Project Title: Objective Monitoring and Prediction System for Drought Classification over the Continental United States

PI: Kingtse C. Mo (Climate Prediction Center, NCEP/NWS/NOAA)
Co-PI: Dennis Lettenmaier (University of California, Los Angeles)

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

- To construct and test an objective integrated index (IDI) of drought monitoring based on output from the North American Land Data Assimilation System;
- To improve seasonal hydroclimate forecasts using the GFS outputs;

2. Results and accomplishments
a) Develop an Integrated Drought Index (IDI) for drought monitoring

We explore an objective scheme for drawing boundaries between the D0-D4 classes used by the USDM. The objective is to use one index to classify drought similar to the Drought Monitor so DM authors can use this as an objective first guess for their products. We use multiple drought indices that are derived from NLDAS outputs. For each land surface model produced by the EMC NLDAS system, we calculate the standardized runoff index (SRI) and total soil moisture percentile (SMP) that includes soil moisture and snow water equivalent (SWE). There are four models in total: VIC, SAC, Noah and Mosaic. The horizontal resolution is 1/8 degrees. We put SMP and SRI3 from each model in percentiles. We then form an ensemble mean of all indices. To assure the index is between 0 and 1, we remap the mean index to a uniform distribution by using the climatology of the ensemble (percentiles) averages. We mean index is called Integrated Drought Index (IDI). To assess uncertainties in the classifications, we use a concurrence measure among indices to measure uncertainties in the classification. It indicates the number of indices that agree with the IDI.

CPC now routinely produces SRI3, SMP and IDI for monitoring. The IDI is based on the NLDAS products from the EMC. They are used in the CPC Monthly Drought Briefing to supply Drought Monitor Authors and Drought Outlook Forecasters the current drought information. The indices are updated daily and displayed at the CPC website. Figure 1 gives an example of the drought indices, the IDI and the concurrent measure for the period from 24 July 2017 to 23 August 2017. It indicates drought over the Dakotas and Midwest. The concurrence of all indices D1 and above is high.

2. Drought variability based on the IDI

We examined drought variability over the conterminous U.S. (CONUS) using observed precipitation (P) and reconstructed total moisture percentile (TMP) that is defined as the sum of soil moisture and snow water equivalent, and runoff from four land surface models (VIC, SAC, Noah and Catchment) from the UCLA over the period 1916-2013. We used an integrated drought index (IDI), which we defined as the equally weighted mean of 3-month standardized runoff index (SRI3) and TMP from four land surface models mapped onto a uniform probability distribution. The IDI is used to study drought variability over the United States. The drought is defined the same way as the indices. For drought to be classified as D0 or above, the IDI needs to be greater than 0.3. One important element for drought is persistence. For a given region, the IDI can be below 0.3 but not persist. If the IDI is below 0.3 for six months or longer, we define the region as under drought.

Figure 2a displays as an example the percentage of months that IDI<0.3 and persists for 6 months or longer. It shows that low IDIs are more likely to persist over the Central United States (85-110 ^{o}W), a consequence of which is that droughts have longer duration in this part of the country. The fraction of months under drought and duration of droughts trends slowly downward across the driest part of the West (keep in mind that IDI measures are relative to climatology), and then decrease rapidly for the coastal Pacific Northwest, where the percentage of months (for which IDI < 0.3) drops to around 40%. The percentage for California is slightly higher. Along the pathway of moisture inland from the Gulf of Mexico into the Southeast and the eastern U.S., the IDI tends to be less persistent.

Using a definition of drought as IDI less than 0.3 for 6 months or longer, we found 16 drought events that covered more than 50% of the CONUS during our study period (1916-2013). 13 of these events were located at least partially over the Central U.S. We found that most of these large droughts occurred when cold sea surface temperatures (SSTAs) were located in the tropical Pacific with warm SSTAs in the North Atlantic. The composite of SSTA of these 13 events is given in Fig. 2b. Figure 2c displays the atmospheric responses represented by the composite of 500 hPa height anomalies of the above 13 drought events. The SSTA composite shows cold SSTAs in the Tropical Pacific and warm SSTAs in the North Atlantic and slightly weaker positive SSTAs in the North Pacific. The height anomaly composite indicates a wave train with an anti- cyclone located at the central United States which prevents moisture transported from the Gulf of Mexico to the Central U.S.

We also found a predominance of decreasing trends in the IDI; droughts occurred less often and events were less severe as time progressed. In addition to long term trends, we found strong decadal variations in drought occurrence. Before the 1970s, droughts were more likely to occur over the Central and Western U.S. when cold SSTAs were located in the tropical Pacific and warm SSTAs in the North Atlantic. After 1980, droughts also began to occur when SSTAs in the tropical Pacific were warm.

3. **Improve CFSv2 seasonal forecasts using the short term GEFS forecasts**

At current time, soil moisture (SM) and runoff forecasts are based on the land surface model VIC driven by forcing derived from the CFSv2 monthly mean forecasts. The forecasts are skillful for one month and skill comes mostly from the initial conditions. The project will test a new method by combining the CFSv2 and GEFS (MRF) daily P and T_{air} outputs. The first 16 days of the CFSv2 forecasts will be replaced by the GEFS (MRF) forecasts of P and T_{air} because the GEFS uses higher resolution and better model and have higher skill than the CFSv2 daily forecasts. Forcing terms were derived from the systematic error corrected T_{air} and P. Forcing was used to drive a VIC model to obtain SM and runoff. Evaluation will be done for different regions and seasons because different indices have strength and weakness over different regions for different seasons. Drought indices will have the horizontal resolution 1/8 degrees to give local details of the drought development. Figure 3 shows the forecast skill for CFSv2, MRF_CFSv2 merged forecast skill for runoff at one month lead and their differences.

For T_{air} and P, there are improvements by replacing the first 16 days of the CFSv2 forecasts by the GERF forecasts because GEFS has high resolution (not shown). CFSv2 has the initial conditions five days apart so members 5 or 10 days away from the target date will have low skill. However for SM and runoff, the differences are small. This suggests that skill for SM and runoff for lead 1 month comes from the initial conditions. The climate forcing does not play a strong role.

4. Flash droughts over the United States.

Flash drought refers to relatively short periods of warm surface temperature and anomalously low and rapidly decreasing soil moisture (SM). Based on the physical mechanisms associated with flash droughts, we classify these events into two categories: heat wave and precipitation (P) deficit flash droughts. Heat wave flash droughts are initialized by severe warm air temperature. Heat waves increase evapotranspiration (ET) due to vegetation. That leads to decreasing SM. Heat wave flash droughts tend to occur in the North Central region and the Pacific Northwest where vegetation is relatively dense.

P deficit flash droughts, as their name suggests, are initialized by P deficits. The lack of P decreases SM. In areas where SM and ET anomalies have a linear relationship, ET decreases. That leads to increasing sensible heat and high temperatures. In this sense, high temperatures are the consequence of P deficits. P deficit flash droughts are most prevalent over the southern United States with maxima over the Southern Great Plains and the Southwest.

We monitor flash droughts using four variables (T_{2m}, P, SM and ET). We take P and T_{2m} from the CPC unified P and surface temperature analyses. SM and ET are outputs from the VIC land surface model (VIC.4.0.6) forced by T_{2m} , P and surface wind speed. Our base period is from 1979 to 2015. We use pentad data in our analyses

4. Highlights of Accomplishments

- To use one index (IDI) to monitor drought;
- Identify the preferred region for drought to occur and the SSTAs to maintain drought
- By replacing the first 14 day CFSv2 by the MRF forecasts, the forecast skill for temperature improves. For soil moisture and runoff, the skill for the first month comes from initial conditions so there is little improvement
- Initial studies of flash drought over the United States.

5. Transition to Applications

The Integrated Drought Index (IDI) is produced daily from the EMC NLDAS and it is used in the CPC monthly drought briefings.

6. Publications from the Project

Mo, K. C. and D. P. Lettenmaier, 2014a: Hydrologic prediction over Conterminous U.S. using the National Multi Model Ensemble. *J. Hydromet*. 15, 1457-1472.

Mo, K. C. and D. P. Lettenmaier, 2014b: Objective drought classification using multiple land surface models, *J. Hydromet*. 15, 990-1010.

Xiao, M., B. Nijssen and D. P. Lettenmaier, 2016: Drought in the Pacific Northwest 1920-2013. *J. Hydromet*. Doi:10.1175/JHM-D-15-0142.1

Mo, K. C., and D. P. Lettenmaier 2017: Drought variability over the central United States. To be submitted to *J. Clim*.

7. PI Contact Information

PI- Kingtse C. Mo
Climate Prediction Center
NCEP/NWS/NOAA
5830 University Research Ct
College Park, Md 20769
Email : Kingtse.mo@noaa.gov

Co-PI
Dr. Dennis P Lettenmaier
Department of Geography
University of California, Los Angeles
Email: dlettenm@ucla.edu

Figure 1

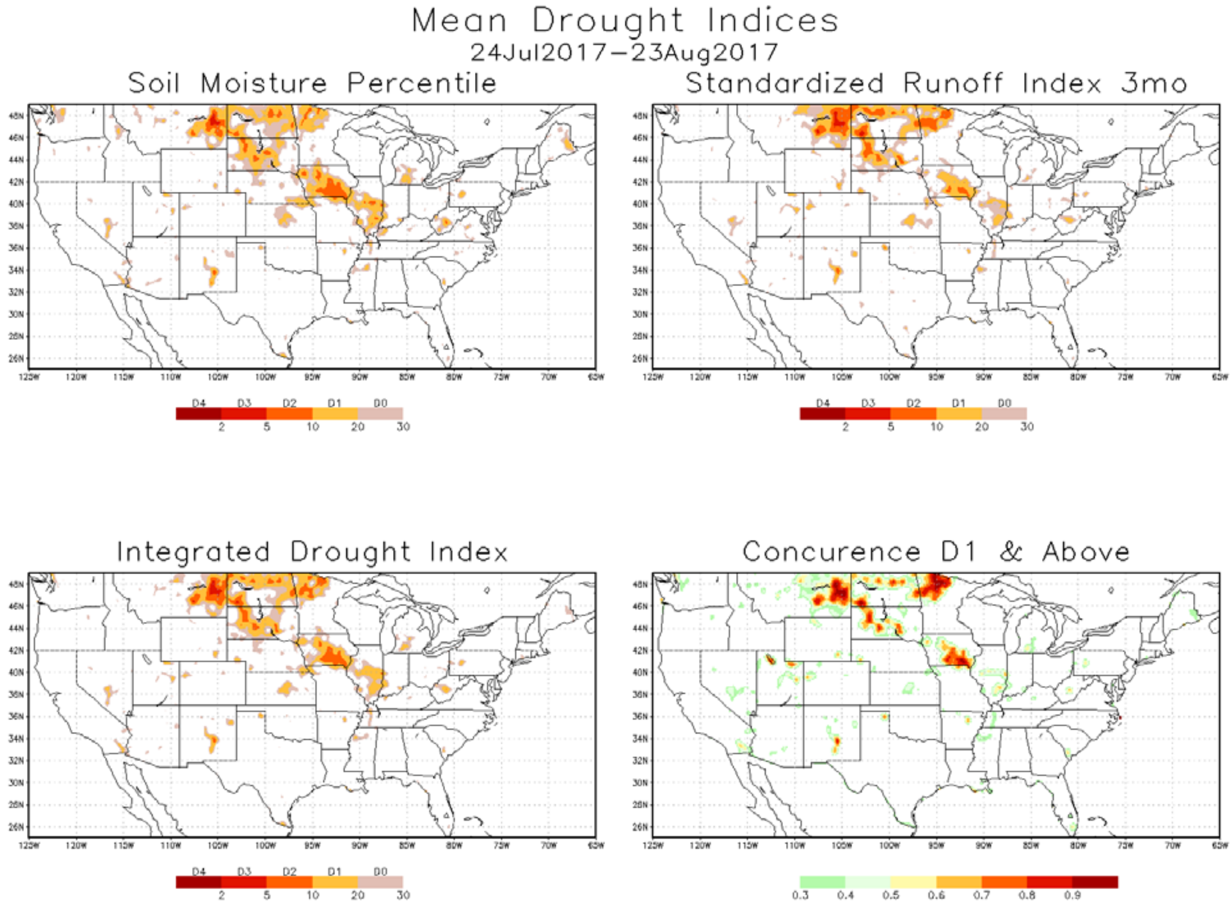

Figure 1: Mean drought indices for the period from 24Jul 2017 to 23 August 2017 for soil moisture percentiles, standardized runoff index with 3 month smoothing, integrated drought index and concurrence measure for drought D1 and above.

Figure 2

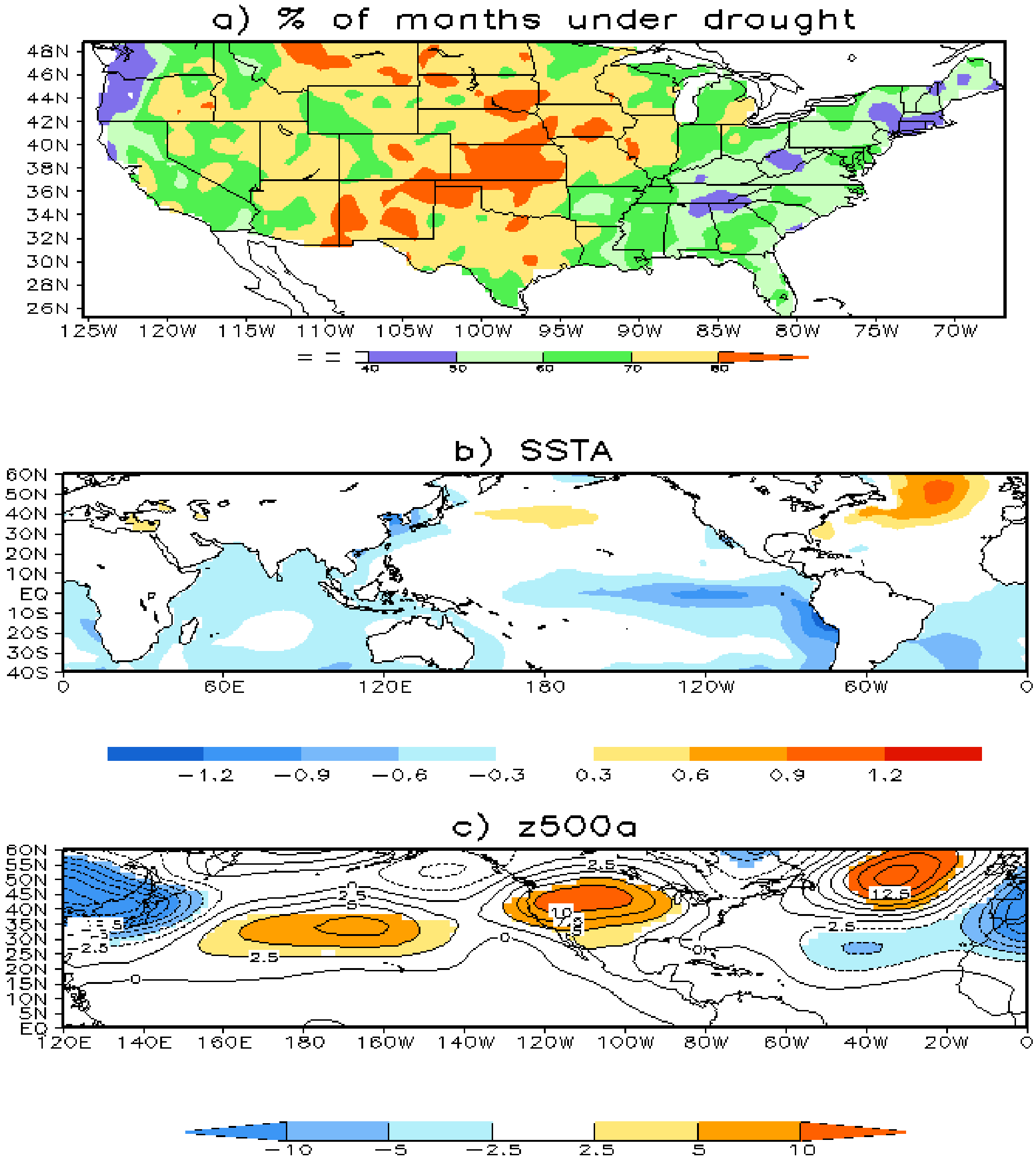

Fig. 2: Conditions of mega droughts. (a) $R=N_d/N_p$, the percentage of months N_d that the IDI<0.3 and persisted for 6 months among N_p (the number of months that IDI<0.3). Contours are given by the color bar; numbers are percent; (b) composite of mean SSTAs averaged over the duration of events for 12 drought events that were associated with cold SSTAs in the Tropical Pacific . Contours are given by the color bar; units are ^{o}C; (c) same as (b) but for mean 500 hPa heights with zonal means removed, units are meters.

Figure 3

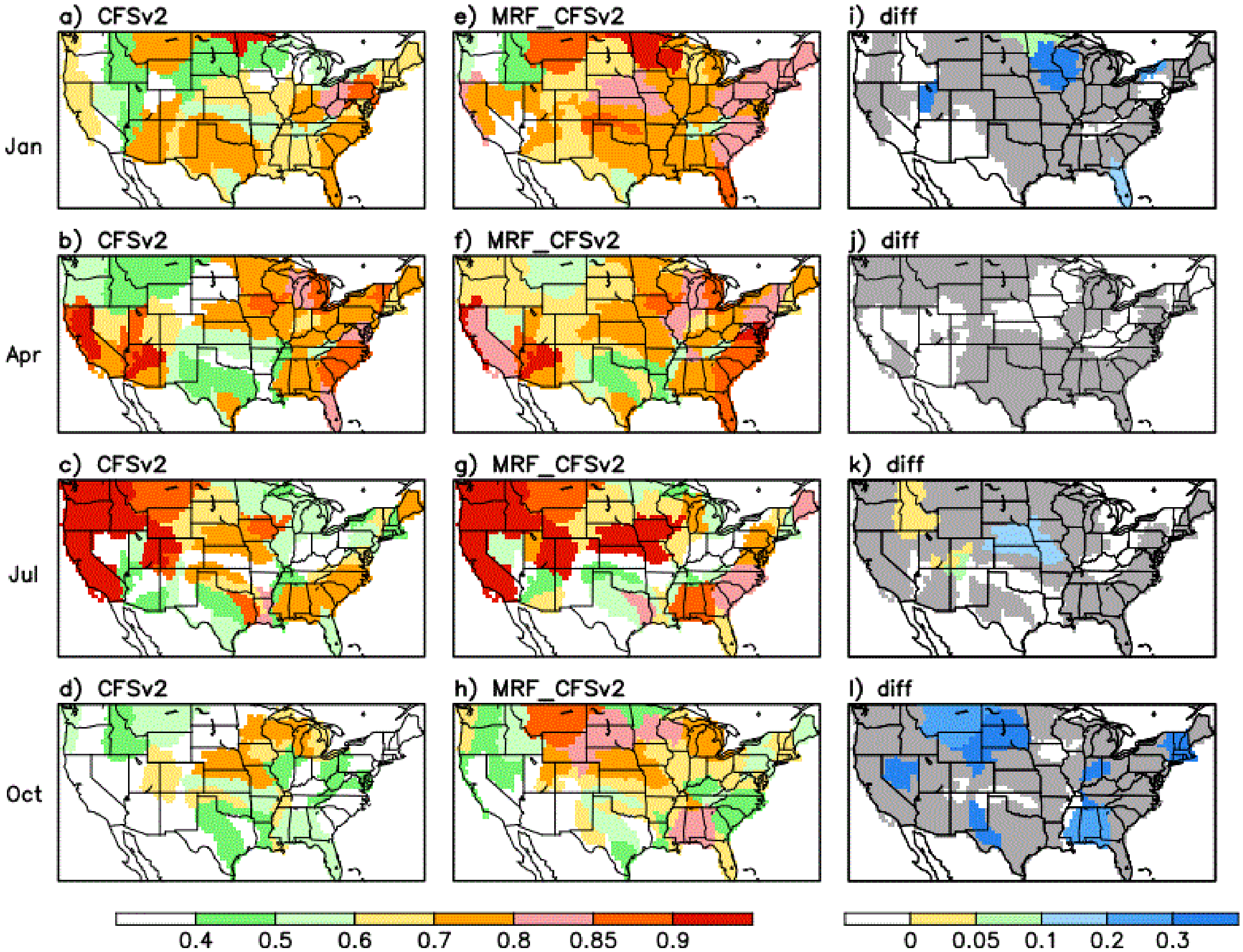

Figure 3. Correlation between forecasted runoff and simulated runoff by the VIC model for lead month 1 for CFSv2 forecasts initialized in (a) 1January, (b) 5 April, (c) 5 July and (d) 3 October. The skill is given by the color bar. White color indicates the sub regions that forecast are not statistically significant at 5% level, (e) -(h) same as (a)-(d) but for the MRF_CFSv2 merged forecasts, and (i)-l) same as (a)- (d) , but for the difference in skill between the MRF_CFSv2 merged forecasts and CFSv2 forecasts. Grey areas indicate areas that differences are not statistically signifiocant at the 5% level.