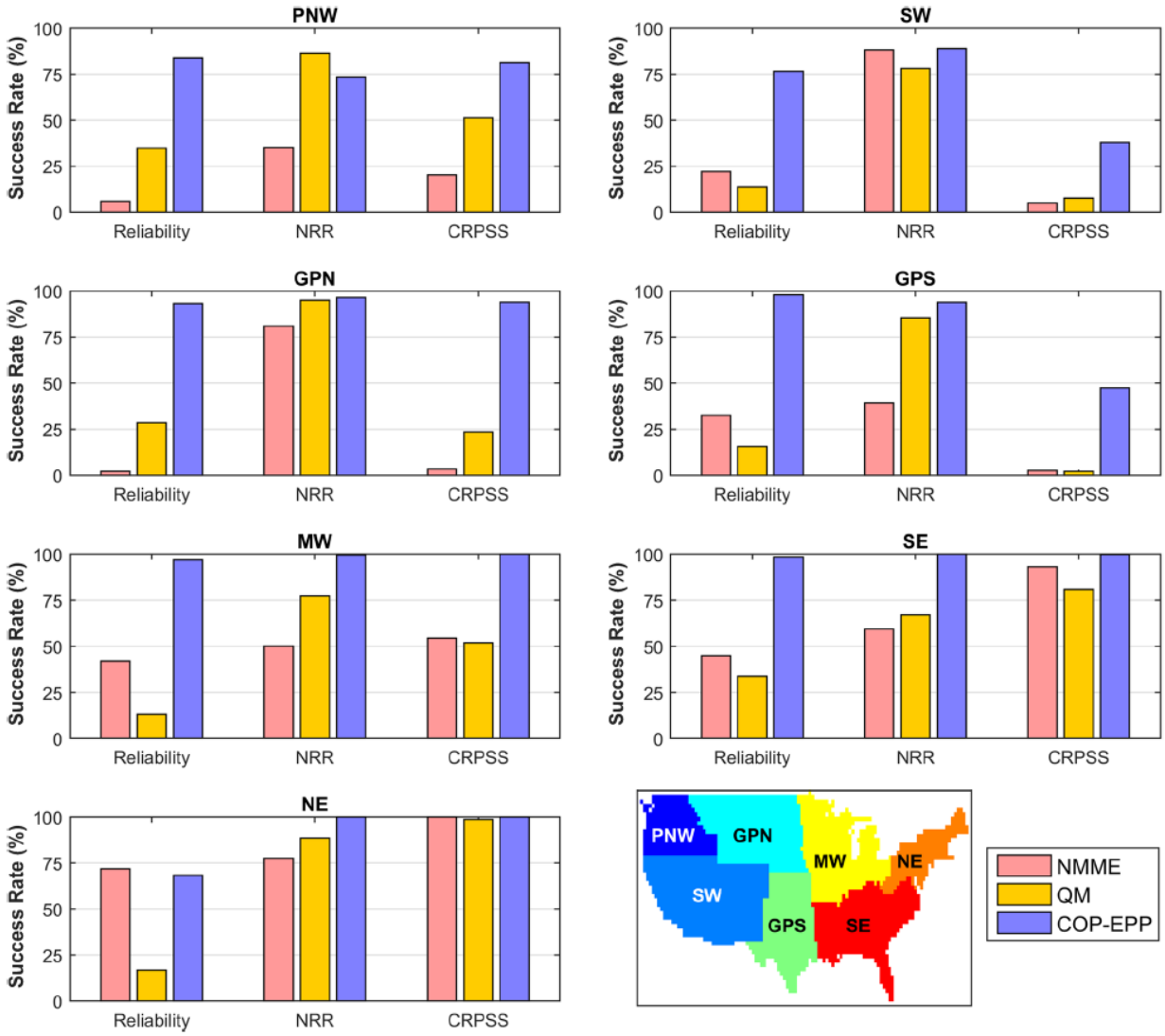

Fig. 4. Success rate calculated for the probabilistic verification measures in seven climate regions of the CONUS

1.2 Uncertainty of ensemble-based gridded observations in land surface simulations and drought assessment

Hydrologic modeling is one of the primary tools utilized for drought monitoring and drought early warning systems. Several sources of uncertainty in hydrologic modeling have been addressed in the literature. However, few studies have assessed the uncertainty of gridded observation datasets from a drought monitoring perspective. This study provides a hydrologic modeling oriented analysis of the gridded observation data uncertainties over the Pacific Northwest (PNW) and its implications on drought assessment. We utilized a recently developed 100-member ensemble-based observed forcing data to simulate hydrologic fluxes at 1/8° spatial resolution using Variable Infiltration Capacity (VIC) model, and compared the results with a

deterministic observation. Meteorological and hydrological droughts are studied at multiple timescales over the basin, and seasonal long-term trends and variations of drought extent is investigated for each case. Results reveal large uncertainty of observed datasets at monthly timescale, with systematic differences for temperature records, mainly due to different lapse rates. The uncertainty eventuates in large disparities of drought characteristics. In general, an increasing trend is found for winter drought extent across the PNW. Furthermore, a ~3% decrease per decade is detected for snow water equivalent (SWE) over the PNW, with the region being more susceptible to SWE variations of the northern Rockies than the western Cascades. The agricultural areas of southern Idaho demonstrate decreasing trend of natural soil moisture as a result of precipitation decline, which implies higher appeal for anthropogenic water storage and irrigation systems.

Table 1. Summary of the characteristics of the gridded observation datasets utilized in this study

Product	Spatial resolution	Temporal resolution	Variables used	Ensemble members used	Precipitation data sources	Interpolation method	Reference
L13	1/16° (~6 km)	Daily, 1950–2013	Prec. Tmax, Tmin, Wind	1	NWS COOP	Inverse distance	Livneh et al. (2013)
N15	1/8° (~12 km)	Daily, 1980–2012	Prec. Tmax, Tmin	100 + Ensemble mean	NWS COOP, NRCS SNOTEL, COCORAHS (GHCN-D)	Probabilistic	Newman et al. (2015)

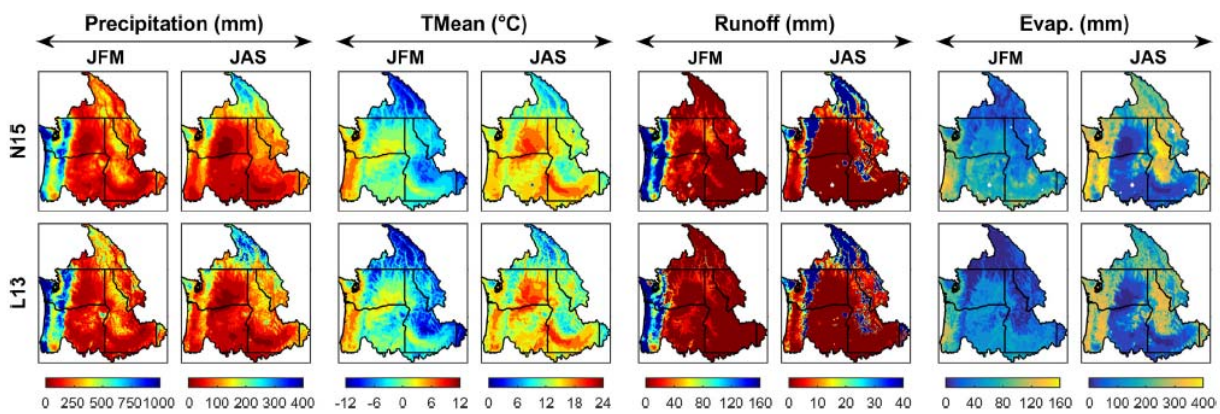

Fig. 5. Long-term seasonal mean of hydro-meteorological variables for the period of 1980–2011.

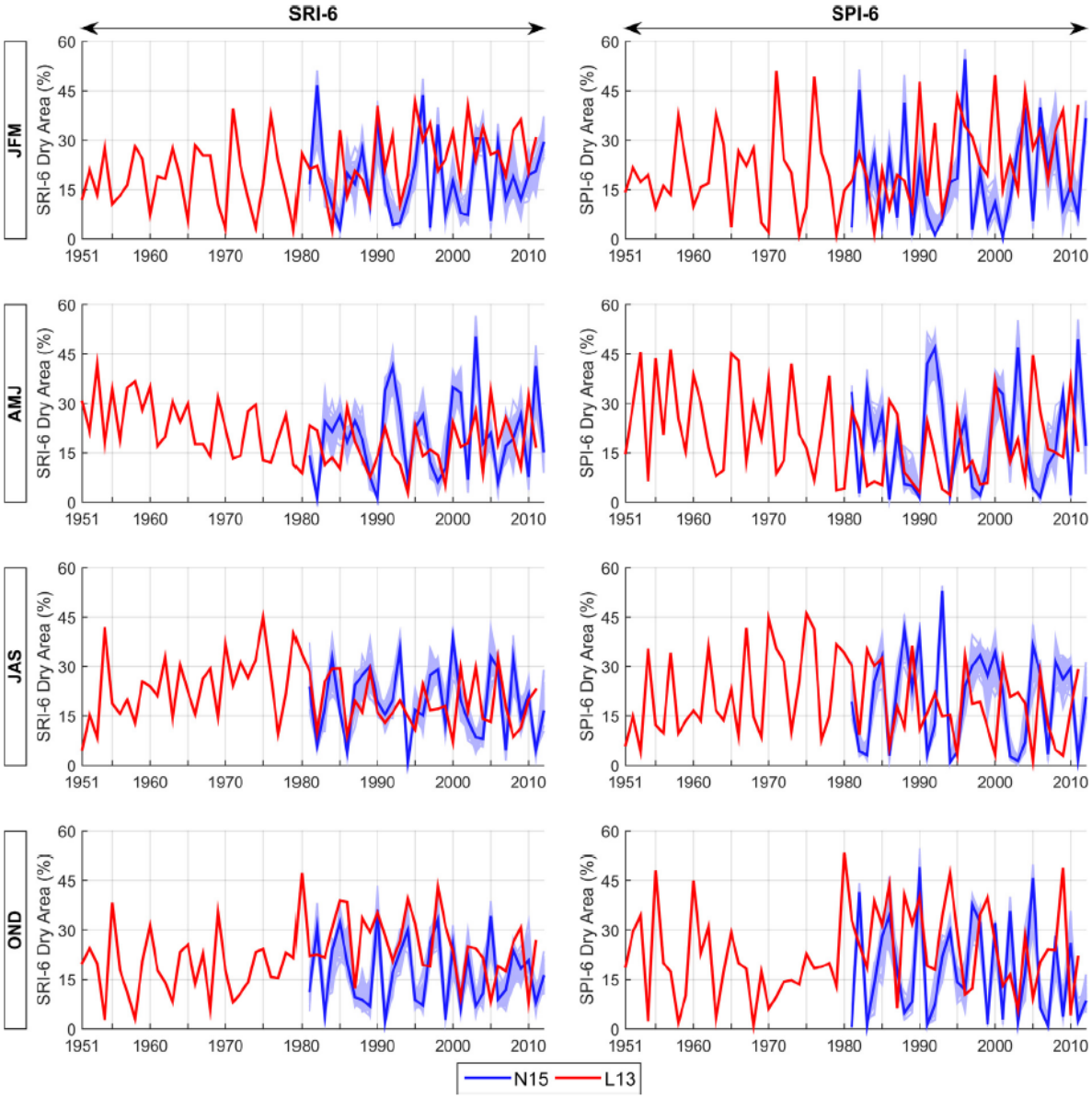

Fig. 6. Time series of mean seasonal drought extent of PNW at 6-month accumulation period for L13 and N15 simulations.

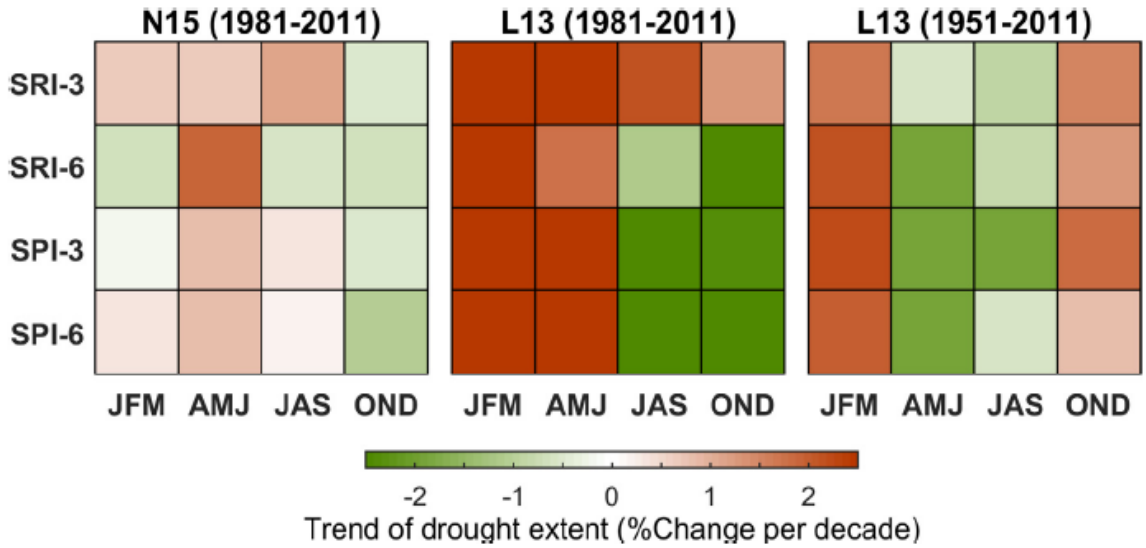

Fig. 7. Linear trend of drought extent in each season presented as the percentage change per decade.

1.3 A comparative assessment of projected meteorological and hydrological droughts: Elucidating the role of temperature

The changing climate and the associated future increases in temperature are expected to have impacts on drought characteristics and hydrologic cycle. This part of study investigates the projected changes in spatiotemporal characteristics of droughts and their future attributes over the Willamette River Basin (WRB) in the Pacific Northwest U.S. The analysis is performed using two subsets of downscaled CMIP5 global climate models (GCMs) each consisting of 10 models from two future scenarios (RCP4.5 and RCP8.5) for 30 years of historical period (1970–1999) and 90 years of future projections (2010–2099). Hydrologic modeling is conducted using the Precipitation Runoff Modeling System (PRMS). Meteorological and hydrological droughts are studied using three drought indices (i.e. Standardized Precipitation Index, Standardized Precipitation Evapotranspiration Index, Standardized Streamflow Index). Results reveal that the intensity and duration of hydrological droughts are expected to increase over the WRB, albeit the annual precipitation is expected to increase. On the other hand, the intensity of meteorological droughts do not indicate an aggravation for most cases. We explore the changes of hydrometeolorogical variables over the basin in order to understand the causes for such differences and to discover the controlling factors of drought. Furthermore, the uncertainty of projections are quantified for model, scenario, and downscaling uncertainty.

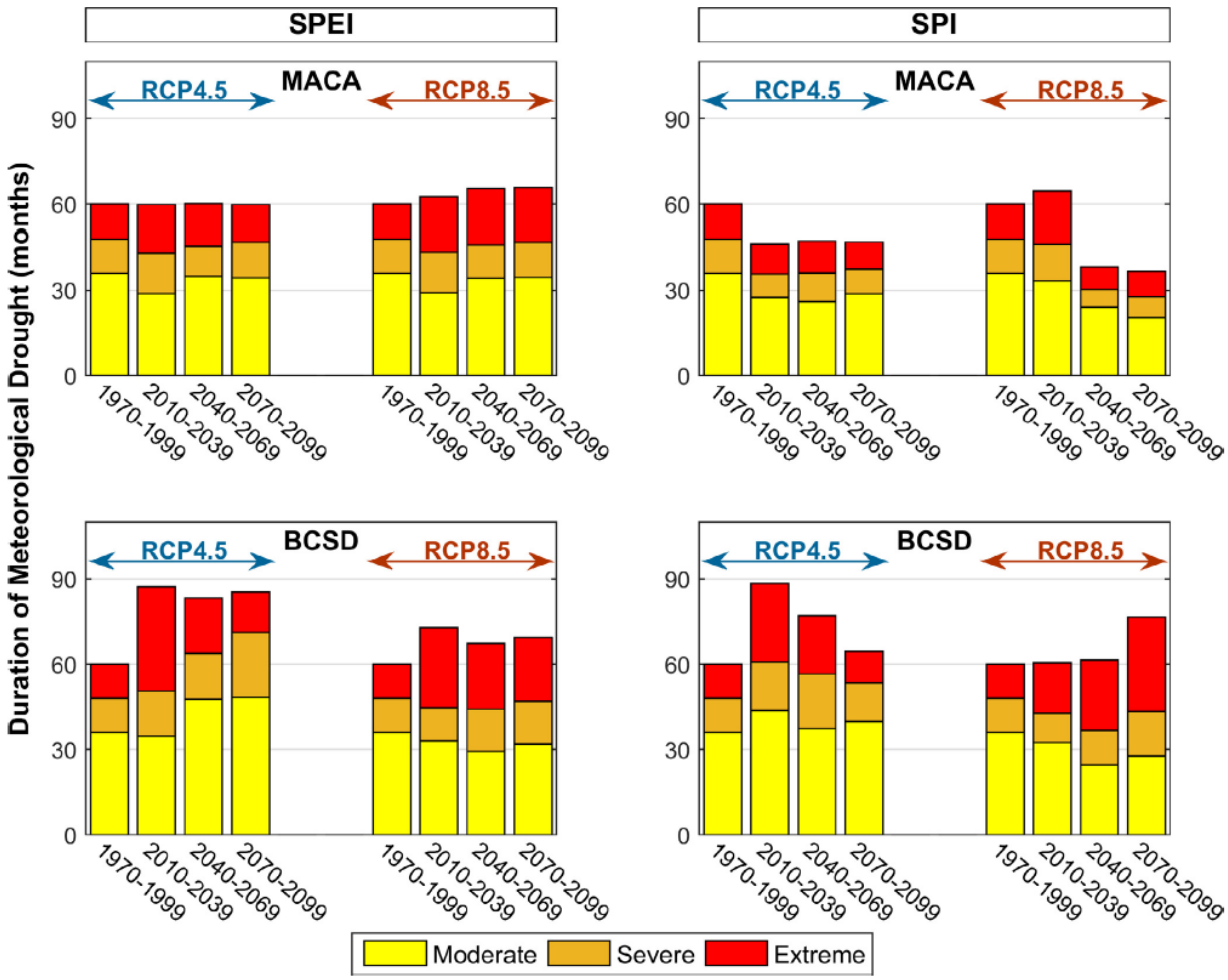

Fig. 8. Duration of meteorological drought in 30-year intervals.

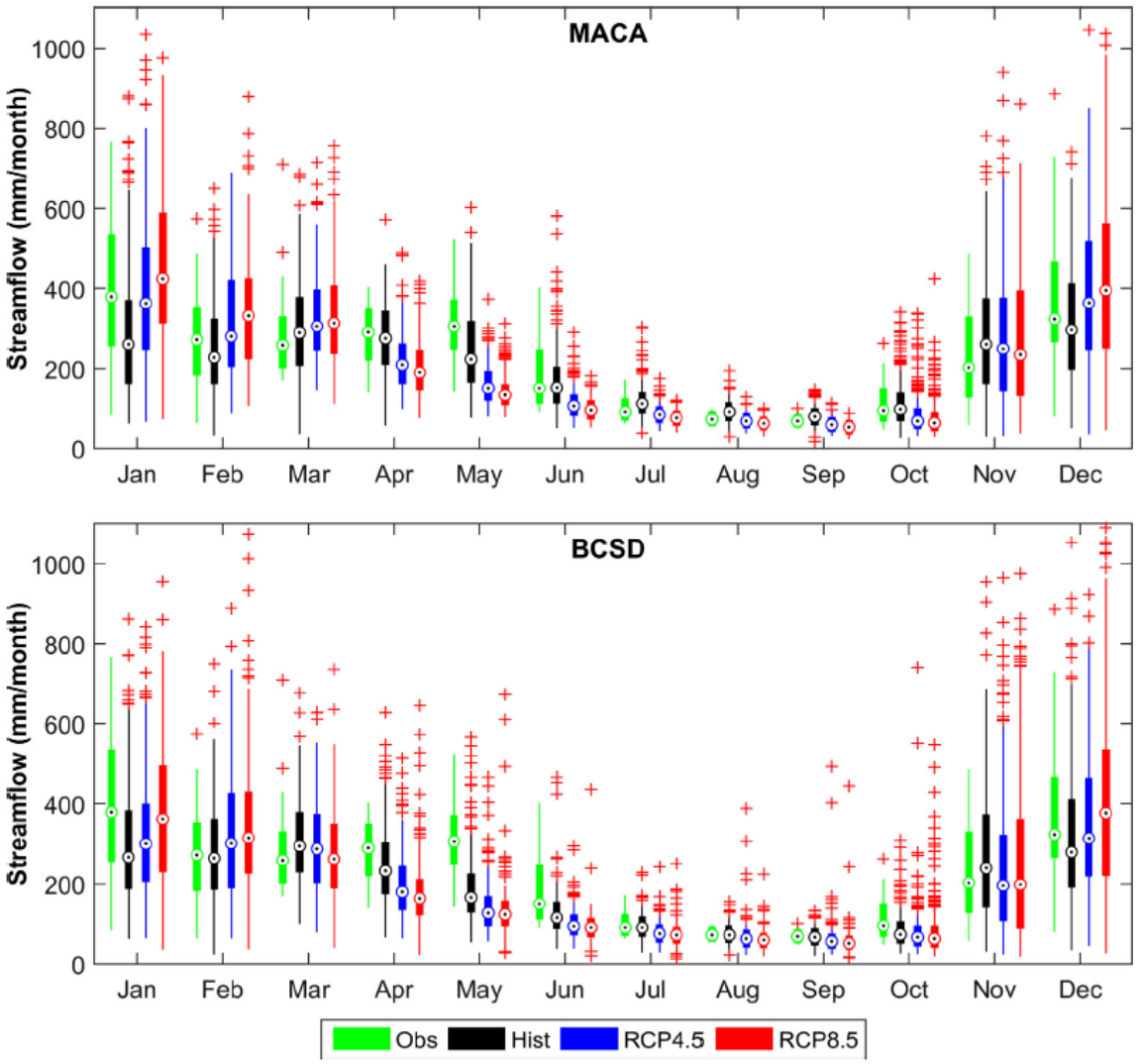

Fig. 9. Observed and simulated monthly streamflow forced by MACA (top) and BCSD (bottom) datasets at the outlet of Willamette Basin.

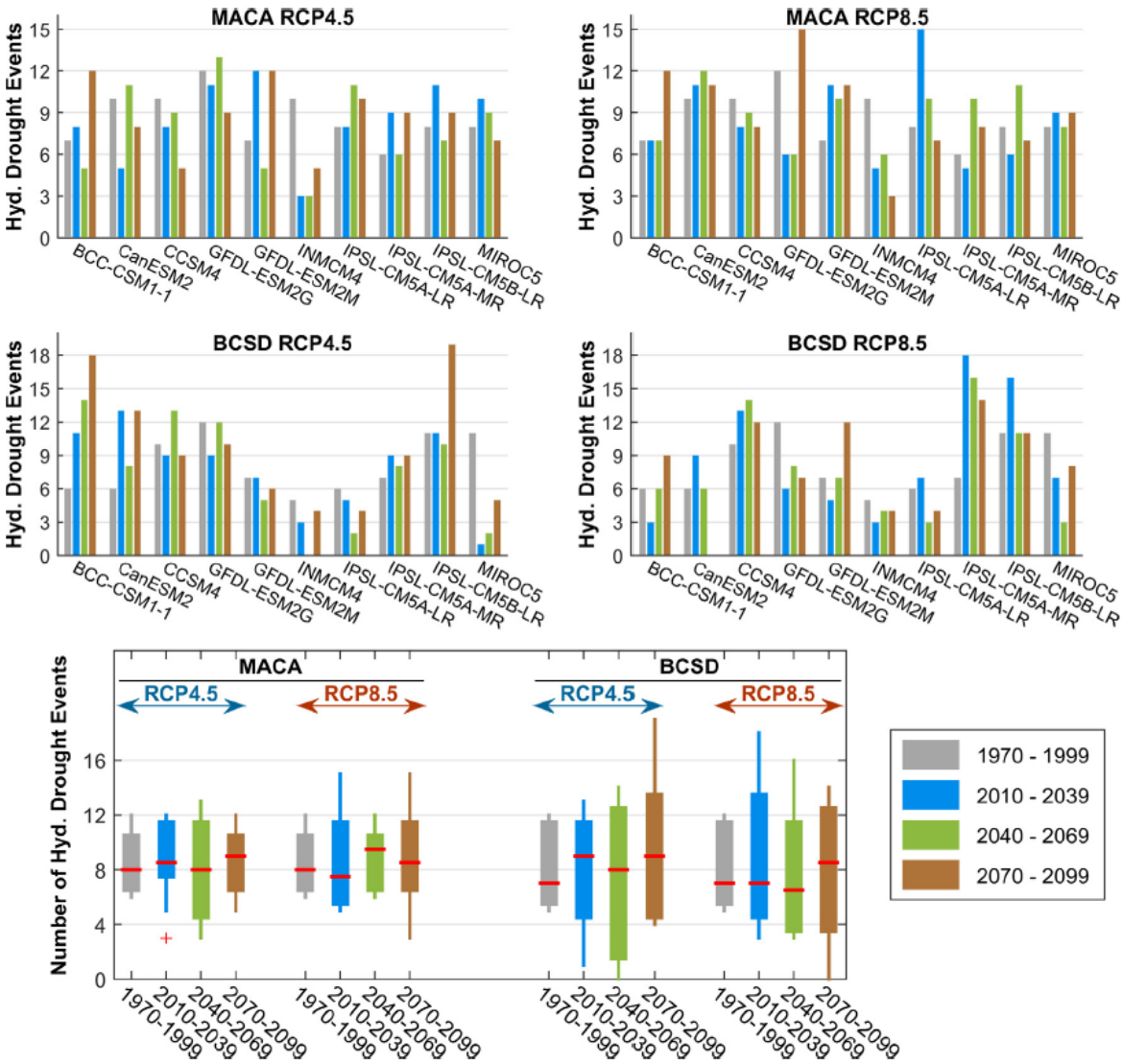

Fig. 10. The number of hydrological drought events for each GCM in 30-year intervals. MACA results are shown in the top panel followed by BCSD in the middle. The boxplots at the bottom are showing the spread of 10 GCMs for each time span.

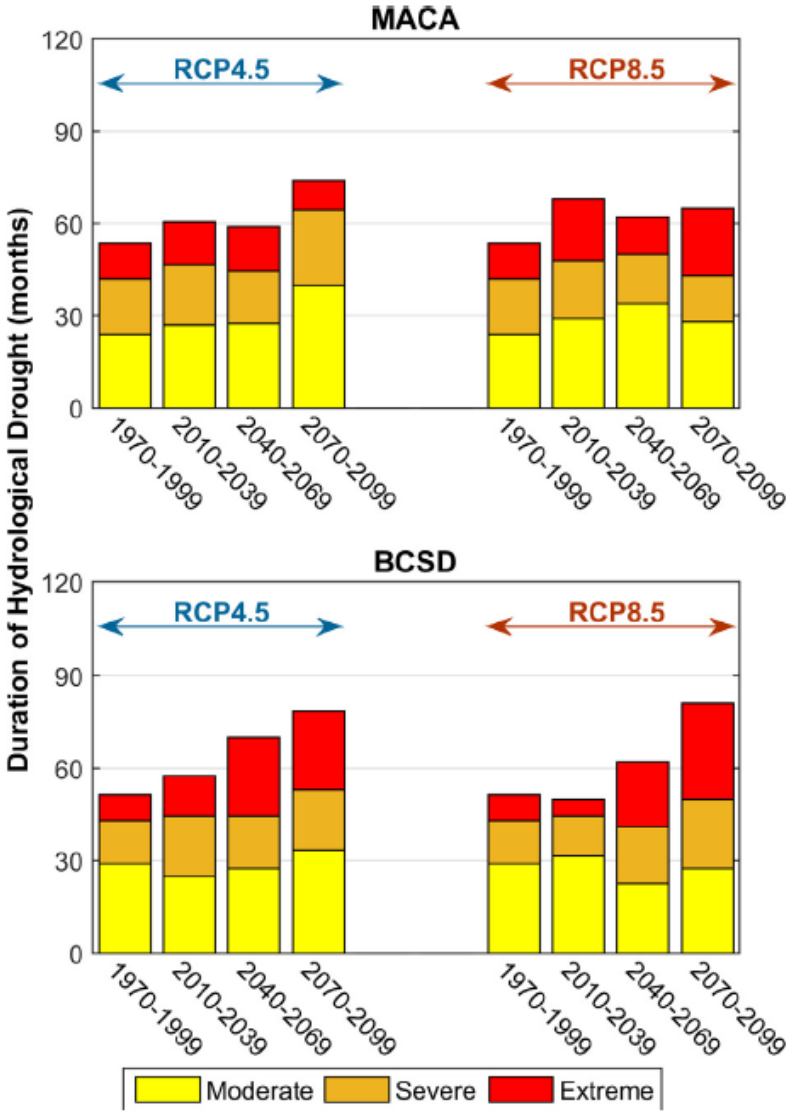

Fig. 11. Duration of hydrological drought in 30-year time intervals. In each case, duration of drought is calculated for each GCM, and then the ensemble mean of 10 GCMs is plotted in the figure.

1.4 A Parallel Particle Filtering Framework for Drought Monitoring using Remotely Sensed Data Assimilation Across CONUS

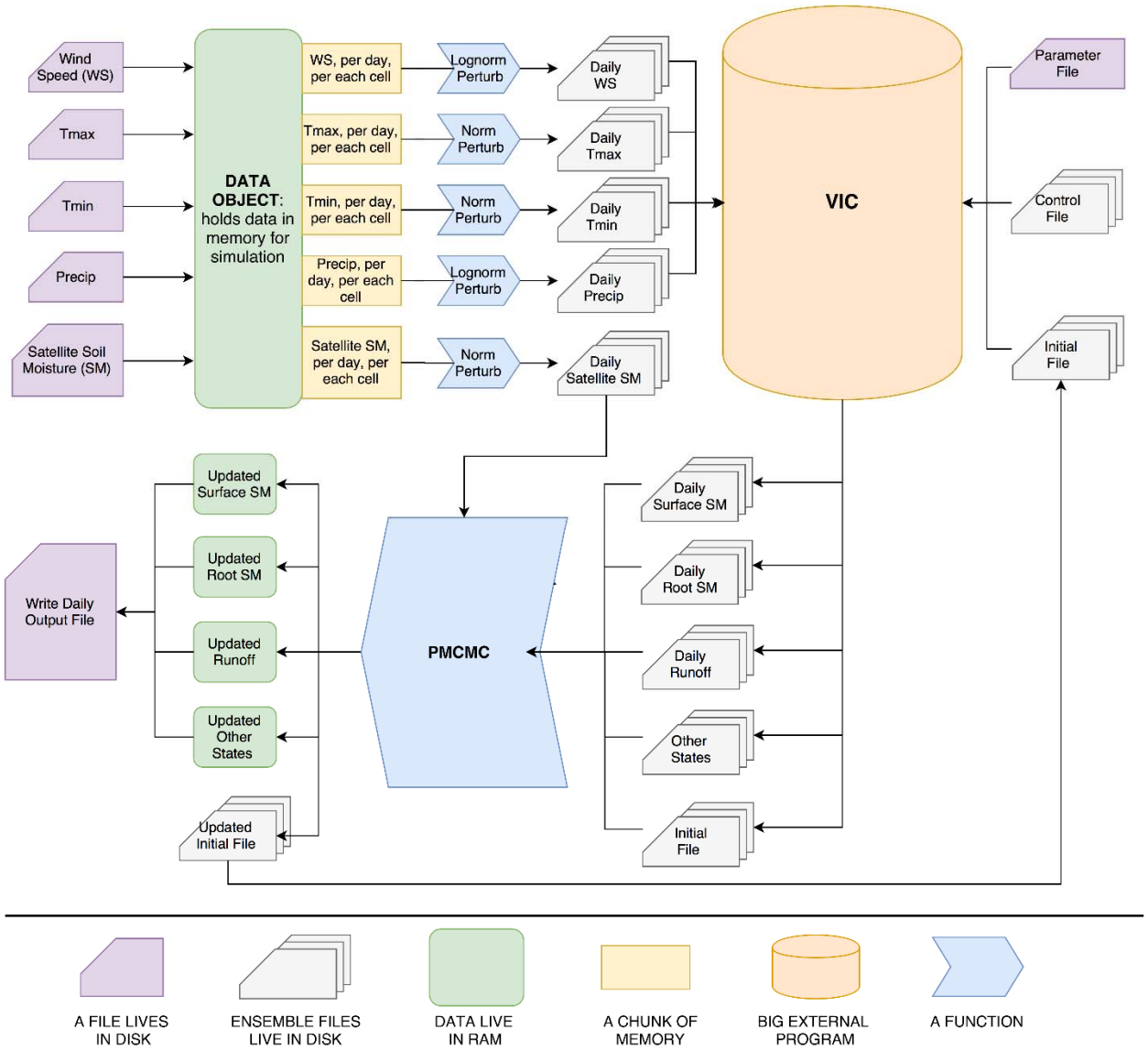

Fig 12. The flowchart of the *offline coupling* interface of the VIC model and the PMCMC data assimilation algorithm. The ensemble files indicate the ensemble members of the PMCMC algorithm. A one-day VIC model simulation and PMCMC updating are shown in this flowchart.

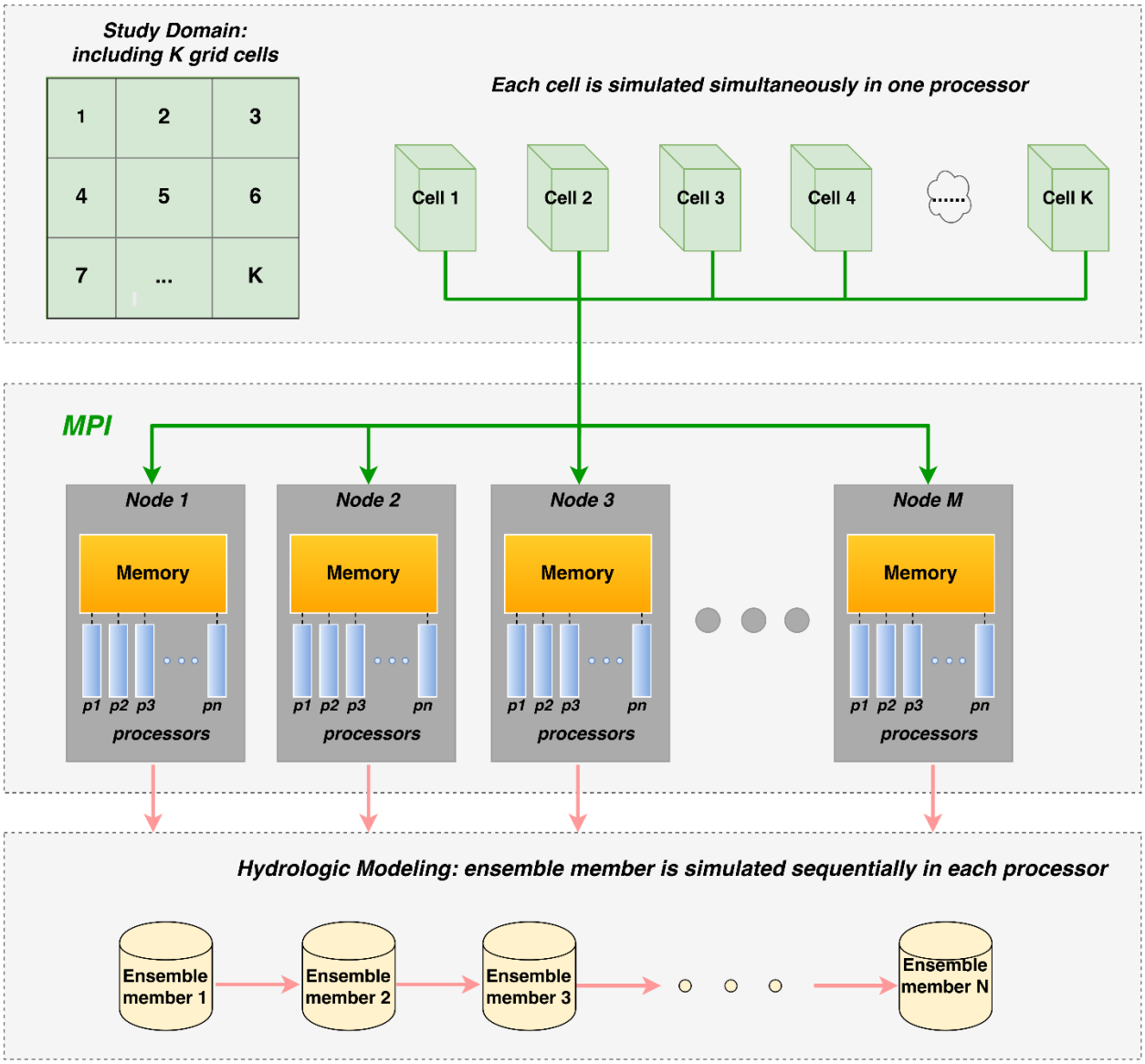

Fig 13. The flow diagram of the parallel particle filtering framework (PPFF) using Message Passing Interface (MPI). The *domain decomposition* parallel strategy is used in the PPFF: each grid cell is simulated in parallel while each ensemble member is simulated sequentially.

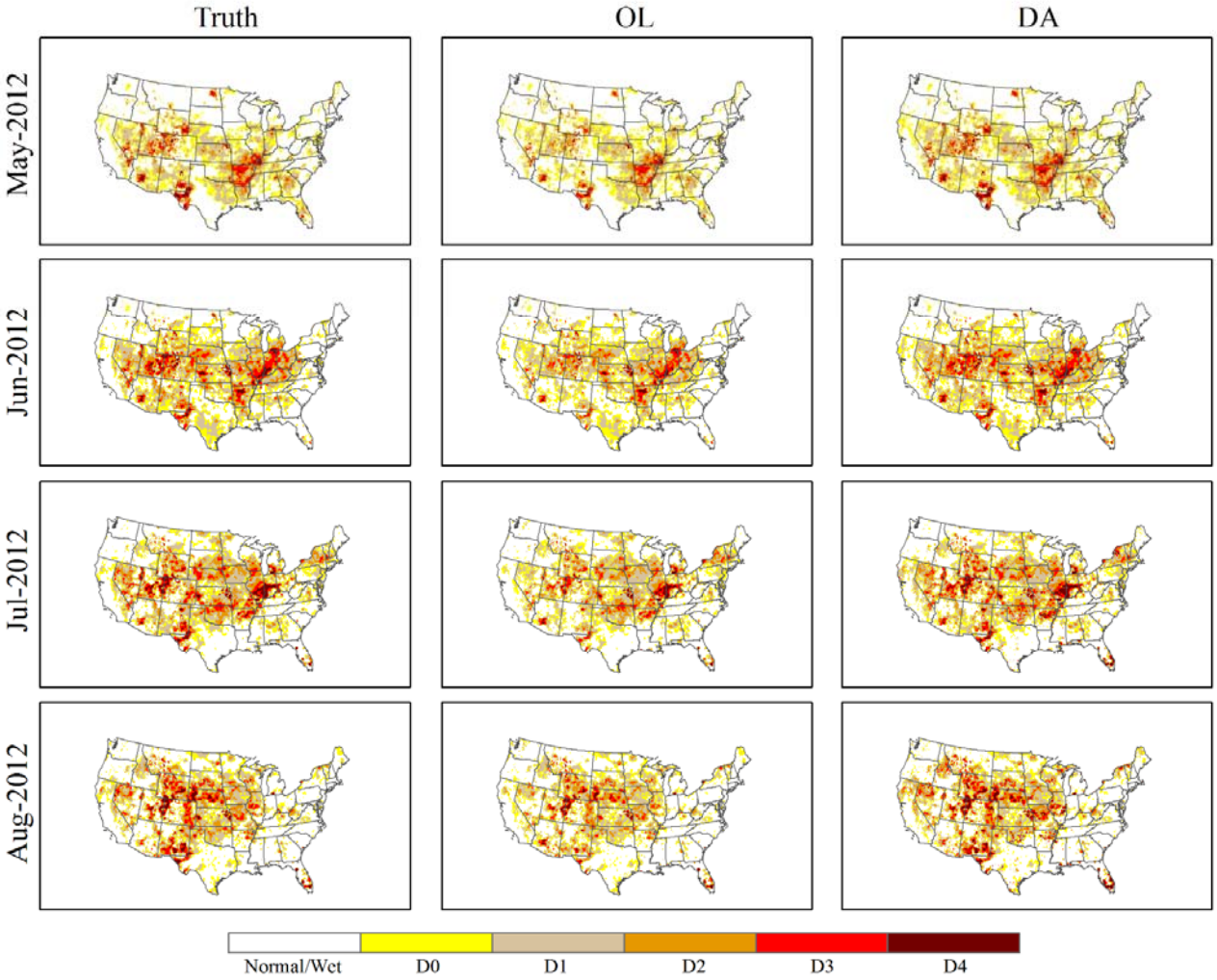

Fig 14. Comparison of the drought monitoring skill between open-loop (OL) and data assimilation (DA) for May-August 2012 (Synthetic Study).

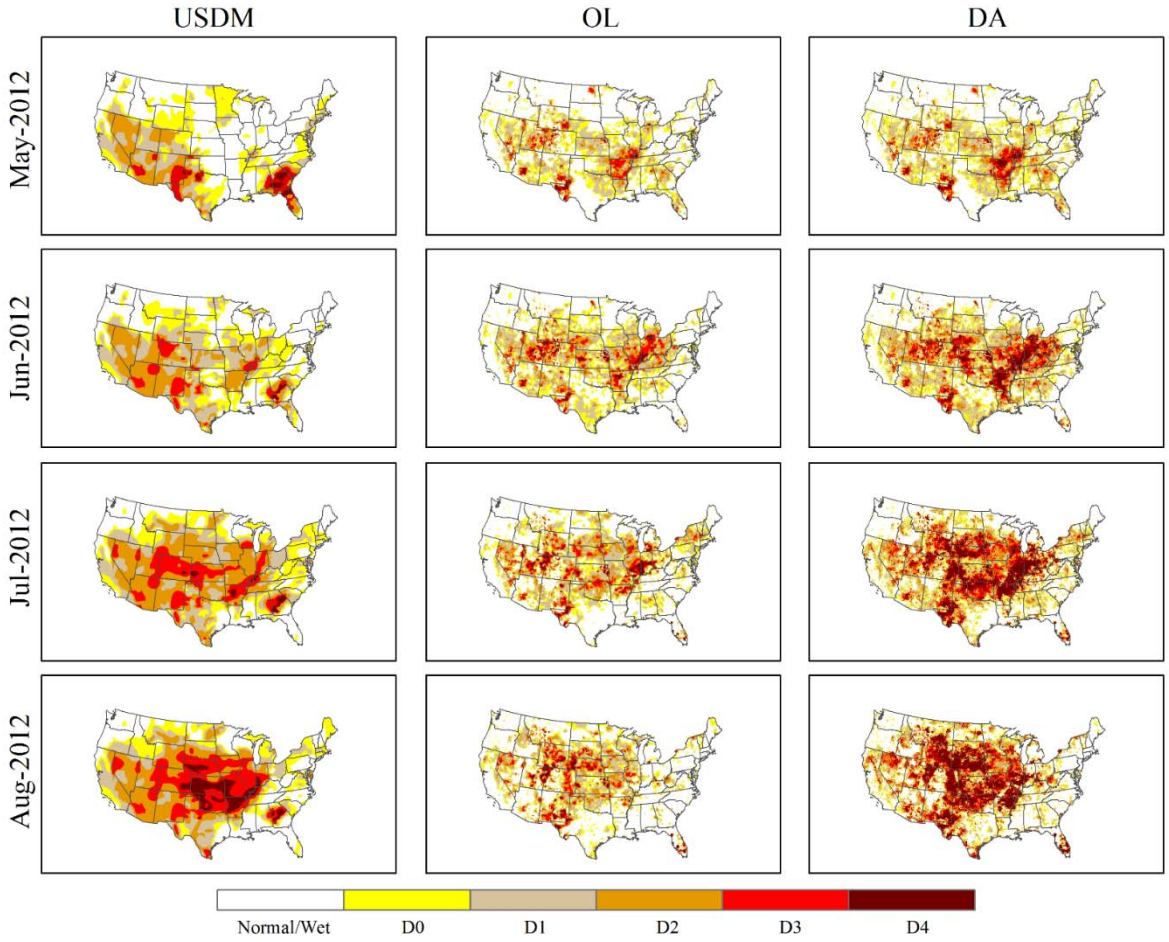

Fig 15. Comparison of the drought intensity over the CONUS from open-loop (OL), data assimilation (DA), and U.S. Drought Monitoring (USDM)

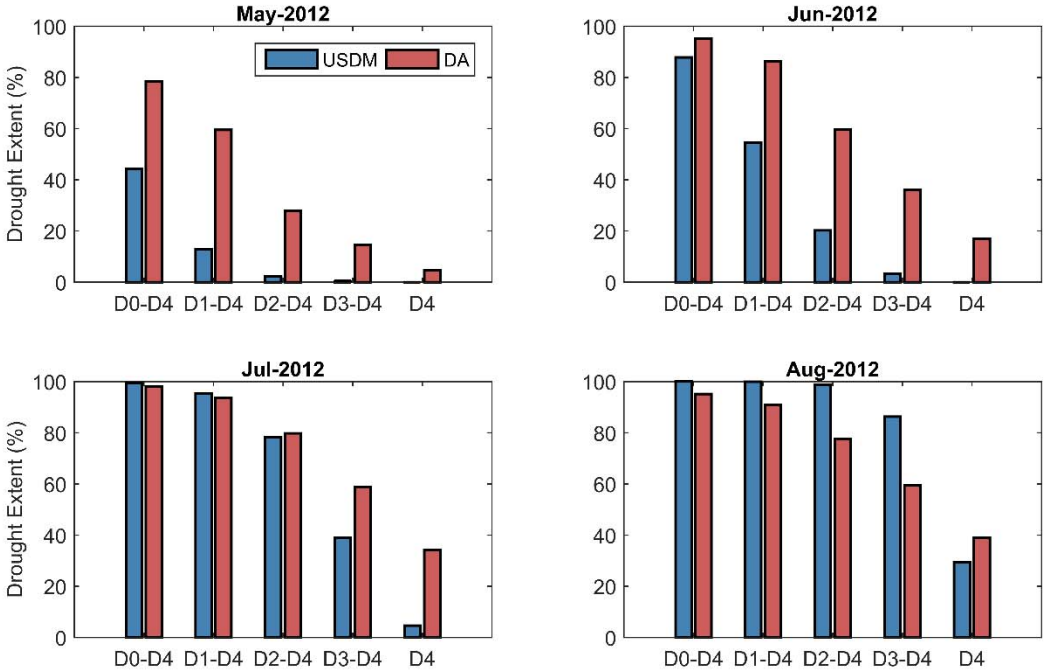

Figure 16. Comparison of U.S. Drought Monitoring (USDM) and Data Assimilation (DA) drought monitoring extent for five different drought categories (D0-D4) over the Central U.S. The drought extent is comprised of the 7-State region of Nebraska, Iowa, Kansas, Missouri, Oklahoma, Arkansas, and Illinois.

1.5 A Dynamical-Statistical Modeling Framework for Probabilistic Drought Forecasting

In order to improve the drought forecasting skills, this part of the study builds on the earlier work we conducted over the pacific Northwest US and present a dynamical-statistical system over the CONUS with a combination of land data assimilation based on particle filtering and a probabilistic drought forecasting model based on multivariate copula functions. The novelty of this hybrid system is to use data assimilation technique to quantify land initial condition uncertainty, as opposed to a single deterministic initial condition implemented in the current operational drought forecasting systems. Consequently, monthly to seasonal drought forecasting products are generated using the updated initial condition. The implementation of the hybrid system is demonstrated with the 2012 summer drought event across the Central U.S. Synthetic study results suggest that the hybrid dynamical-statistical system improves the monthly to seasonal drought forecasting skills. For real case study, compared with the National Oceanic and Atmospheric Administration Climate Prediction Center's Seasonal Drought Outlook, the hybrid system can better forecast the 2012 summer drought event in Central U.S. Also, it is shown how sensitive the monthly to seasonal drought forecasting skill is to the initial conditions, which can better facilitate the state drought preparation and mitigation.

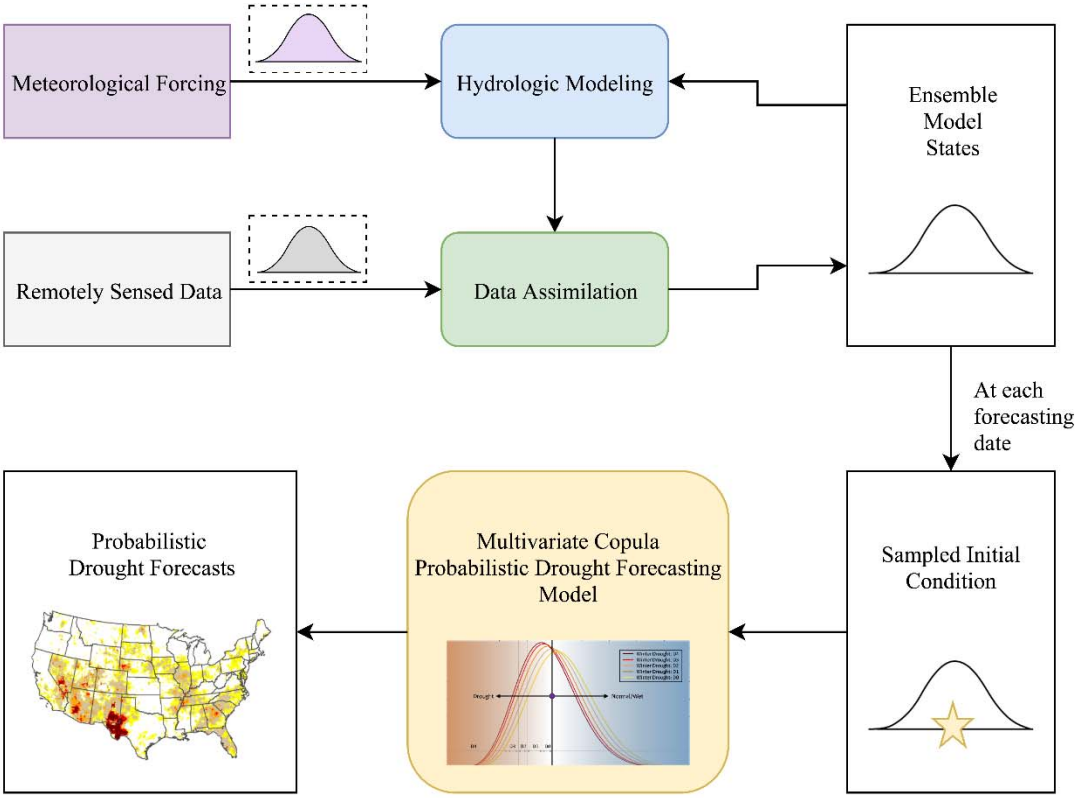

Figure 1. The framework of the hybrid dynamical-statistical drought forecasting system. The four probability distributions associated with the meteorological forcing, remotely sensed data, model predictions, and initial conditions represent the corresponding uncertainties. For each forecasting date, an updated initial condition shown as "yellow star" is sampled from the probability distribution and input to the multivariate copula model to generate probabilistic drought forecasts.

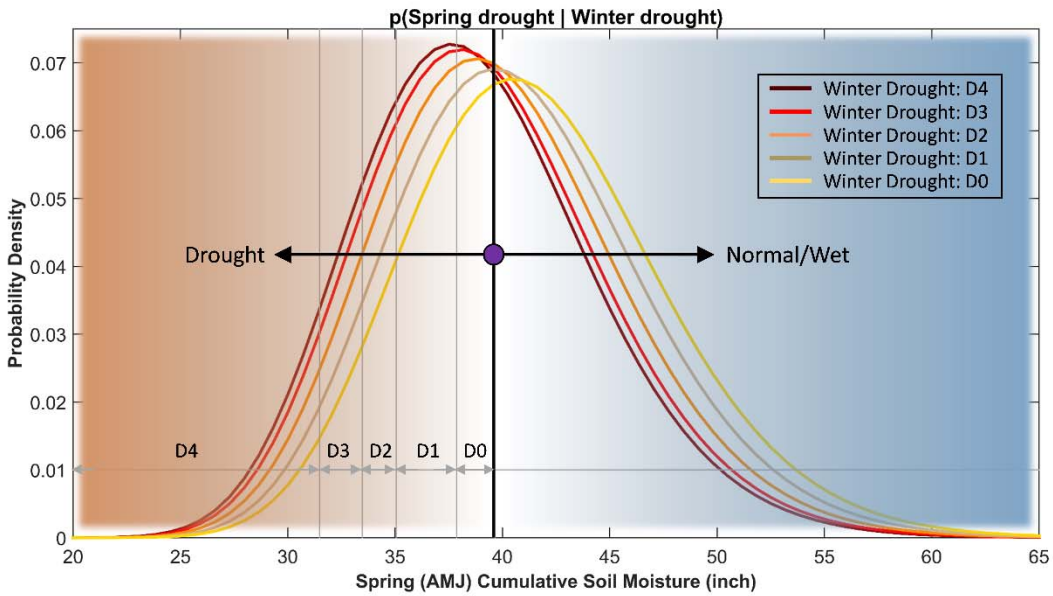

Figure 2. Conditional probability density distributions (PDFs) of spring (April–June, AMJ) cumulative soil moisture given the drought status in the past winter. Each PDF is associated with a particular winter drought status (D0–D4). Darker lines indicate more severe drought in the past winter.

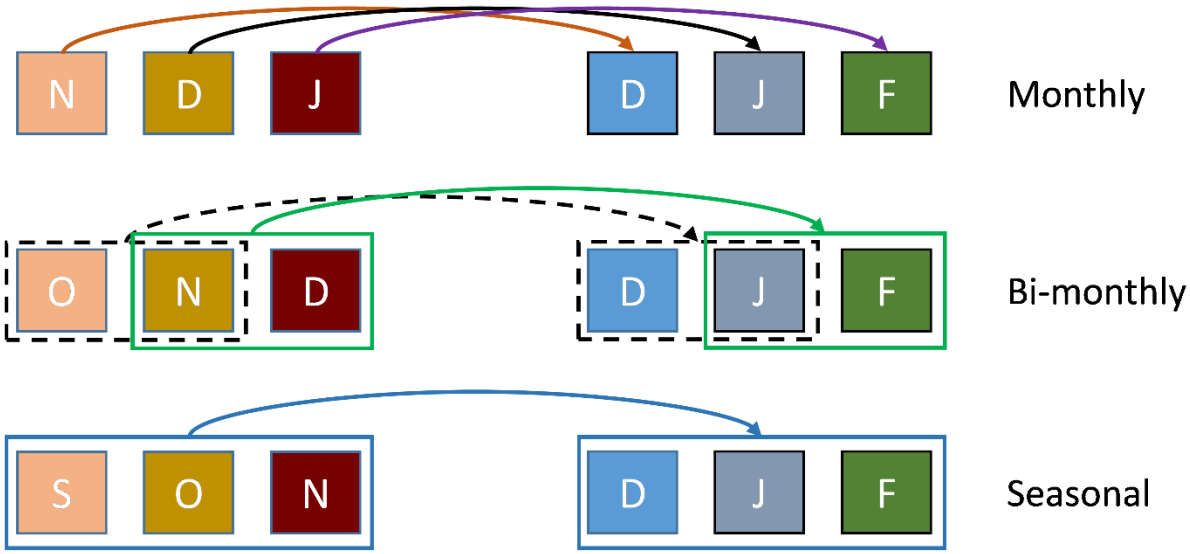

Figure 3. The monthly to seasonal drought forecasting framework using the multivariate copula model.

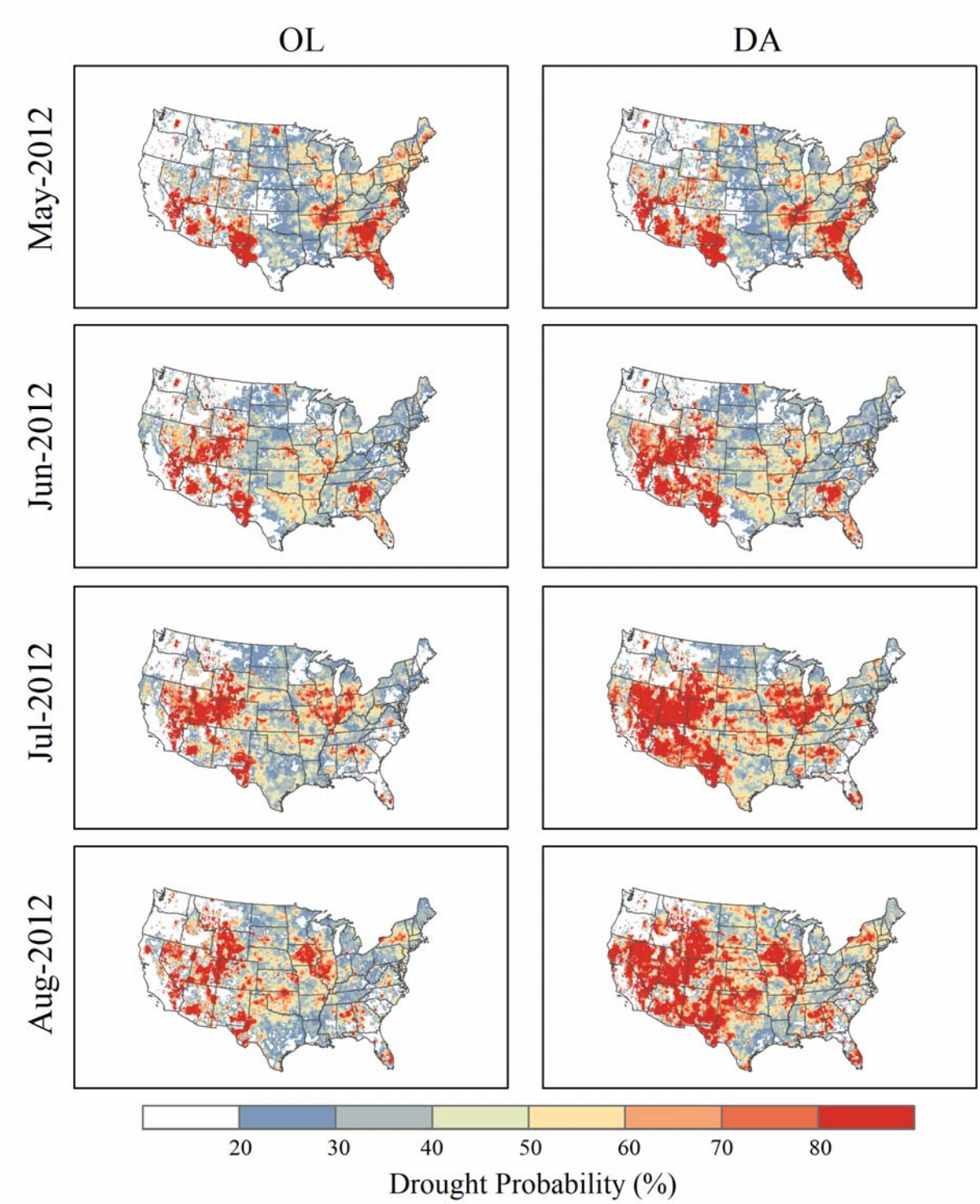

Figure 4. Synthetic study- Monthly probabilistic drought forecasts of both OL and DA for May–August in 2012. The probabilistic drought conditions in each month are forecasted using the root-zone soil moisture in the previous month. The color bar indicates the probability (%) of a grid cell under drought (D0–D4).

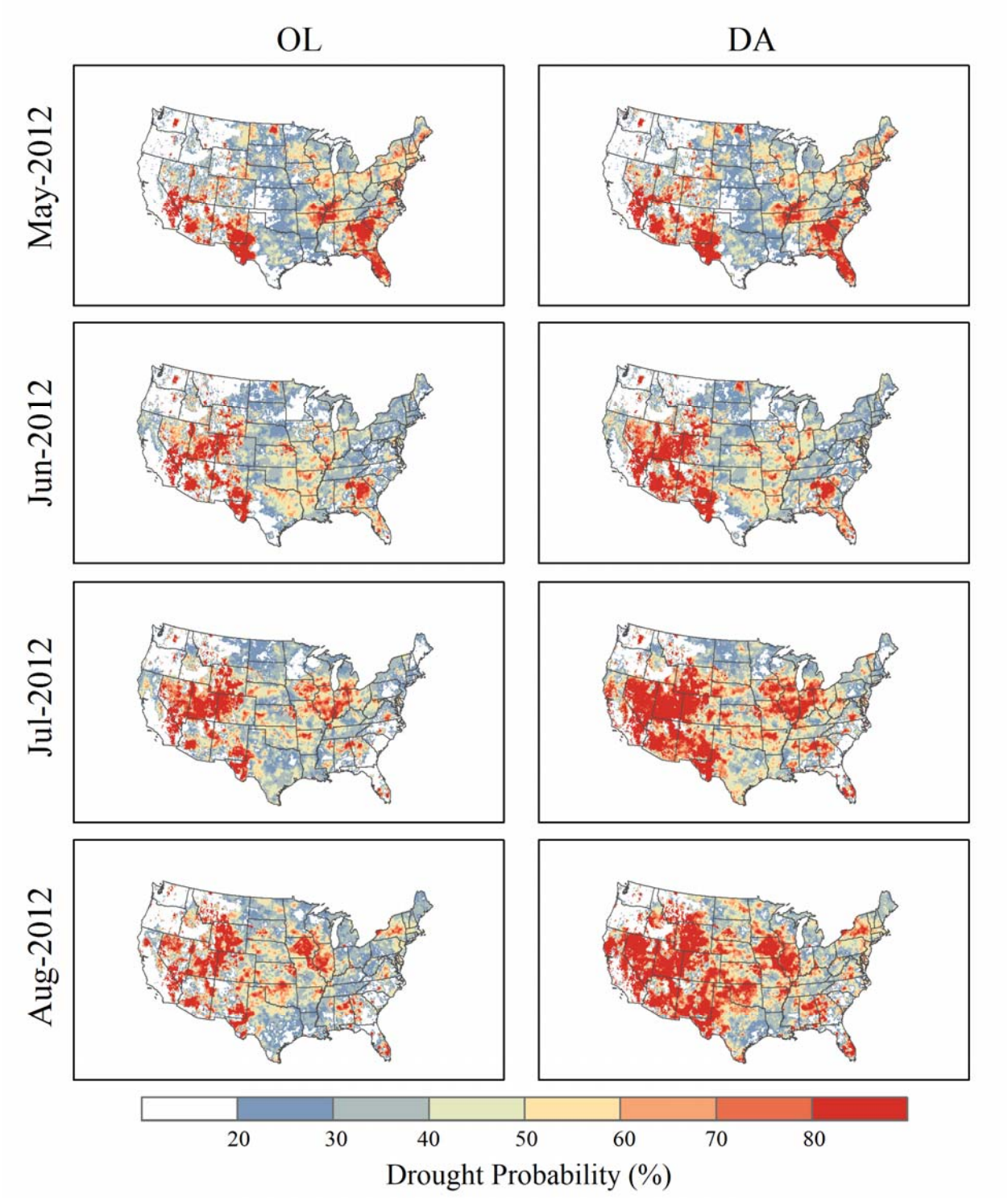

Figure 4. Monthly probabilistic drought forecasts of both OL and DA for May–August in 2012. The probabilistic drought conditions in each month are forecasted using the root-zone soil moisture in the previous month. The color bar indicates the probability (%) of a grid cell under drought (D0–D4).

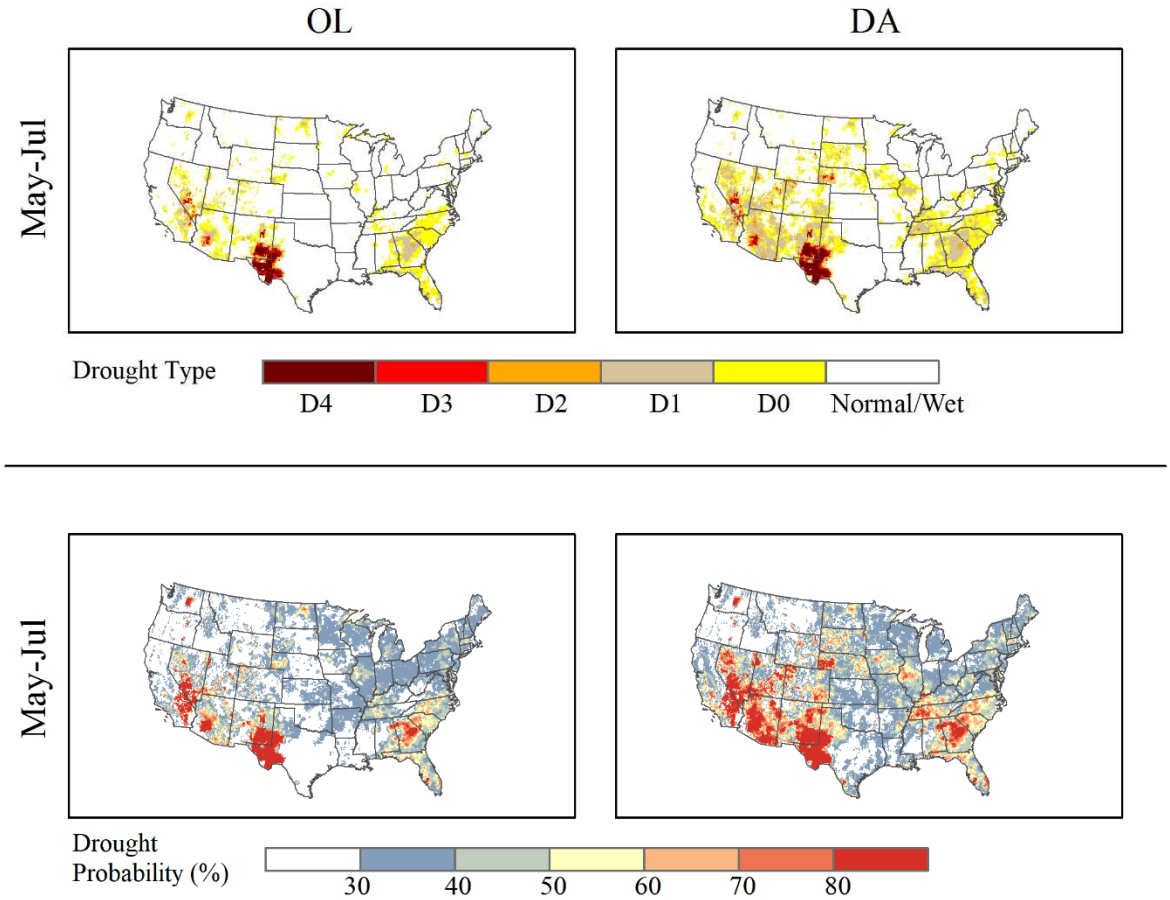

Figure 9. The seasonal probabilistic drought forecasts between the open-loop (OL) and data assimilation (DA) for May–July 2012. The probabilistic drought conditions in May–July are forecasted using the root-zone soil moisture in February–April. Top panel: the maximum likelihood forecasted drought type. Bottom panel: the forecasted probability (%) under drought (D0–D4).

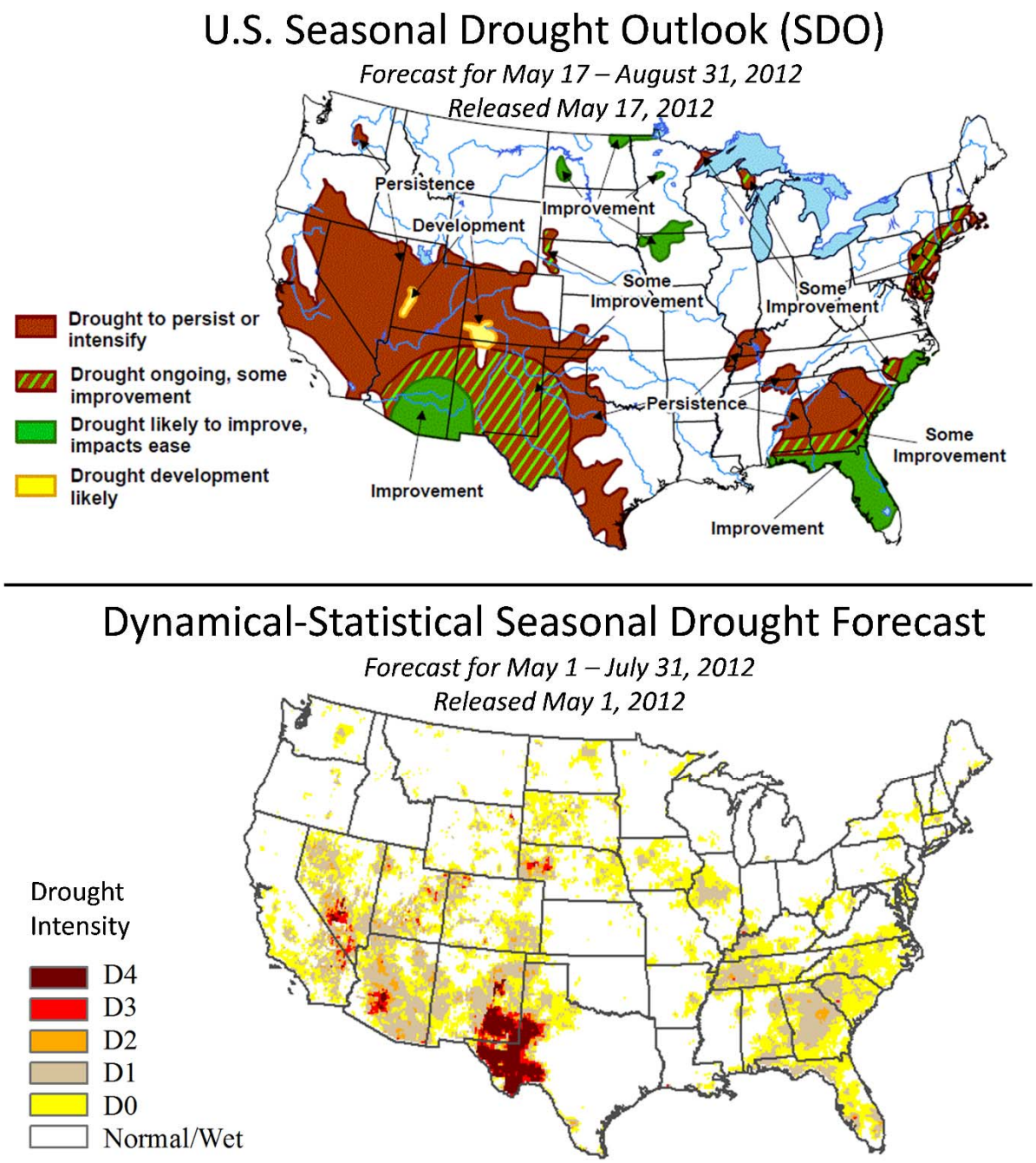

Figure 11. The comparison of the NOAA CPC's Seasonal Drought Outlook (top) and the maximum likelihood estimation (MLE) seasonal drought forecast (bottom) based on the proposed dynamical-statistical system for summer drought event in 2012.

Results from both synthetic and real case studies suggest that the dynamical-statistical drought forecasting system improves monthly to seasonal drought forecasting skills, and can facilitate the drought detection, preparation, and effective response. In addition, our dynamical-statistical forecasting system can generate both the probabilities for areas under drought and the most likely

intensity of future drought events. Compared to a single drought forecasting product provided in the current operational system, these two drought products can provide much more flexibility and information for decision makers and water resource managers. It is noted that the dynamical-statistical system is examined using one drought event in this study. We acknowledge that more case studies are needed to further verify the efficiency of this drought forecasting system. A practical path forward that we are currently implementing is to make this system operational and then examine the monthly to seasonal drought forecasts with USDM and other resources.

2 Highlights of Accomplishments

- A modular parallel data assimilation framework (PDAF) based on particle filter has been developed for the computational-demand large-scale hydrologic modeling.
- Copula-based probabilistic drought forecasting model is developed to couple with the updated initial conditions through data assimilation
- Based on the meteorological drought index used, significant changes are anticipated for the future drought characteristics.
- The duration and intensity of hydrological drought events are estimated to increase. Also, increasing trend in streamflow of high-flow months and decreasing trend in streamflow of low-flow months are seen, indicating higher risk of winter floods and summer droughts.
- The temperature changes will alter the amount of snowpack as well as the snowmelt onset, which will change the streamflow patterns, resulting in exacerbated hydrological droughts.
- A parallel computing for particle filtering data assimilation is necessary for large-scale applications.
- Remotely sensed soil moisture assimilation considerably improves drought monitoring skills
- Solely assimilating streamflow can lead to biased soil moisture estimation
- When the study area is partially covered by the satellite data, the geostatistical approach can help estimate the soil moisture for those uncovered grid cells
- Joint assimilation of streamflow and soil moisture from geostatistical modeling can further improve the surface soil moisture prediction.

- Two drought case studies in the Pacific Northwest showed that the proposed system improved the drought forecasting skill and can facilitate the state drought preparation.
- Studying drought using the SPI is found to be inadequate for climate change impact assessment, and SPEI can be a practical alternative, which also considers the effects of temperature.
- Copula based- postprocessing (COP-EPP) is successful in improving the accuracy of the NMME. However, COP-EPP shows robustness in bias-correcting precipitation in arid and semi-arid areas (Great Plains and southwestern US), and it generally shows superiority over QM results.
- COP-EPP proves to be a robust technique for bias-correcting future precipitation forecasts and it is able to enhance the spatial variability at monthly to seasonal timescales.
- Observation forcing uncertainty is high at monthly timescale, which eventuates in high disparities in hydrologic fluxes and drought characteristics.

3 Publications

- Yan, H., M Zarekarizi, and H. Moradkhani (In review), A Dynamical-Statistical Modeling Framework for Probabilistic Drought Forecasting.
- Yan, H., M Zarekarizi, and H. Moradkhani (2018), Toward Improving Drought Monitoring using the Remotely Sensed Soil Moisture Assimilation: A Parallel Particle Filtering Framework, *Remote Sensing of Environment,* 216:456-471, DOI: 10.1016/j.rse.2018.07.017.
- Moradkhani H., Nearing G., Abbaszadeh P., Pathiraja S. (2018) Fundamentals of Data Assimilation and Theoretical Advances. In: Duan et al. (eds), *Handbook of Hydrometeorological Ensemble Forecasting*. Springer, Berlin, Heidelberg, doi: https://doi.org/10.1007/978-3-642-40457-3_30-1.
- Khajehei, S., A., Ahmadalipour, and H. Moradkhani (2017), An Effective Post-Processing of the North American Multi-Model Ensemble (NMME) Precipitation Forecasts over the Continental US, *Climate Dynamics*, doi 10.1007/s00382-017-3934-0.

- Ahmadalipour, H. Moradkhani, M. Demirel, (2017), A comparative assessment of projected meteorological and hydrological droughts: Elucidating the role of temperature, *J. of Hydrology*, 553 (2017) 785–797.
- Khajehei, S. and H. Moradkhani (2017), Towards an Improved Ensemble Precipitation Forecast: A Probabilistic Post-Processing Approach, *J. of Hydrology*, 546, 476–489.
- Yan, H., and H. Moradkhani (2016), Combined Assimilation of Streamflow and Satellite Soil Moisture with the Particle Filter and Geostatistical Modeling, *Advances in Water Resources,* 94 364–378, doi:10.1016/j.advwatres.2016.06.002.
- Madadgar, S. and H. Moradkhani (2016), Copula Function and Drought, Handbook of Drought and Water Scarcity, Vol. 1: Principles of Drought and Water Scarcity*, Francis and Taylor*.
- Ahmadalipour, A. and H. Moradkhani and M. Svoboda (2016), Centennial drought outlook over the CONUS using NASA-NEX downscaled climate ensemble, *International Journal of Climatology,* doi: 10.1002/joc.4859.
- Ahmadalipour, A., H. Moradkhani, H. Yan, M. Zarekarizi (2016), Remote Sensing of Drought: Vegetation, Soil Moisture and Data Assimilation, Remote Sensing of Hydrological Extremes, Springer International Publishing Switzerland 2017, doi:10.1007/978-3-319-43744-6_7.

4 Presentations

- (Invited) Drought Vulnerability at Continental Scale: a Multi-dimensional Framework, EGU, Vienna, April 2018.
- A hybrid data assimilation framework for robust hydrologic forecasting, EGU, Vienna April 2018.
- (Invited) Recent Developments In Evolutionary Data Assimilation And Model Uncertainty Estimation For Hydrologic Forecasting- HEPEX Annual Meeting, Melbourne, Australia, Feb 2018.
- (Invited) Model Uncertainty Quantification Methods In Data Assimilation, AGU fall meeting, New Orleans, December 2017.
- An online tool for Operational Probabilistic Drought Forecasting System (OPDFS): a Statistical-Dynamical Framework, AGU fall meeting, New Orleans, December 2017.

- Comprehensive Analysis of Drought Persistence, Hazard, and Recovery across the CONUS, AGU fall meeting, New Orleans, December 2017.
- Comprehensive Analysis of Drought Persistence, Hazard, and Recovery across the CONUS, AGU fall meeting, New Orleans, December 2017.
- (Invited) How to Enhance Hydroclimate Forecasting for Water Resources and Emergency Management, USACE, Engineering Research and Development Center, March 2016.
- Remotely Sensed Satellite Data Assimilation: State-of-the art of Ensemble Inference in Hydrogeophysical Applications**,** University of New South Wales, Sydney, Australia, June 2015.
- A Novel Data Driven Approach to Model Error Estimation in Data Assimilation, EGU General Assembly, Vienna, April 2016.
- Assimilation of Satellite Soil Moisture Observation With the Particle Filter-Markov Chain Monte Carlo and Geostatistical Modeling, EGU General Assembly, Vienna, April 2016.
- A New Approach in Downscaling Microwave Soil Moisture Product using Machine Learning, EGU General Assembly, Vienna, April 2016.
- Dynamically Evolving Models for Dynamic Catchments: Application of the Locally Linear Dual EnKF to a Catchment with Land Use Change, *American Geophysical Union*, San Francisco, December, 2015.

5 Convened Panels and Technical Sessions

- Hydroclimatic Extremes: Drought, AGU fall Meeting, 2015 (San Francisco), 2016 (San Francisco), 2017 (New Orleans)
- Water and Society: Implications of Climate and Hydrologic Forecasting Management in Risk Mitigation and Management, AGU fall Meeting, New Orleans, December 2017
- State-of-the-Art of Uncertainty Analysis in Hydroclimate Modeling, Panel Discussion, EWRI, 2016, 2017 (Sacramento), 2018 (Minnesota)
- Advances in Hydrometeorological Extremes Forecasting: Estimation, Integrated Risk Analysis, and Applications, AGU Fall meeting, San Francisco 2015

6 Personnel Supported

- Ali Ahmadalipour (PhD), Dissertation title: "Multi-dimensional Drought Risk Assessment based on Socio-economic Vulnerabilities and Hydro-Climatological Factors". Now postdoctoral scholar at the University of Alabama
- Hongxiang Yan (PhD), Dissertation title: "From Drought Monitoring to Forecasting: A Combined Dynamical-Statistical Framework now postdoctoral scholar at the Pacific Northwest National Lab
- Mahkameh Zarekarizi (PhD Candidate)
- Sepdeh Khajehei (MSc, now PhD candidate)
- Amin Mehdipour (PhD student)

7 PI Contact Information

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