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Overview of Predictability & Experimental Forecasting Work for California & the Upper Colorado River Basin

2017-2022

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Evolution and Milestones for CA DWR Sponsored S2S Water Forecast Guidance R&D to Support Drought Preparedness

Driving Questions	**How well are ARs represented in global models?**
Results & Outcomes	**AR detection** algorithm advances/validation & **model evaluation**
Main Publications	Guan et al. (2018) Guan & Waliser (2017) *(outcomes extend into later years; *, ** -->)*
Experimental Forecasts	*N/A*
Partners	w/ UCSD, UCLA

*International Research Institute/Columbia, Western States Water Council, Water Education Foundation

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Evolution and Milestones for CA DWR Sponsored S2S Water Forecast Guidance R&D to Support Drought Preparedness

	2017 Task Plan Start	2018-19 Rev A	2019-20 Rev B	2020-22 Rev C
Driving Questions	**How well are ARs represented in global models?**	**How well are ARs forecast in global models?**	**Does atmospheric ridging offer a useful and longer-lead perspective?**	**Can progress be made on seasonal precipitation and snowpack skill? Predictability Estimates?**
Results & Outcomes	**AR detection** algorithm advances/validation & **model evaluation**	Global **AR forecast skill** assessments & experimental products for "weather" and subseasonal leads	Atmospheric **ridge detection** algorithm; Experimental ridge **forecast product** development and **model evaluation**	Explore and develop methods for **seasonal forecasts** as outlined in DWR forecast "requirements"
Main Publications	Guan et al. (2018) Guan & Waliser (2017) *(outcomes extend into later years; *, ** -->)*	DeFlorio et al. (2018a) DeFlorio et al. (2018b) DeFlorio et al. (2019)	Gibson et al. (2019) Gibson et al. (2020a) Gibson et al. (2020b) *Guan & Waliser (2019) **Guan et al. (2020)	*DeFlorio et al. (2021)* *Gibson et al. (2021)* *White et al. (2021)* *Jiang et al. (2022)* *Sengupta et al. (2022)*
Experimental Forecasts	*N/A*	Week 3 AR Activity	Week 3 & Seasonal Ridging	*Seasonal Products*
Partners	w/ UCSD, UCLA	w/ UCSD, UCLA	w/ UCSD, UCLA	w/ UCLA, U Az, IRI*, WSWC*, WEF*

*International Research Institute/Columbia, Western States Water Council, Water Education Foundation

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Experimental S2S Prediction Products

All prediction products are hosted at
https://cw3e.ucsd.edu/s2s_forecasts/

JPL Led Products*

1. Dynamical Model Atmospheric River Activity Forecasts (subseasonal - right)
2. Dynamical Model S2S Ridging Forecasts (subseasonal, see slide +1)
3. Seasonal Precipitation Forecast based on a Machine Learning Approach (seasonal, see slide +1)
4. Precipitation Prediction Based on Multi-Season Sea Surface Temperature Evolution (seasonal, see slide +2)

IRI and U Az Led Products

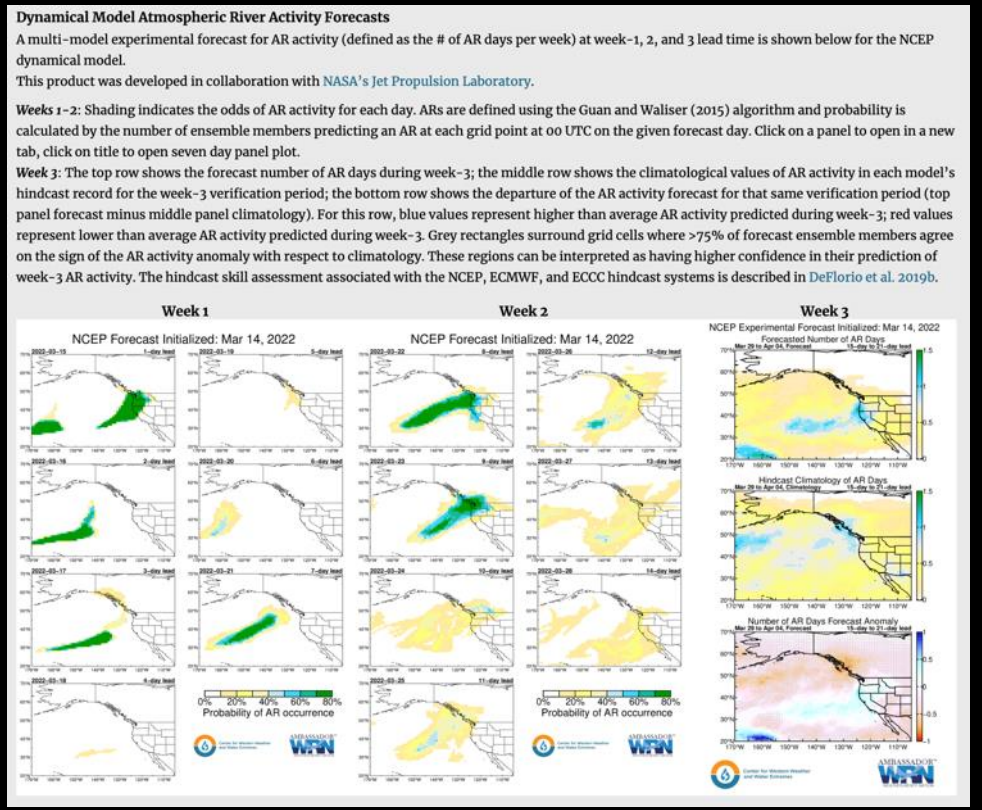
5. See slide +3

Community Seasonal Products

6. See Slide +4

* Routine updates of the products denoted JPL are undertaken by CW3E.

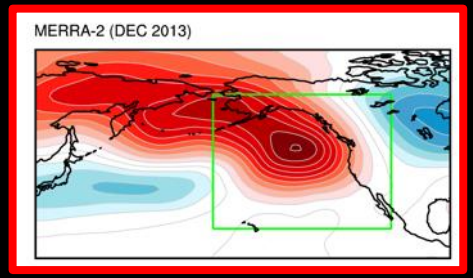
Dynamical Model Atmospheric River Activity Forecasts

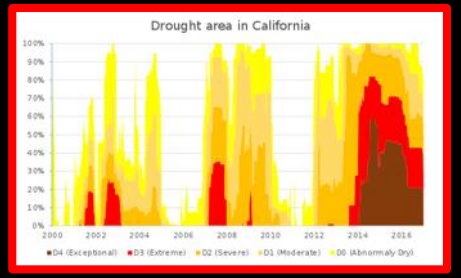


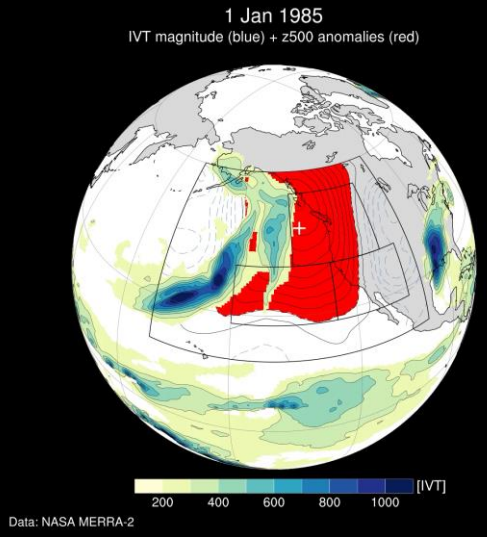
DeFlorio, M. J., Waliser, D. E., Ralph, F. M., Guan, B., Goodman, A., Gibson, P. B., et al., 2019. Experimental Subseasonal-to-Seasonal (S2S) Forecasting of Atmospheric Rivers Over the Western United States. JGR, 124.

Atmospheric “Ridges” and ARs/Precipitation

- “Ridges” are large regions of unusually high atmospheric pressure & clear skies.
- Persistent “ridges” reduce ARs/precipitation and contribute to drought.
- The 2013-16 drought occurred during the “ridiculously resilient ridge”.
- The large spatial scales and persistent nature of ridges suggest a source of S2S predictability.







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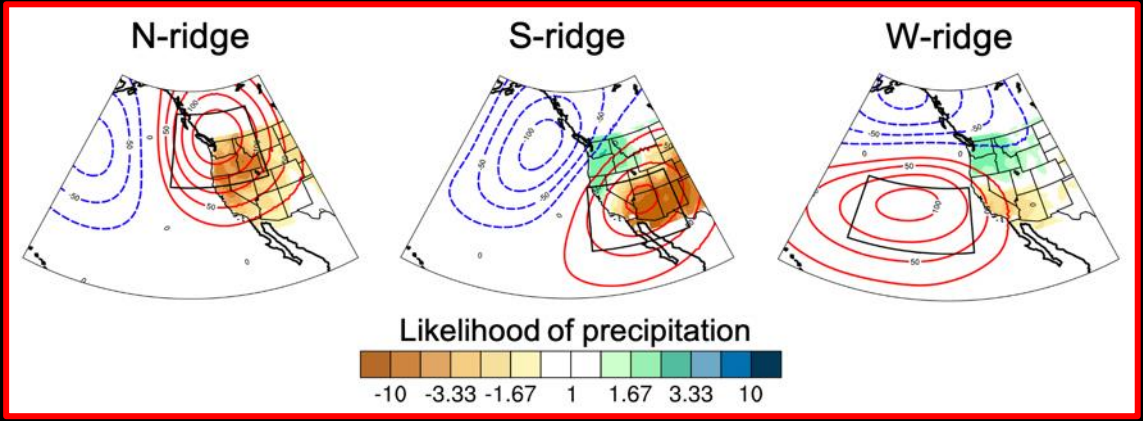
California Drought and Atmospheric “Ridges”

Developing Seasonal Prediction for Water Management



- 3 main ridge types were identified via a co-variability analysis between 500 hPa geopotential heights and western U.S. precipitation.
- An experimental ridging forecast product has been developed based on forecast output from NCEP CFS, ECMWF, and GEOS.

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S2S Experimental Prediction Products

https://cw3e.ucsd.edu/s2s_forecasts/

Dynamical Model S2S Ridging Forecasts

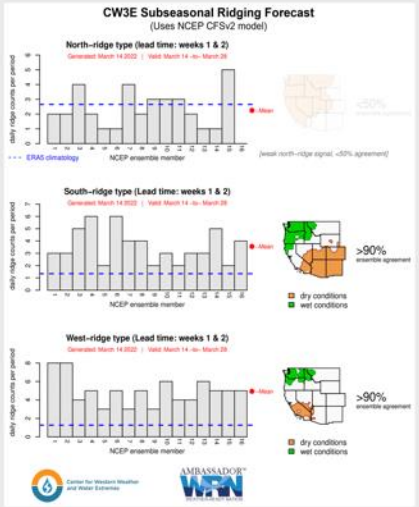
Dynamical Model S2S Ridging Forecasts

An atmospheric ridge is defined as elongated area of relatively high atmospheric pressure (American Meteorological Society; 2020). Persistent ridging events play an important role in determining if and where precipitation falls. Ridging forecasts are shown below for lead-times of weeks 1 and 2, weeks 3 and 4 and weeks 5 and 6. These forecasts are for three different 'ridge types' that have been shown in recent research [Gibson et al. 2020a; more methodology information here] to strongly influence atmospheric river and precipitation likelihood across the US West Coast. The North-ridge type is typically associated with widespread dry conditions across the entire US West. The South and West-ridge types are typically associated with dry conditions across Southern California and the Colorado River Basin but can also increase the likelihood of wet conditions across the Pacific Northwest. The hindcast skill assessment associated with this outlook is provided in Gibson et al. 2020b.

This product was developed in collaboration with NASA's Jet Propulsion Laboratory.

Interpretation: In these plots, the left panel shows the occurrence frequency of each ridge type (bars) compared to climatology (horizontal line) for each of the model ensemble members. If over 50% of the ensemble members predict more ridging than expected (for this time of year) then the right panel maps are displayed indicating the likelihood of wetter or drier conditions based on how these ridge types typically influence precipitation.

Forecast Period: Weeks 1 & 2



Gibson, P. B., Waliser, D. E., Goodman, A., DeFlorio, M. J., Delle Monache, L., & Molod, A. (2020b). Subseasonal-toseasonal hindcast skill assessment of ridging events related to drought over the western United States. JGR, 125, e2020JD033655. https://doi.org/10.1029/2020JD033655

Seasonal Precipitation Forecast based on a Machine Learning Approach

Seasonal Precipitation Forecast based on a Machine Learning Approach

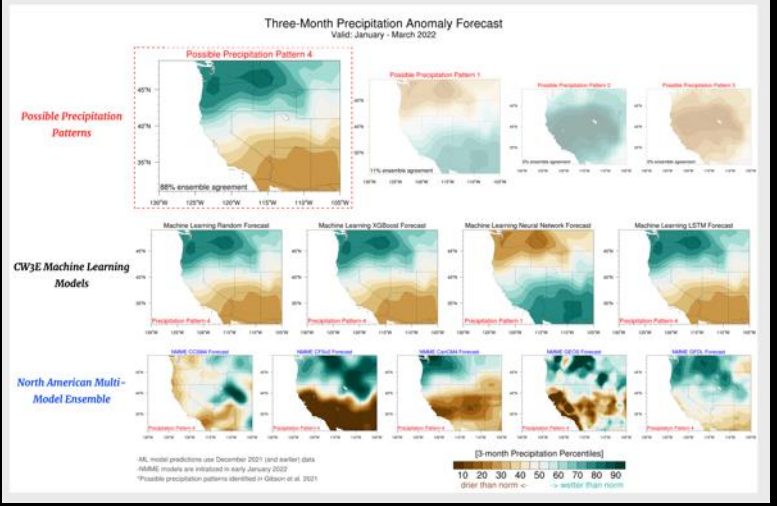
This CW3E forecast product predicts likely seasonal precipitation anomaly patterns for January–February–March over the western U.S. based on machine learning models and dynamical ensemble predictions. Four different machine learning models (Random Forest, XGBoost, LSTM, and neural networks) were pretrained based on learning relationships between remote ocean and atmospheric patterns and characteristic seasonal precipitation anomalies over the Western United States. Instead of training on observations, the machine learning models were here trained on a large climate model ensemble, which enabled more robust relationships to be established due to the very large sample size in the training phase (Gibson et al. 2021). Seasonal forecast skill is also enhanced by focusing on four characteristic large-scale precipitation patterns across the Western United States. Our historical skill assessment found that the probability of a correct forecast improves when the Machine learning models show stronger consensus for a particular pattern. As such, the ensemble agreement (or lack of) provides useful guidance on forecast uncertainty.

This product was developed in collaboration with NASA's Jet Propulsion Laboratory.

Top row: Four precipitation anomaly patterns identified in Gibson et al. 2021. Percentages represent the number of ensemble models predicting that pattern for January – March 2022 with the red outline and plot size representing the most predicted pattern.

Middle row: Three-month precipitation anomaly pattern forecasts from the four CW3E developed machine learning models valid for January – March 2022.

Bottom row: Three-month precipitation anomaly forecasts from five North American Multi-Model Ensemble (NMME) models valid for January – March 2022. The associated precipitation pattern for each forecast is noted in the bottom right of each image.



Gibson, P.B., Chapman, W.E., Altinok, A. et al. Training machine learning models on climate model output yields skillful interpretable seasonal precipitation forecasts.Commun Earth Environ 2, 159 (2021). https://doi.org/10.1038/s43247-021-00225-4

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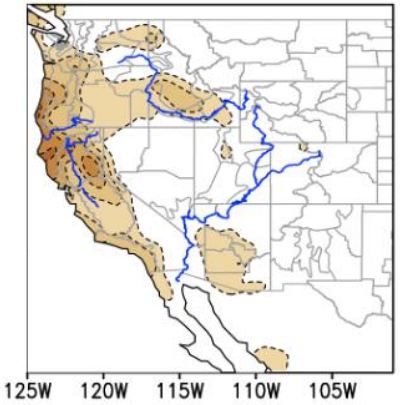
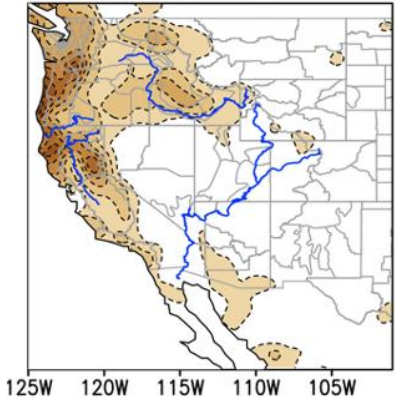
Seasonal Precipitation Prediction Based on Multi-season Sea Surface Temperature Evolution

2021-22 ***Nov-Mar*** **Forecast**:
Seasonal Precipitation Anomalies

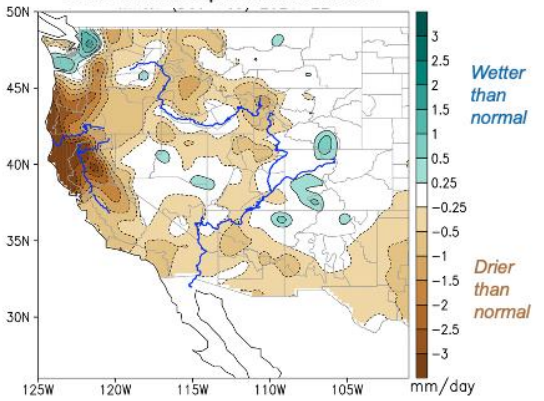


2021-22 ***Dec-Feb*** **Forecast** *(issued 7 Nov '21)*:
Seasonal Precipitation Anomalies



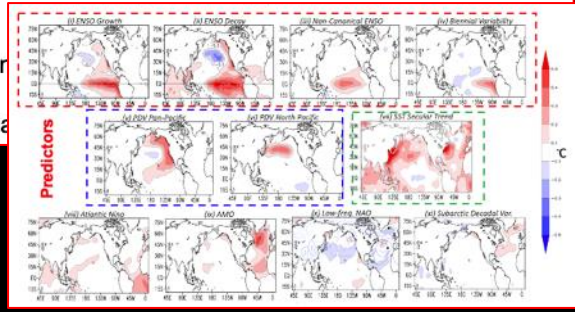
NOAA NCEI Climate Divisions outlined in grey, major western rivers in blue. Base period for precipitation anomalies: 1981-2010

2021-22 ***Dec-Feb*** **Observed**:
Seasonal Precipitation Anomalies



based on NOAA CPC Unified RT dataset (base period: 1981-2010)

- Our experimental forecast favored *drier-than-normal* condition
- *Near-normal* rainfall forecasted in the Upper Colorado river ba



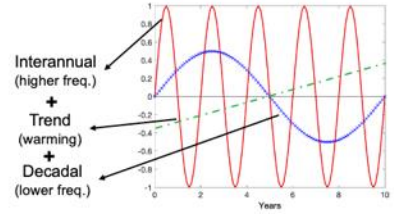


Figure *(left) Leading modes of global SST variability – ENSO (top row), Pacific Decadal Variability and Secular Trend (middle row), Atlantic modes (bottom row) informing seasonal prediction of precipitation. (right) Idealized representation of the frequency of SST modes*

Publication and Website Product in Progress

Sengupta et al. (2022)

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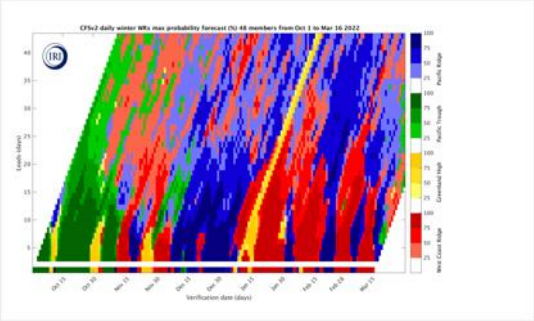
Other Experimental S2S Prediction Products

Sub-seasonal Forecast of North American Weather Regimes

Forecast from IRI.

The graphic shows forecasts of large scale meteorological patterns, issued every day during winter (along x-axis) by the NCEP CFSv2 model. The four large scale "weather regimes" are the West Coast Ridge (reds), Pacific Ridge (blues), Pacific Trough (greens), and Greenland High (yellows), each of which leads to distinct precipitation and temperature conditions over the West. Darker colors indicate more confident forecasts, which run diagonally up the chart from 0 to 45 days ahead. This product was developed with support from NOAA's Next Generation Global Prediction System (NGGPS) program and the California Department of Water Resources. Please see https://wiki.iri.columbia.edu/index.php?n=Climate.S2S-WRs for the precipitation and temperature signatures of the regimes or Robertson, Vigaud, Yuan & Tippett (2020) for additional details.



https://cw3e.ucsd.edu/s2s_forecasts/

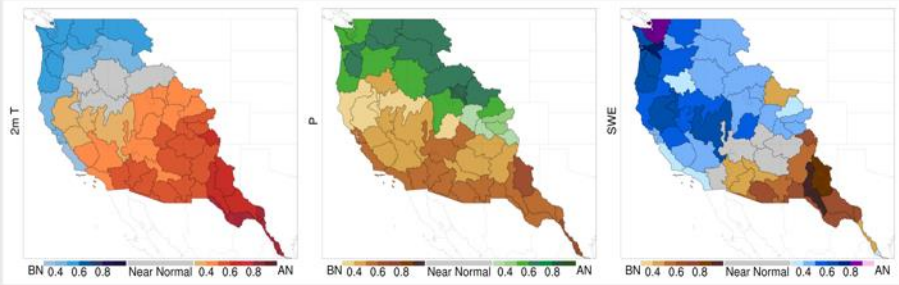
The Task helped to facilitate the presentation and inclusion of the IRI Subseasonal (left) and U. Az Seasonal (lower) Experimental Prediction Products into an "operational" form on the cw3e.ucsd.edu website.

The U. Az one below is behind the firewall until the peer reviewed publication gets accepted – see page 3.

University of Arizona Seasonal Temperature, Precipitation, and Snowpack Forecasts

Three month (January – March) forecasts of two-meter temperature (2mT; left), precipitation (P; middle), and snow water equivalent (SWE; right) produced by the University of Arizona. Methodology utilizes two dynamic seasonal climate models (NCEP CFS_{v2} and ECMF SEAS5) post-processed through a two-stage process along with empirical forecasting approaches to create a final super ensemble forecast. Forecasts below show the prediction for January – March 2022 initialized in early January 2022. The dominant tercile probability forecasts are generated by counting the number of ensembles below the observed 33rd percentile (BN), between the 33rd and 67th percentile (NN) and above the 67th percentile (AN). While 2m T and P show a strong dipole pattern, above normal snowpack is forecasted across much of the west due to above normal snowpack at the end of December 2021.

Click here to see skill maps for these forecasts. Skill is calculated using JFM forecasts generated in January for 2011-2020. Top row shows correlation between ensemble mean and observations. Bottom row shows the Ranked Probability Skill Score, which compares how well the forecast ensemble encompasses observations versus how well a reference ensemble of all past observed years used in the training encompasses the same observations.



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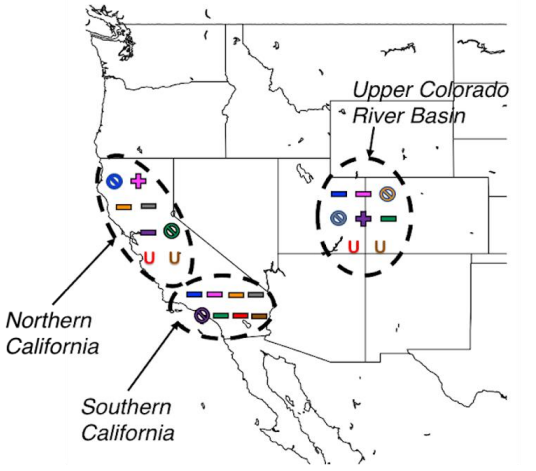
Experimental Seasonal Prediction Products

A Community View

The Task led the development (via Agniv, Mike, etc) a summarizing seasonal forecast graphic (below) intended to provide general guidance to water managers regarding winter seasonal precipitation forecasts. Its final presentation form is a work in progress, and it is anticipated to be updated monthly and provided via the CW3E website.

Synthesizing Experimental Seasonal Precipitation Forecasts during Winter 2021-22



DeFlorio et al. 2022 (BAMS, in prep)

Methods	Forecast Period	Organization(s)	Nor Cal	So Cal	Upper Colo
Machine Learning based Forecast (Gibson et al.)	Jan-Mar	Jet Propulsion Laboratory, California Institute of Technology; Center for Western Weather and Water Extremes	Normal	Below Normal	Below Normal
CCA Seasonal Precipitation Forecast (Gershunov et al.)	Jan-Mar	Center for Western Weather and Water Extremes	Above Normal	Below Normal	Below Normal
Univ. of Arizona Hybrid Seasonal Forecast (Zeng et al.)	Nov-Mar		Below Normal	Below Normal	Normal
Evolution-centric Statistical Forecast (Sengupta et al.)	Nov-Mar	Jet Propulsion Laboratory, California Institute of Technology	Below Normal	Below Normal	Normal
IRI Forecast based on Weather Regimes (Robertson et al.)	Nov-Mar	IRI	Below Normal	Normal	Above Normal
NOAA ESRL Seasonal Forecast (Switanek et al.)	Nov-Mar		Normal	Above Normal	Above Normal
NMME Seasonal Forecast	Jan-Mar	The North American Multi-Model Ensemble	U/Below Normal	Below Normal	U
NOAA CPC Operational Outlook	Jan-Mar		U	Below Normal	U/Below Normal

Credit: A. Sengupta, M. DeFlorio, D. Waliser, F. M. Ralph, A. Robertson, X. Zeng, J. Jones

Plan to Submit to BAMS by DeFlorio et al.

Contribution to WMO's S2S Prediction Project's

Real-Time Pilot Studies

This DWR S2S activity represents 1 of 16 Pilot Studies for the WMO S2S Prediction Project – see s2sprediction.net

This team's participation raises the visibility of western U.S. water manager S2S forecast needs to the international applied research community

WORLD METEOROLOGICAL ORGANIZATION

WCRP World Climate Research Programme

WWRP WORLD WEATHER RESEARCH PROGRAMME

Subseasonal-to-Seasonal S2S Prediction Project

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S2S Workshop, March 2022

Virtual Workshop on Sub-seasonal to Seasonal Climate Forecasting for Water Management in the Western U.S.

Date	March 15-17, 2022
Venue	Virtual (Zoom), three 3-hour online sessions, 2:00-5:10pm EDT (18:00-21:10 UTC)
Agenda	Link to Agenda
Target Audience	Cimate researchers and forecasters, hydrologists, water managers
Organizing Committee	A.W. Robertson and B. Singh/IRI, X. Zeng/U.Az, M. DeFlorio/CW3E/Scripps, D.Waliser/JPL, A. Lam-Wright/IRI
Contact	s2s-water-2022@iri.columbia.edu
Register (Free)	https://events.columbia.edu/go/s2s_water_2022

It is widely recognised that effective climate services for water management requires co-development involving climate researchers, forecasters, hydrologists and water managers. This workshop will provide a forum for cross-community dialog and sharing of the latest research results and work on integrating science with services. It will highlight recent advances in short-term climate predictions of conditions concerning water availability (e.g. precipitation, snowpack, drought) over the western US to better inform water resource managers, and on translating climate forecasts into products to directly inform water management decisions. While the workshop topics will include the subseasonal range, emphasis and priorities for presentations and discussion will be on 1) seasonal to interannual lead-times, 2) seamless prediction systems across time scales, and then 3) subseasonal lead-times.

Nationally, several federal agencies (e.g., NOAA, NASA, USGS), state agencies (e.g., California Department of Water Resources, Western States Water Council), research centers (e.g., CW3E, IRI), and universities are involved in the observations, modeling, and understanding relevant to such forecasts. Internationally, the World Meteorological Organization (WMO) has developed the Action Plan on Hydrology. To support this plan, WMO is developing the research strategy for the next decade on the areas of priority research (e.g., through WCRP/GEWEX in collaboration with other international programs) that has a direct application to improving operational hydrology and the operations of National Hydrological and Meteorological Services.

Special thanks to IRI, Andy, Bohar, Angel

S2S Prediction Project April 2022 Newsletter

BAMS Mtg Summary to be Submitted by Sengpta et al.

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Moving Forward - Recommendation

Based on

- need for continued & more coordinated discussion and effort on S2S western water prediction research at the working level (i.e. foster a community and activities > PI-driven)
- experience with the US CLIVAR, WCRP/WWRP/YOTC and now WMO/WGNE …..MJO /Task Force

Recommendation: WSWC Sponsor a Western Water Prediction Task Force

Key Ingredients:

- Not affiliated with a given agency, university or lab –rather something agnostic like WSWC or US CLIVAR
- ~5-10 year time frame
- 2 early to mid career co-chairs, rotating ~3 years
- ~10 highly motivated & interested S2S scientists w/ diversity across university, lab, agency, career stage
- Sponsor provides (at a minimum) meeting support for ~1 working meeting per year
- Group meets virtually ~bimonthly
- Task Force identifies group-level, executable research/task priorities, activities and outcomes
- One or more early career graduate students and postdocs entrained to get work done -> big career boost

Backup

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Peer Reviewed Publication References

- DeFlorio, M., D. E. Waliser, B. Guan, D. Lavers, F. M. Ralph, and F. Vitart, 2018a: Global assessment of atmospheric river prediction skill, J. Hydrometeorology, 10.1175/JHM-D-17-0135.1.
- DeFlorio, M., D. E. Waliser, B. Guan, F. M. Ralph, and F. Vitart, 2018b: Global Evaluation of Atmospheric River Subseasonal Prediction Skill, Climate Dynamics, 10.1007/s00382-018-4309-x.
- DeFlorio, M. J., Waliser, D. E., Ralph, F. M., Guan, B., Goodman, A., Gibson, P. B., et al., 2019. Experimental Subseasonal-to-Seasonal (S2S) Forecasting of Atmospheric Rivers Over the Western United States. JGR, 124.
- DeFlorio, M. J., F. M. Ralph, D. E. Waliser, J. Jones, and M. L. Anderson (2021), Better subseasonal-to-seasonal forecasts for water management, EOS, 102, https://doi.org/10.1029/2021EO159749
- Gibson, P., D. E. Waliser and M. DeFlorio, 2019. A critical examination of a newly proposed interhemispheric teleconnection to Southwestern US winter precipitation. Nature Communications, 10.1038/s41467-018-04722-7.
- Gibson, P.B., D.E. Waliser, B. Guan, M.J. DeFlorio, F.M. Ralph, and D.L. Swain, 2020a: Ridging Associated with Drought across the Western and Southwestern United States: Characteristics, Trends, and Predictability Sources. J. Climate, 33, 2485–2508, 10.1175/JCLI-D-19-0439.1.
- Gibson, P. B., Waliser, D. E., Goodman, A., DeFlorio, M. J., Delle Monache, L., & Molod, A. (2020b). Subseasonal-toseasonal hindcast skill assessment of ridging events related to drought over the western United States. Journal of Geophysical Research: Atmospheres, 125, e2020JD033655. https://doi.org/10.1029/2020JD033655
- Gibson, P.B., Chapman, W.E., Altinok, A. et al. Training machine learning models on climate model output yields skillful interpretable seasonal precipitation forecasts.Commun Earth Environ 2, 159 (2021). https://doi.org/10.1038/s43247-021-00225-4
- Guan, B., D. E. Waliser, and F. M. Ralph, 2018: An Inter-comparison Between Reanalysis and Dropsonde Observations of the Total Water Vapor Transport in Individual Atmospheric Rivers, J. Hydrometeorology, 10.1175/JHM-D-17-0114.1.
- Guan, B., and D. E. Waliser, 2017, Atmospheric rivers in 20 year weather and climate simulations: A multi-model, global evaluation, J. Geophys. Res. Atmos., 122, doi:10.1002/2016JD026174
- Guan, B. and D. E. Waliser, x2019. Tracking Atmospheric Rivers Globally: Spatial Distributions and Temporal Evolution of Life Cycle Characteristics. Journal of Geophysical Research: Atmospheres, 124, 12,523–12,552. 10.1029/2019JD031205
- Guan, B., D.E. Waliser, F.M. Ralph, 2020. A Multi-model Evaluation of the Water Vapor Budget in Atmospheric Rivers, Ann. N. Y. Acad. Sci, doi: 10.1111/nyas.14368.
- White, C. J., Domeisen, D. I. V., Acharya, N., Adefisan, E. A., Anderson, M. L., Aura, S., Balogun, A. A., Bertram, D., Bluhm, S., Brayshaw, D. J., Browell, J., Büeler, D., Charlton-Perez, A., Chourio, X., Christel, I., Coelho, C. A. S., DeFlorio, M. J., Delle Monache, L., Di Giuseppe, F., García-Solórzano, A. M., Gibson, P. B., Goddard, L., González Romero, C., Graham, R. J., Graham, R. M., Grams, C. M., Halford, A., Katty Huang, W. T., Jensen, K., Kilavi, M., Lawal, K. A., Lee, R. W., MacLeod, D., Manrique-Suñén, A., Martins, E. S. P. R., Maxwell, C. J., Merryfield, W. J., Muñoz, Á. G., Olaniyan, E., Otieno, G., Oyedepo, J. A., Palma, L., Pechlivanidis, I. G., Pons, D., Ralph, F. M., Reis, D. S., Jr., Remenyi, T. A., Risbey, J. S., Robertson, D. J. C., Robertson, A. W., Smith, S., Soret, A., Sun, T., Todd, M. C., Tozer, C. R., Vasconcelos, F. C., Jr., Vigo, I., Waliser, D. E., Wetterhall, F., & Wilson, R. G. (2021). Advances in the application and utility of subseasonal-to-seasonal predictions, Bulletin of the American Meteorological Society, In Press

In review or preparation

- DeFlorio, M. J., A. Sengupta, D. E. Waliser, F. M. Ralph, A. W. Robertson, X. Zeng, J. Jones, M. L. Anderson, and L. Delle Monache (2022), Synthesizing subseasonal-to-seasonal forecast information to benefit western U. S. water management. BAMS. In Preparation.
- Guan, B., D. E. Waliser, and F. M. Ralph (2022), Global Application of the Atmospheric River Scale. J. Geophys. Res. Atmos., under review.
- Jiang, X, D. E. Waliser, P. Gibson, G. Chen, and W. Guan, 2022: Why seasonal prediction of California winter precipitation is challenging? Bulletin of the American Meteorology Society, BAMS, submitted.
- Muñoz, Á.G., A.W. Robertson, B.Singh, D. Resnick, L. Goddard, “Water Year Precipitation Scenarios for the Western United States: bridging subseasonal and seasonal forecasts”, TBD, In Preparation.
- Scheftic, W., Zeng, X., & Brunke, M. (2022). Seasonal forecasting of precipitation, temperature, and snow mass over the western U.S. by combining ensemble post-processing with empirical ocean-atmosphere teleconnections. Weather and Forecasting, submitted.
- Sengupta, A., D.E. Waliser, B. Guan, and M. DeFlorio, 2022: An evolution-centric statistical forecast technique for seasonal precipitation forecasts over the western United States. J. Climate, In Preparation.
- Sengupta, A., B. Singh, M. DeFlorio, C. Raymond, A. W. Robertson, X. Zeng, D.E. Waliser, and J. Jones, 2022: Advances in sub-seasonal to seasonal prediction relevant to water management in the western United States. BAMS Meeting Summary. In Preparation.
- Singh, B., A.W. Robertson, Á.G. Muñoz, M.A. Ehsan, J. Yuan, "Winter-time ENSO-precipitation teleconnection modulation by QBO over the United States”, TBD, In Preparation.