Project Title: ASSESSING NMME PHASE-2 FORECASTS FOR IMPROVED PREDICTIONS OF DROUGHT AND WATER MANAGEMENT

Grant: NAl50AR43l0075
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Final Report

Project Overview
The over-arching goal of the proposed project is *to assess and document the NMME Phase-2 seasonal forecasts for hydrological seasonal forecasts of drought and water management and compare these to the skill from the Phase-1*. The availability under NMME-2 of a broader suite of variables, and daily forecasts rather than monthly, offers the potential for significant improvements that need to be documented through forecast experiments and systematic analysis.

In the project we proposed to include the following research activities:

1. Spatial downscaling of NMME Phase-2 forecasts. For the first time ever, the variables needed as inputs to hydrological models will be offered from seasonal forecast models, although at a 1-degree resolution. Currently, the NMME-1 precipitation and temperature forecasts are downscaled both spatially and temporally to resolutions appropriate for hydrological and agricultural drought forecasting. Under Phase-2, spatial downscaling needs to be carried out to bring the forecasts to scales approaching 10km or finer, while utilizing the higher Phase-2 temporal resolution. The impact to applications like drought forecasting and water availability will be assessed and quantified.

2. Assessment of Phase-2 skill in comparison to Phase-I. Can the skill from the earlier (NMME-1) applications developed by PI Wood be improved by using NMME-2 forecasts, which have higher temporal fidelity and more forecast variables? A set of experiment will be drawn from earlier Phase-1 studies and will be carried out to address this important question.

3. Sub-seasonal forecast skill. How can drought and hydrologic forecasts for month 1 be improved using NMME-2? With the daily NMME-2 forecasts variables, we can build a seasonal hydrologic forecast system within a multi-model framework, either with or without GEFSv2 for weeks 1-2. This will advance the usefulness of a seamless forecast system as well as assess sub-seasonal predictive skills.

Overview of the Project Challenges and Results

The project made significant headway in developing a seamless hydrological seasonal forecasting system using NMME phase 2 reforecast. In Wanders et al. (2016), we demonstrated that optimal weighting of the forecasts led to significant improvement in forecast skill. This demonstrates the potential for NMME2 seasonal forecasts for improved climate services for the water resources sector.

That said, the significant delays in populating the NCAR NMME-2 re-forecast archive seriously impacted the project. Many models had incomplete data sets; some like CFS-v2 delivered minimal data far after the deadlines; and some like GEOS-5 failed to include critical variables like precipitation until very recently.

Table 1: NMME-Phase2 Data Archive Status as of August, 2015

Model	% Daily Atm Received	% Daily Atm Published	Notes
CanCM3	**100%**	**100%**	Complete
CanCM4	**100%**	**100%**	Complete
FLOR-B	**100%**	**100%**	Complete Tas, Tasmin/max, Prec fields only
CCSM4	**99%**	**98%**	Filling in gaps to complete
GEOS5	**95%**	**95%**	Filling in gaps to complete
CFSV2	**100%**	**10%**	NetCDF conversion complete Daily production underway ETA: 9/15/2015
CESM1	**6%**	**0%**	1981, 1982 years received ETA: 9/30/2015

As of July 2016, the status hardly improved with surface level precipitation from CESM1not available, precipitation from GEOS-5 existing but not in the archive yet; precipitation from CFSv2 potentially available at a 6hourly time step and for CCSM4 in the process of finalizing precipitation and surface air temperature. Overall, the project seemed indifferent to moving this forward with recognizable urgency.

With the potential of the archive being completed, the project developed the infrastructure to expand the hydrological seasonal forecasts by including not only the VIC land surface model, but PRC-GLOBWB model that contains extensive water use and management parameterizations (e.g. groundwater, irrigation, reservoirs, etc.)

Year 1 Results and Accomplishments

In the first year, the project focused on developing seamless hydrologic forecasting, investigating predictability of subseasonal hydroclimate events, and assessing seasonal drought forecasting of the NMME Phase 2.

1 Spatial downscaling of NMME Phase-2 forecasts

The original available Phase-2 hindcast dataset was obtained from the download portal at earthsystemgrid.org. The Princeton research team developed scripts that can automatically pull the available data for future applications and update the existing archive when more data becomes available. This gives the advantage the we have the potential that we can implement it in the real-time Princeton Flood and Drought monitor when more forecasts become or when forecasts become available in real-time. As of now only 3 out of the 6 models are fully available to the community (CanCM3, CanCM4, FLOR-B01) and one model has an incomplete archive (CCSM4, 70% data coverage, Table 2). Using the available data, we applied a statistical downscaling technique to downscale the data to a 0.5-degree spatial resolution. The statistical downscaling was done based on observed climatology from the Princeton Global Forcing dataset. The 0.5-degree resolution is still coarser than the planned future spatial resolution of 10km, however, this resolution already allows us to use the forecast for global hydrological sub-seasonal forecasting.

We discovered that to successfully use the NMME Phase-2 forecast for hydrological forecasts, a bias correction was necessary. We implemented a CDF matching approach to correct the number of rainy days and rainfall totals to be in line with the observations climatology as derived from the Princeton Global Forcing dataset.

Table 2 North American Multi Model Ensemble phase 2 data availability and required reprocessing

	CanCM3	CanCM4	FLOR-B01	CCSM4
Institute	Environment Canada	Environment Canada	GFDL	NCAR/University of Miami
Temperature data availability	100%	100%	100%	71.4%
Precipitation data availability	100%	100%	100%	76.5%
Resampling	None	None	Bicubic	Bicubic
Ensemble members	10	10	12	10

2 Assessment of Phase-2 skill in comparison to Phase-1

The anomalies in the bias corrected Phase-2 forecasts from CanCM3, CanCM4, FLOR-B01 and CCSM4 (limited by availability) were compared to the observed anomalies in the Princeton Global Forcing dataset at the global scale. We evaluated the forecast skill for bi-weekly aggregated periods for leads up to 12 months and compared the obtained skill with the monthly aggregated forecasts that are similar to the NMME Phase-1. Currently, we have focused on precipitation and 2m air temperature, because these are the necessary variables to run most global hydrological models.
We found that the forecast skill of NMME Phase-2 approximates or is comparable to the skill of NMME Phase-1 monthly forecast. The regions with the largest difference in forecast skill between Phase-1 and Phase-2 can be found where the seasonal forecasts have a low initial forecast skill (e.g. Russia and Canada). In these regions, the bi-weekly forecasts show a lower performance than the monthly forecast, which is not very surprising given the low skill of seasonal forecast in general in these areas. In the tropical regions, with a known high seasonal forecast skill, we find a strong performance of the NMME Phase-2 forecasts (Figure 1 and 2). In general, we find a lower forecast skill in the precipitation forecast compared to forecasted temperature anomalies.

In terms of model performance, we cannot find significant difference between the models, with the exception of FLOR-B01 for the earlier weeks. The FLOR model uses AMIP climatology for the forecast initialization (compared to observed data for the other models), which results in a low initial forecast skill which is compensated by an overall higher forecasts skill for the longer leads. To fully utilize the potential of the NMME Phase-2 data, we have constructed weighted ensemble forecast that utilizes known information on the forecast skill. Although not common practice in seasonal forecasting, we wanted to see how a weighted forecast could benefit from the strength and weaknesses of an individual forecast. We show that (when done with care), a weighted forecast will outperform an unweighted forecast or individual model forecasts (Figure 1 and 2, 6th and 7th columns). This is a promising finding that not only helps the sub-seasonal forecasting, but it can also help to point out strengths and weaknesses in individual models compared to other.

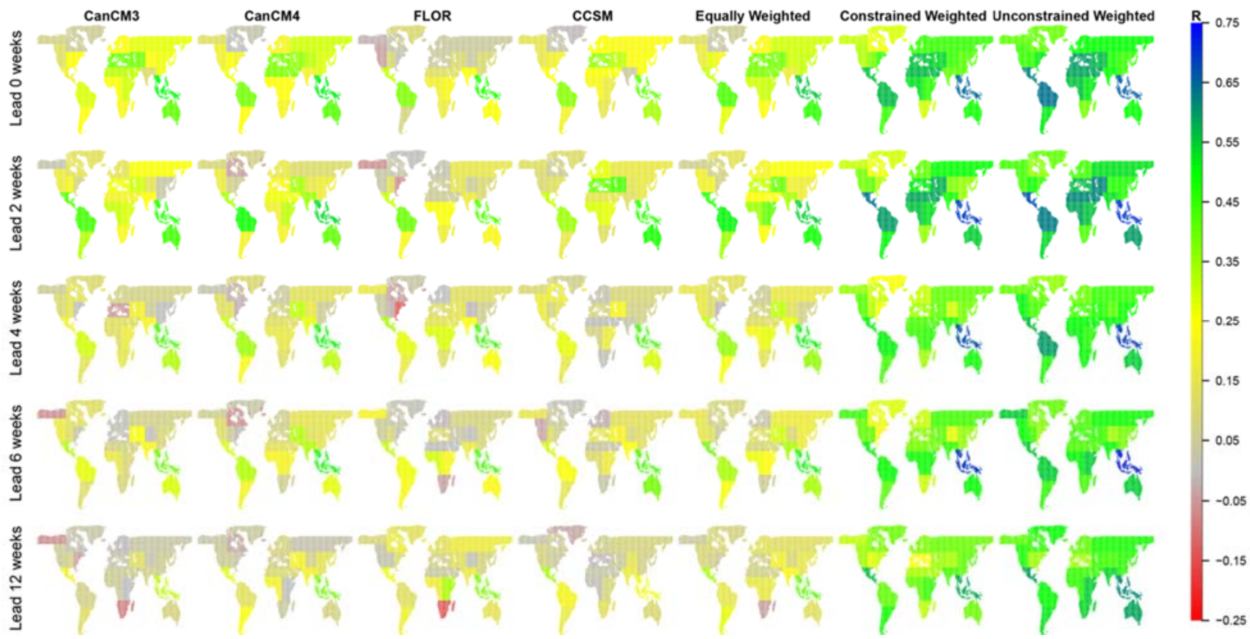

Figure 1 Anomaly correlation between sub-seasonal forecasted and observed precipitation anomalies. Forecasted anomalies are aggregated for specific lag times.

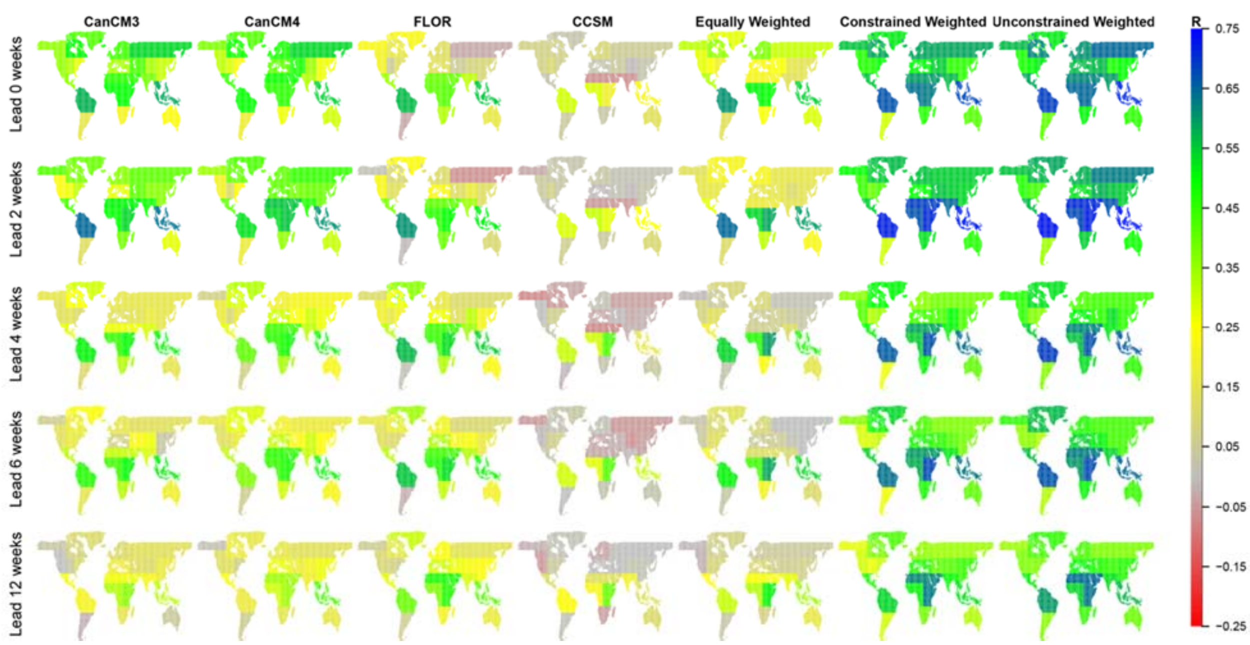

Figure 2 Anomaly correlation between sub-seasonal forecasted and observed temperature anomalies. Forecasted anomalies are aggregated for specific lag times.

3. Sub-seasonal forecast skill.

For the first time ever, the variables needed as inputs to hydrological models are offered from seasonal forecast models and the daily temporal. This increased temporal resolution removes the necessity to perform temporal downscaling, and thereby reduces the barriers for operational hydrological applications. To demonstrate the added value of NMME Phase-2 for hydrological forecasting we have performed a hindcasting experiment for the period 1982-2011. We used the bias-corrected sub-seasonal forecast information to produce global hydrological forecasts of streamflow, runoff, snow water equivalent, soil moisture, groundwater, actual evaporation, water demand and reservoir storage with a bi-weekly temporal resolution at a 0.5-degree spatial resolution. We find that NMME Phase-2 improves the forecast skill (compared to an Ensemble Streamflow Prediction baseline) for longer lead times. In the first weeks to months, the forecast skill (depending on the forecast variable) is more dependent on the initial conditions than on the correct forecast of the meteorological information. This confirms finding by earlier studies, but also clearly shows the potential for NMME at the longer lead times. We show an example of forecasting the evaporation deficit derived from a hydrological model, that uses actual vegetation cover and the soil moisture content to compute the evaporation reduction (Figure 3). We can clearly see that the forecast skill of NMME has added value beyond the 2-4 week lead. Since the evaporation deficit is a good approximation of the water use in irrigated areas, these skillful forecast are very promising for sub-seasonal water management decisions.

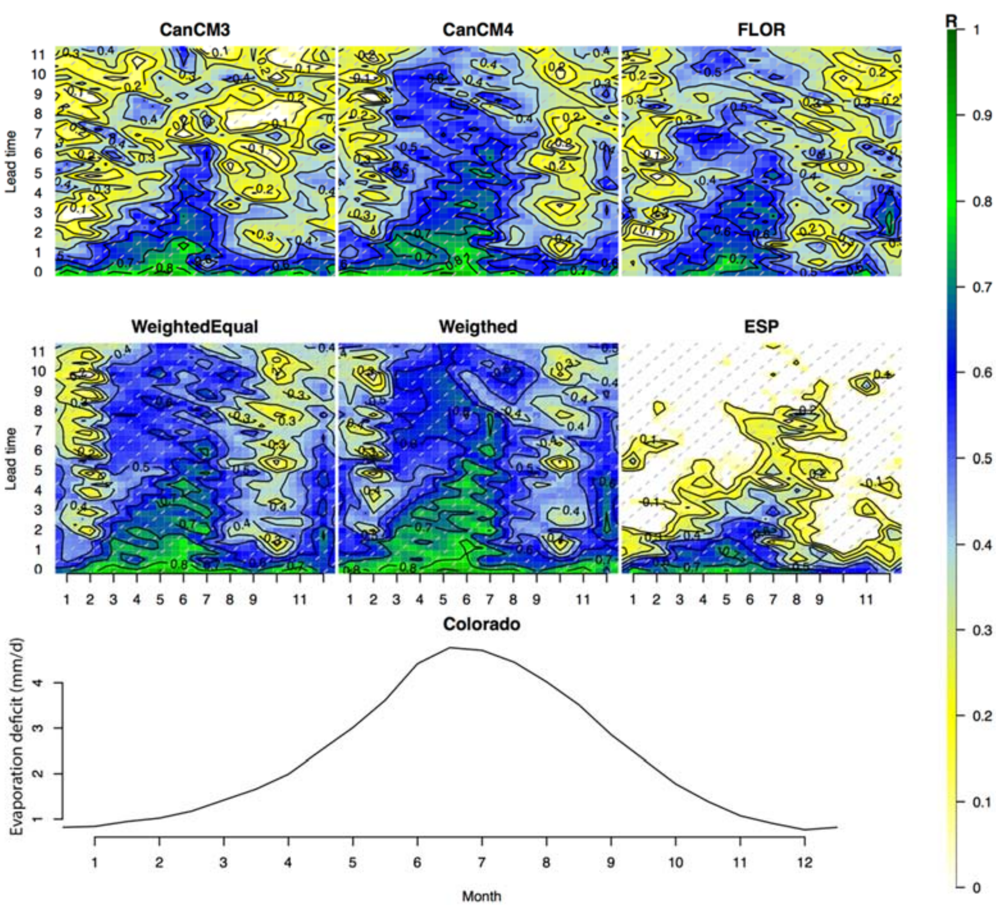

Figure 3 Forecasted Evaporation deficit for the Colorado river basin, based on hydrological simulation with a global hydrological model. The top diagrams, give the forecast skill (anomaly correlation) as a function of target month (x-axis) and the lead time (y-axis). The ESP is used as a reference for the forecast skill.

Year 2 Results and Accomplishments

In the second year of the project, we focused on developing seamless hydrologic forecasting, investigating predictability of subseasonal hydroclimate events, and assessing the potential for real-time applications and high-spatial resolution applications of NMME-2 forecasts. Since we had already completed research activity 3 in the first year of the project, we essentially focused on additional work related to activities 1 and 2.

1 Spatial downscaling of NMME Phase-2 forecasts

The project developed scripts that can automatically pull the available data from the server and use state-of-the-art statistical methods (kriging with external drift in combination with cumulative density function matching) to downscale and bias-correct the forecasts. We have implemented this procedure for the European domain resulting in 5-km resolution forecasts that are consistent with the E-OBS dataset which is widely used in Europe for hydrological applications. In this project we used the model forecasts from FLOR-B01 and CanCM4 to best cover the range of skill that can be obtained from seasonal forecast models (CanCM4, short leads, high skill, FLOR-B01, high skill, long leads). Furthermore, we have established an ongoing collaboration with the Canadian Meteorological Service, where they provide us with real-time sub-seasonal forecasts. These forecasts are downscaled and bias-corrected in real-time at the global scale and used for Africa in our Flood and Drought monitor (http://stream.princeton.edu).

2 Assessment of Phase-2 skill in comparison to Phase-1

We used the bias corrected Phase-2 forecasts from CanCM3, CanCM4, FLOR-B01 and CCSM4 (limited by availability) to make global hydrological forecasts of water scarcity. To demonstrate the added value of NMME Phase-2 for hydrological forecasting we have performed a hindcasting experiment for the period 1982-2011. We used the bias-corrected sub-seasonal forecast information to produce global hydrological forecasts of streamflow, runoff, snow water equivalent, soil moisture, groundwater, actual evaporation, water demand and reservoir storage with a bi-weekly temporal resolution at a 0.5-degree spatial resolution. We find that NMME Phase-2 improves the forecast skill (compared to an Ensemble Streamflow Prediction baseline) for longer lead times. In the first weeks to months, the forecast skill (depending on the forecast variable) is more dependent on the initial conditions than on the correct forecast of the meteorological information. Figure 4 provides an overview of the forecast skill for these forecasts compared to the ESP, which is used a reference.

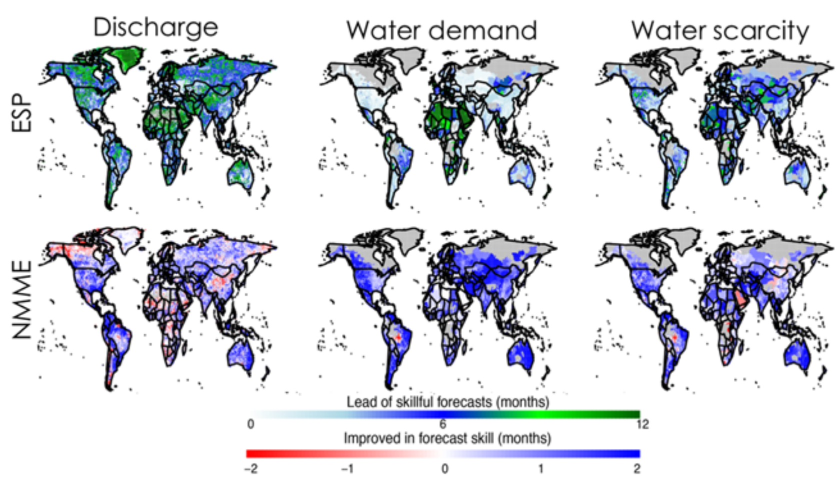

Figure 4 Forecast skill of hydrological sub-seasonal forecast system, compared to the ESP (top row) and the improvements found when NMME-2 is used for the forecasts of Discharge, water demand and water scarcity.

Figure 5 clearly indicate that we have an add skill when using NMME compared to climatological methods. The ESP is a very skillful benchmark, due to pronounced impact of the initial conditions on forecast skill. We have investigated the impact of the initial conditions on the forecast skill using a reverse ESP forecast experiment and we found that the initial conditions are dominant for the first months (Figure 5). This will clearly have an impact on the potential impact of sub-seasonal forecasts as provided by NMME-2.

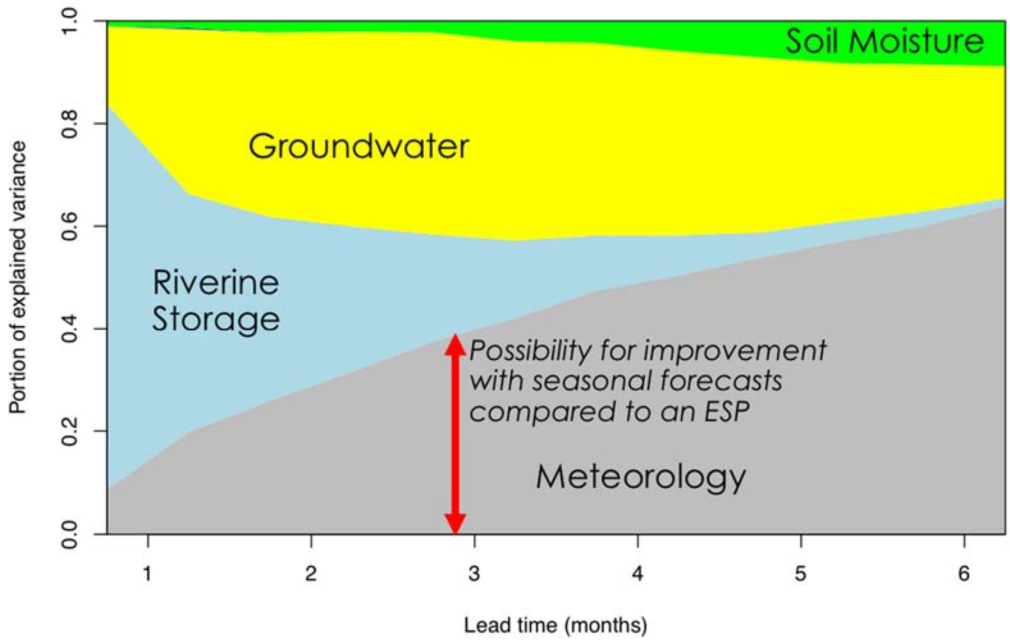

Figure 5 Assessment of the impact of the initial conditions on the explained variance in seasonal forecasts at the global scale. It is clear that the initial conditions are dominant for the first months, leaving only limited potential for seasonal forecast in those months.

During year 2 the sub-seasonal to seasonal hydrological seasonal forecasting skill was assessed through two studies. In Wander et al. (2017), the performances of the NMME forecast models in predicting the 2016 western U.S. hydroclimate were compared to other forecast approaches – mainly statistical methods.

The western U.S. experiences severe drought conditions from 2013-2016, and the emergent, strong El Nino signal led to the expectation that increased precipitation during the 2016 winter would relieve drought in the southern portion of the region. In Wanders et al. (2017) a student forecasting challenge is reported (the challenge was also made to the NMME Task Force and the Drought Task Force of which no one participated). Forecasts of winter hydroclimate across the western U.S. were made on January 1st, 2016 for the winter hydroclimate using several dynamical and statistical forecast methods. The precipitation forecasts had a large spread and no NMME forecasts were skillful, while anomalously high observed temperatures were forecasted with a higher skill and precision. The poor forecast performance, particularly for precipitation, is traceable to high uncertainty in the NMME forecast, which appears to be related to the inability of the models to predict an atmospheric blocking pattern over the north Pacific region.

The results show that the overly strong El Niño sensitivities in dynamical models results in an over-prediction of precipitation in the southern part of the domain. Although the El Niño teleconnection is widely acknowledged in the literature, the sensitivity of large scale climate patterns (and especially precipitation) to the ENSO signal is not as strong as generally believed (see Figure 6). Apart from a small warm anomaly in the Pacific Northwest and a wet anomaly in the West and Southwest, teleconnections between ENSO and observed anomalies are absent throughout most of the region. When the sensitivities are up-scaled using gridded observations at the one-degree spatial resolution of the NMME models, we find a discrepancy between the two patterns. The dynamical forecast models show a much higher sensitivity to ENSO compared to observations (Figure 6).

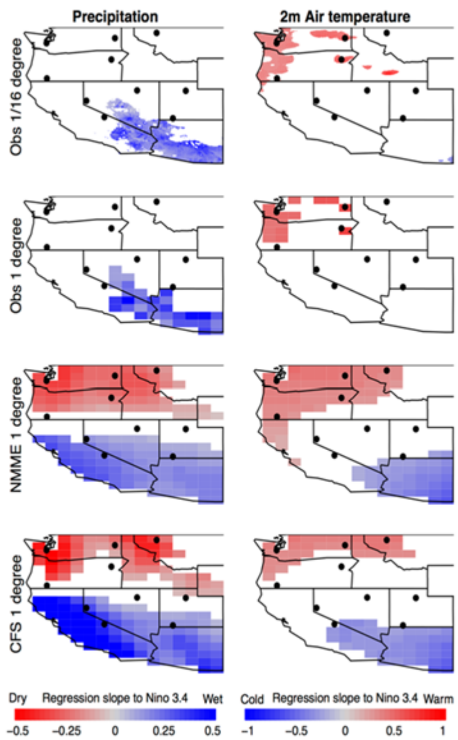

Figure 6: Regression slope between precipitation and temperature anomalies for the winter season (January, February and March) as a function of the Niño 3.4 Index for the period 1982-2010 for gridded observations at 1/16th degree and 1 degree spatial resolutions (upper two rows); NMME (third row), and CFSv2 (lower row). For the NMME and CFS forecasts, the hindcast data from the 1982-2010 for the forecast issued on January 1st were used to determine the regression slope, only regions with significant slopes are shown.

Making operational hydrological seasonal forecasts forced by NMME-2 models should be a high priority for NOAA. The on-going work being developed in Wanders et al. (in preparation) is developing global, operational hydrological seasonal forecasting system based on NMME-2 forecasts. It is critical for regions like Africa that such forecasts be made available to help water resources managers and farmers to improve their decision making. Figure 7 shows the skill of three NMME-2 models over South Africa where we are assessing such forecasts for agriculture management. As discussed in the beginning of this report, its progress is being hindered by the incomplete NMME-2 archive at NCAR.

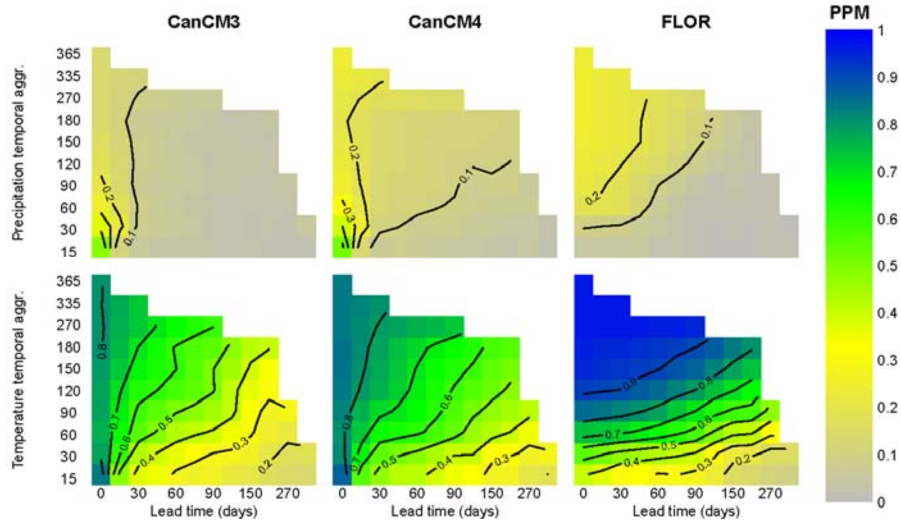

Figure 7 Skill of three NMME-2 seasonal models with lead-time over South Africa.

Highlights from the Project

- We have successfully downscaled the available NMME Phase-2 data to a higher resolution (e.g. to 5-km over Europe). This indicates that there is a potential for using NMME-2 data at these higher spatial resolutions whilst taking advantage of the high temporal resolution that is provided by NMME-2, compared to NMME-1. This higher temporal resolution eliminates the need for temporal bias-correction. We have created a framework that allows us to implement the NMME Phase-2 data into our drought monitoring system if NMME transitions into a real-time phase. This framework will also allow us to include more models of the NMME Phase-2 if they become available.
- We have shown that the NMME Phase-2 forecast skill at the bi-weekly resolution is almost identical to the NMME Phase-1 monthly data. This provides a good prospect for future sub-seasonal forecasting applications that benefit from the higher temporal resolution provided by the Phase-2 data. The new data also creates an opportunity for more seamless forecasts in drought and flood forecasting systems, as can be seen from the high initial skill of some of the models for the first weeks.
- We have shown that the NMME Phase-2 forecast skill provides added value to hydrological seasonal forecast. This is a promising finding that increases the potential impact of NMME-2 for hydrological applications.
- Finally, we have produced one of the first global hydrological sub-seasonal forecasting frameworks that uses sub-seasonal forecast information to produce hydrological forecasts. The results show that there is a high potential for accurate hydrological sub-seasonal forecasting with significant leads, using the new NMME Phase-2 hindcast dataset. We have included real-time sub-seasonal hydrological forecast in our flood and drought monitor and make the forecasts freely available to the public. If more real-time data will become available, we will add this in the existing framework. These forecasts will be available for the general public, and they will have full access to our hindcast archive as reference for forecast skill and forecast climatology.

Publications from the project

- Wanders, N., Wada, Y, Fisher, C.F.K., Wood, E.F., 2017 Operational forecasting of sub-seasonal water scarcity at the global scale, in prep
- Wanders, N., Bachas, A., He, X.G., Huang, H., Koppa, A., Mekonnen, Z.T., Pagán, B.R., Peng, L.Q., Vergopolan, N., Wang, K.J., Xiao, M., Zhan, S., Lettenmaier, D.P., Wood, E.F., 2017,

Forecasting the hydroclimatic signature of the 2015/16 El Niño event on the Western United States, Journal of Hydrometeorology, 18, 177-186, doi: 10.1175/JHM-D-16-0230.1

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- Wanders, N. and Wood, E.F.. 2015, Improved sub-seasonal meteorological forecast skill of extremes using a weighted multi-model ensemble simulation. *Environ, Res. Letts.* 11(9). Art. 094007. DOI: 10.1088/1748-9326/11/9/094007

- Wanders, N. and Wood, E.F., 2015. Assessing seasonal climate forecasts over Africa to support decision making, C-P. Chang, M. Ghil, M. Latif, J.M. Wallace, In World Scientific Series on Asia-Pacific Weather and Climate: Volume 6

Presentations from the project

- Wanders, N., Wood, E.F., 2015. Assessment of (sub-) seasonal prediction skill using a canonical event analysis. Poster at American Geographical Union Fall meeting, San Francisco, USA, 14-18 December 2015
- Wanders, N., Wood, E.F., 2016. The value of the North American Multi Model Ensemble phase 2 for sub-seasonal hydrological forecasting. European Geosciences Union General Assembly, Vienna, Austria, 18-22 April 2016
- Wanders, N., Wada, Y, and Wood, E.F., 2016. Sub-seasonal multi-model predictability of water scarcity at global and local scales, American Geographical Union Fall meeting, San Francisco, USA, 12-17 December 2016
- Ming Pan, Niko Wanders, Eric F. Wood, Justin Sheffield, Luis Samaniego, Stephan Thober, Rohini Kumar, Christel Prudhomme, and Helen Houghton- Carr 2017 High-resolution hydrological seasonal forecasting for water resources management over Europe, Paper EGU2017-9629 European Geosciences Union Meeting, Vienna April 24-28, 2017

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