



Monitoring and predicting the 2007 U.S. drought

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[1] Severe droughts developed in the West and Southeast of the U.S. starting early in 2007. The development of the droughts is well monitored and predicted by our model-based Drought Monitoring and Prediction System (DMAPS). Using the North America Land Data Assimilation System (NLDAS) realtime meteorological forcing and the Variable Infiltration Capacity (VIC) land surface model, DMAPS is capable of providing a quantitative assessment of the drought in near realtime. Using seasonal climate forecasts from NCEP's Climate Forecast System (CFS) as one input, DMAPS successfully predicted the evolution of the droughts several months in advance. The realtime monitoring and prediction of drought with the system will provide invaluable information for drought preparation and drought impact assessment at national and local scales. **Citation:** Luo, L., and E. F. Wood (2007), Monitoring and predicting the 2007 U.S. drought, *Geophys. Res. Lett.*, *34*, L22702, doi:10.1029/2007GL031673.

1. Introduction

[2] Droughts are as much a part of weather and climate extremes as floods, hurricanes and tornadoes are, but they are the most costly extremes among all natural disasters in the U.S. [Ross and Lott, 2003]. The estimated annual direct losses to the U.S. economy due to droughts are about \$6–\$8 billion, with the drought of 1988 estimated to have damages over \$39 billion [Federal Emergency Management Agency, 1995]. One possible reason for such huge losses is the lack of prompt and comprehensive preparation and response to droughts due to the lack of proper recognition of drought development. Unlike other natural disasters, droughts develop slowly over large areas and over an extended period of time, making it difficult to identify them until they have become severe and some damage has already occurred. Therefore, accurate quantitative assessment of drought conditions and the prediction of the on-set, duration and recovery of droughts in realtime are critical for drought planning and preparedness.

[3] Since the beginning of 2007, new drought conditions have been developing in several large regions within the continental U.S. In the West, very little rain fell over much of California during the winter-spring of 2006-2007. The severe-to-extreme drought across the West has resulted in the dramatic spread of fire activities in some parts of the

region, also putting the rest of the region in high risk for fire. However, drought conditions have probably been most severe in the Southeast in terms of the impact on agriculture and the local economy. Much of Alabama was in the midst of the worst drought it has experienced in more than one hundred years (B. Riley, State of Alabama, Governor's office press release, available at http://www.governorpress.alabama.gov/pr/pr-2007-07-16-01-water_shortchanged-video.asp, July 30, 2007).

[4] In the continental U.S., direct measurements of soil moisture are only available at the point scale at a limited number of sites, such as the Oklahoma Mesonet, ARM/CART, Illinois, and NRCS sites. With these limited observations, it is impossible to construct a realtime soil moisture map for drought monitoring over the U.S. However, extensive observational networks have been established to measure meteorological variables such as precipitation (NEXRAD, NWS CO-OP sites) and temperature, as well as hydrological variables like streamflow (USGS). The availability of reliable measurements of meteorological variables in realtime creates the opportunity to assess soil moisture conditions across the continent via a model-based framework since state-of-the-art hydrological models can produce land surface states reasonably well when forced with observed meteorological forcing [Robock *et al.*, 2003].

[5] Starting in 2005, we have been developing a model-based drought monitoring and prediction system (DMAPS) that takes advantages of available observations, the state-of-the-art land surface and climate models, and innovative statistical methods. DMAPS is essentially the seasonal hydrologic prediction system described by L. Luo and E. F. Wood (Seasonal hydrologic prediction with the VIC hydrologic model for the eastern U.S., submitted to *Journal of Hydrometeorology*, 2007, hereinafter referred to as Luo and Wood, submitted manuscript, 2007) combined with a hydrologic nowcast system. This paper presents the application of DMAPS to monitoring and predicting the 2007 drought over the U.S., focusing on the prediction of the drought evolution over the West and the Southeast, where the drought is most severe and drought monitoring and prediction are most valuable. The next section briefly describes the methodology behind the drought monitoring and prediction system, followed by the verification of the prediction for the recent drought.

2. DMAPS Methodology

[6] Figure 1 provides a schematic diagram of our current approach for drought monitoring and prediction over the U.S. The central element of DMAPS is the Variable Infiltration Capacity (VIC) hydrological model [Liang *et al.*, 1996; Cherkauer *et al.*, 2003] that transforms meteorological information into hydrological information such as soil moisture and streamflow. VIC is one of the state-of-the-

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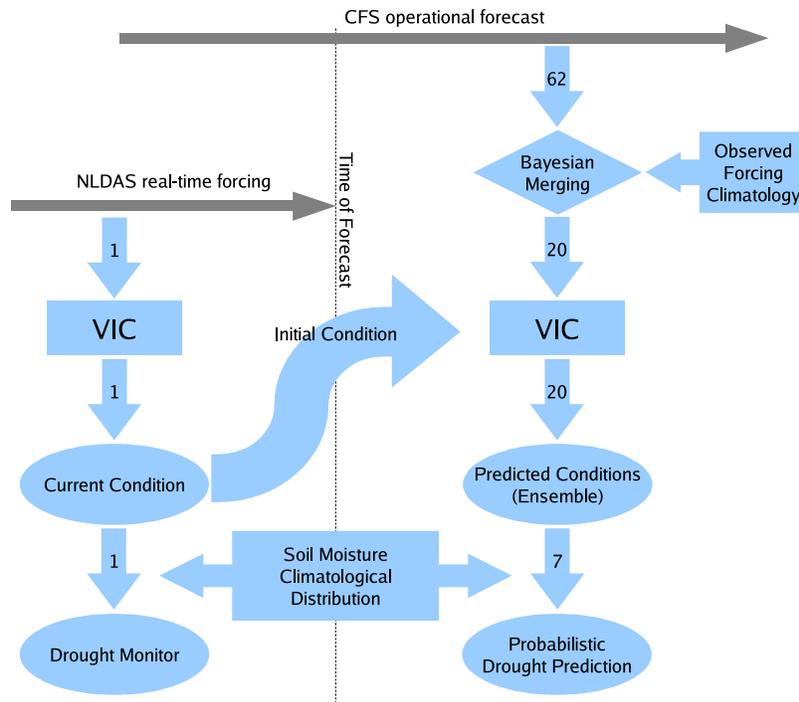


Figure 1. Schematic diagram of the drought monitoring and prediction system (DMAPS). Numbers on the arrows indicate the number of ensemble members.

art macroscale hydrological models available, and it has been calibrated, validated and evaluated in numerous studies at grid, basin and continental scales [Nijssen *et al.*, 1997; Wood *et al.*, 1997; Cherkauer and Lettenmaier, 1999; Maurer *et al.*, 2002; Roads *et al.*, 2003; Nijssen *et al.*, 2001; Sheffield and Wood, 2007].

[7] For drought monitoring, the approach is to use the VIC model with realtime atmospheric forcing provided by the North American Land Data Assimilation System (NLDAS) [Mitchell *et al.*, 2004] to estimate the current total column soil moisture at each 1/8 degree grid across the continental U.S. A drought index value is computed for each grid, where the index is expressed as a percentile value of the current soil moisture with respect to its climatological probability distribution [Sheffield *et al.*, 2004]. The climatological distribution at each grid was obtained by running the VIC model with an observational atmospheric forcing dataset [Maurer *et al.*, 2002; Cosgrove *et al.*, 2003] for the period of 1949–2004, then sampling daily soil moisture values from days that are within a 49-day sampling windows centered on the current day of each year. This gives a reasonable representation of the modeled soil moisture climatology with over 2500 samples. Both the realtime NLDAS forcing and the historical forcing are observation based and their quality was validated in several studies [Luo *et al.*, 2003; Maurer *et al.*, 2002]. The soil moisture values obtained from these simulations have been shown to accurately represent soil moisture dynamics [Robock *et al.*, 2003; Maurer *et al.*, 2002]. Because the soil moisture percentile-based drought index provides a quantitative measure as a spatially continuous field, it can be used in drought forecasting. The drought assessment from our index and those of the Climate Prediction Center’s (CPC) Drought

Monitor [Svoboda *et al.*, 2002] are very comparable (see <http://hydrology.princeton.edu/forecast/>). The major differences between the two are that CPC’s drought monitor is subjective to some extent since its drought intensity map blends five key indicators and numerous supplementary indicators together by analysts, and that CPC’s drought monitor includes hydrologic drought which is defined as a low snowpack, lowflows in rivers and reservoirs.

[8] The drought prediction component utilizes the seasonal hydrologic prediction system described in detail by Luo and Wood (submitted manuscript, 2007). A brief description of the forecast approach is provided here. As illustrated in Figure 1, the system implements a Bayesian merging procedure [Luo *et al.*, 2007] to combine seasonal forecasts from dynamical climate models with observed climatology at monthly level to obtain posterior distributions for monthly precipitation and temperature at each grid for each month of the forecast period. During this process, it effectively removes biases in climate model seasonal forecasts and statistically downscales the forecasts from climate model scales to the smaller scale that is more appropriate for hydrologic applications. When making seasonal hydrologic predictions at the beginning of each month, DMAPS takes all the members from NCEP’s Climate Forecast System (CFS) [Saha *et al.*, 2006] seasonal forecast issued during the previous month and pass them through the Bayesian merging procedure to obtain the posterior distributions that are sampled to generate 20 atmospheric forcing ensembles for the hydrologic prediction. The 20 atmospheric forcing time series are based on 20 historical daily forcing time series from the dataset provided by Maurer *et al.* [2002] and adjusted at the daily level to match the monthly forecast values sampled from the posterior distribution. Half of the

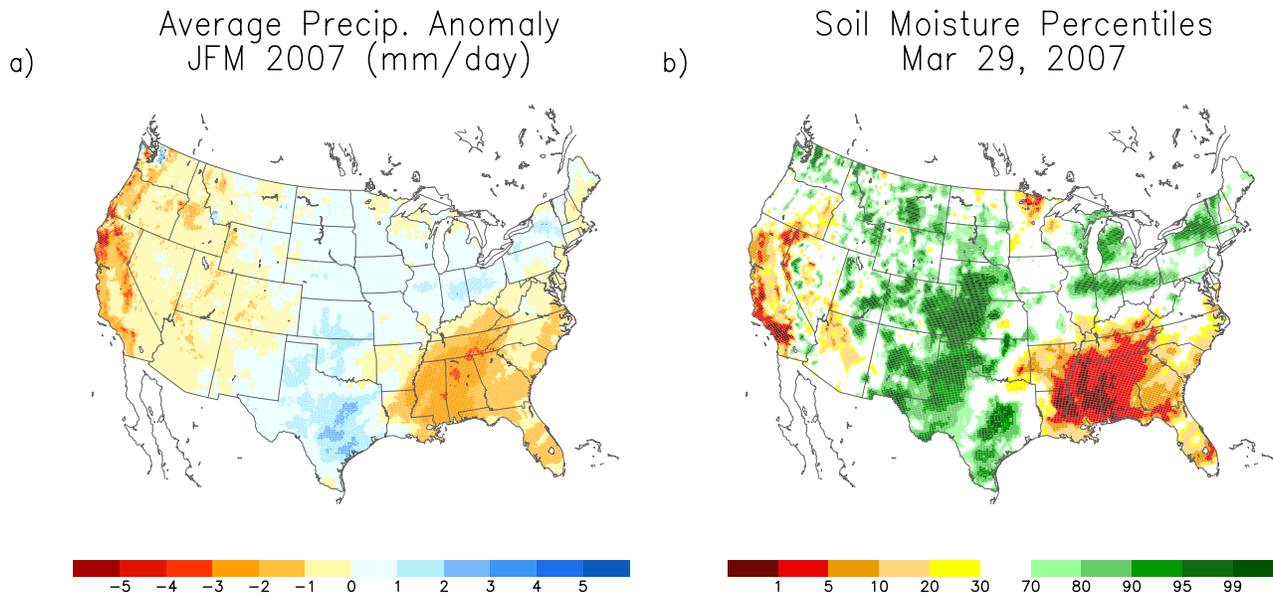


Figure 2. Average precipitation anomaly for JFM 2007 and the soil moisture conditions on March 29, 2007.

members are selected randomly from all available historical records and the other half are selected with a historical-analogue criterion. In the historical-analogue criterion, all historical precipitation patterns are compared with the current predicted precipitation pattern (mean of the posterior distribution) and are sorted by their similarities to the current predicted pattern. The similarity is simply measured by the root mean square difference (RMSD) of the two, calculated for all grids in the region and all six-month periods. The likelihood of realization for each ensemble member is considered to be larger if its RMSD value is smaller. Therefore the 10 historical years with the smallest RMSD values are selected. Although simple and empirical, this selection criterion considers the similarity in spatial and temporal patterns in monthly precipitation anomalies. The small ensemble set formed by the seven members with largest likelihood of realization is noted as the “most-likely ensemble set”. As shown in the next section, using the CFS seasonal climate forecasts, the hydrological prediction with the most-likely ensemble set has shown promising skills in predicting the recent droughts over the West and Southeast of U.S.

3. Results

[9] The drought monitoring portion of our DMAPS system started running in realtime in August 2005, and the soil moisture index maps are updated weekly on Sundays. Figure 2 shows the precipitation anomaly for the first three months of 2007 over the U.S. and the soil moisture condition at the end of the period. During this period, the lack of precipitation in the West and the Southeast U.S. has resulted in a drier-than-normal soil moisture condition. Southern California and part of Alabama show soil moisture values lower than the 5th percentile of the historical distribution – exceptional drought conditions. This corresponds well with the CPC’s U.S.

Drought Monitor, but provides a quantitative estimate with more spatial detail. Because we are monitoring the soil moisture index, our system also indicates regions where soil is wetter than normal due to excess precipitation, such as the northern part of Texas during 2007. This information will help us to evaluate the flooding potential in the future, which is not the focus of this paper.

[10] The recent U.S. droughts over the West started to develop from January 2007 and worsened in February and March, but the severe drought over the Southeast mainly developed during March. These developments were well captured by the monitoring and well predicted by our drought prediction made from the initial conditions on January 1, 2007. Figure 3 compares the predicted soil moisture conditions from the most-likely ensemble set of the 200701 forecast with the “observed” soil moisture condition from our realtime drought monitoring. The prediction indicates a severe drought developing over California and the ensemble spread (expressed as the difference in percentile values of the lower and upper quartile of the ensemble distribution) is small suggesting a highly confident prediction over the region (see the contours of the inter-quartile range in the left hand portion of Figure 3). Over the Southeast, it is predicted that a relatively weaker drought condition develops in February and expands to the entire Southeast in March. However, the ensemble spread is large (~ 30), suggesting that less confidence should be given to the prediction. Compared with the soil moisture conditions from the drought monitoring, the prediction over the West gives a very good correspondence in terms of the area and severity of the drought with accuracy values of 0.93, 0.92 and 0.88 for predicting the event of soil moisture below the 20th percentile over the region during the first three months. Over the Southeast, the prediction is satisfactory but slightly less skillful with accuracy values of 0.94, 0.54 and 0.44. It under-predicted the severity of the drought locally over Mississippi, Alabama and Tennessee, but over-predicted the severity for the East Coast. Since the ensemble

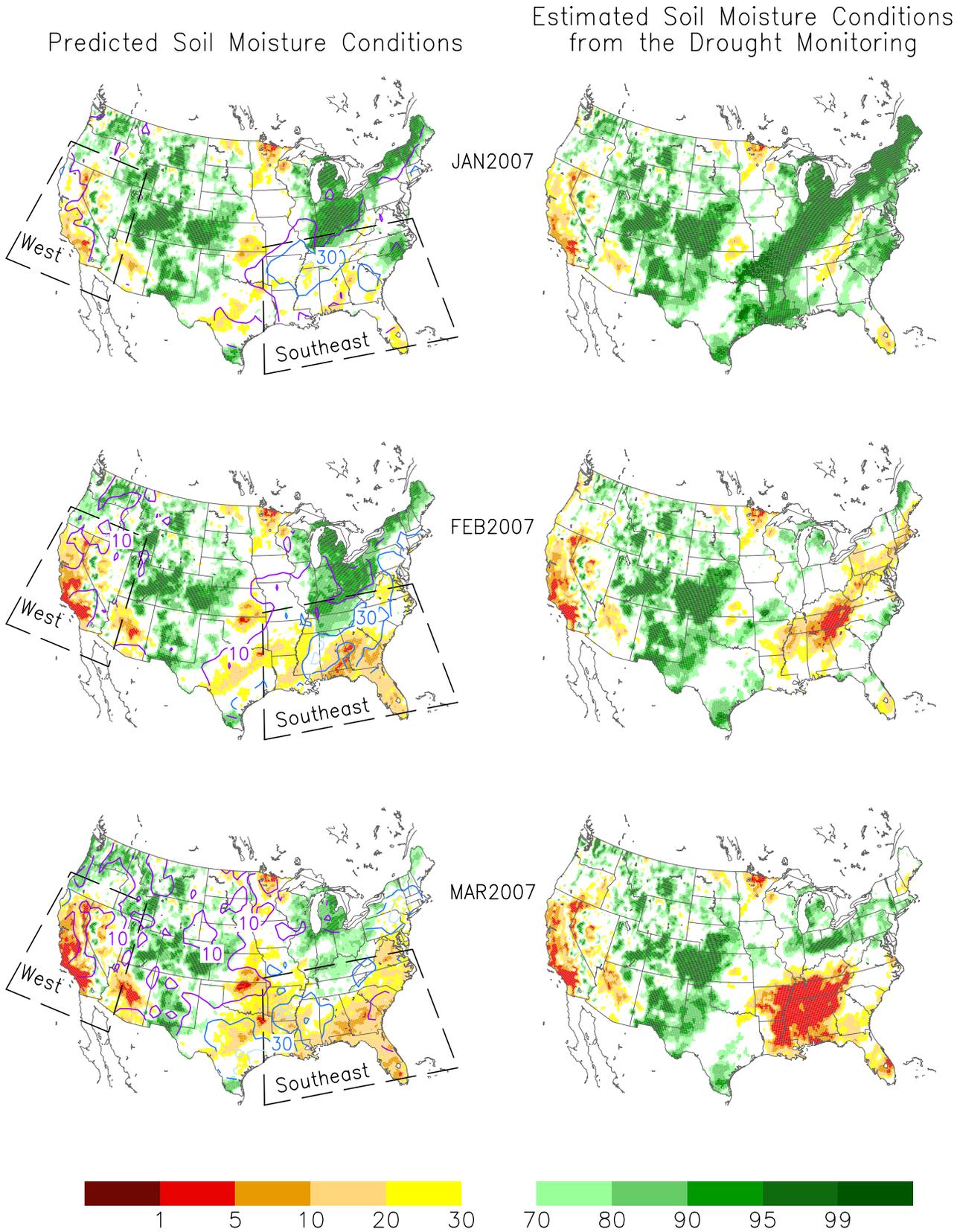


Figure 3. Predicted soil moisture index for the first three months of the 200701 forecast that uses the initial condition on January 1, 2007, compared with the estimated soil moisture index from the realtime drought monitoring. Left column shows the mean of the most-likely ensemble set (shaded) and their spread (contour). See section 2 for the definition and basis of the index.

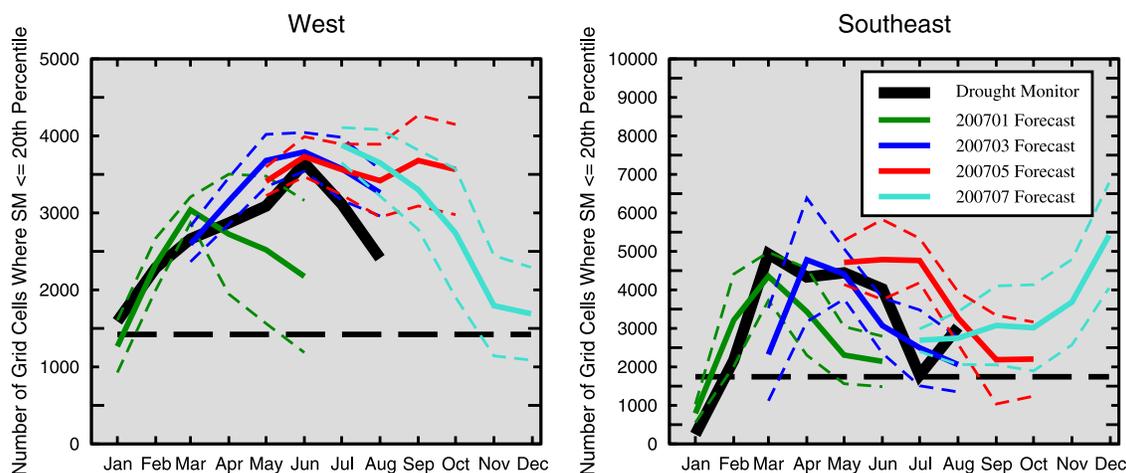


Figure 4. Drought predictions with DMAPS over the West and the Southeast. Shown is the area (number of grid cells) where soil moisture index is below 20 (i.e., the 20th percentile of the climatological soil moisture distribution from the offline simulation). See text for a further discussion.

spread is quite large over these regions, such forecast errors are not surprising.

[11] To further evaluate the skill of the predictions, Figure 4 shows the evolution of the droughts and their predictions over the West and the Southeast defined by boxes on Figure 3. Within each region, the number of 1/8 degree grids where the monthly mean soil moisture value is below the 20th percentile threshold is counted for each month. The black solid lines in Figure 4 are from the realtime drought monitoring and represent the development of the droughts. For the predictions, grids that satisfy the same criteria are counted in each of the seven ensemble members and the counts are averaged to give the mean forecasts (solid green, blue and red lines). The spread of each ensemble forecast is indicated by the dashed color lines as one standard deviation from their mean. Evidently, the predictions are very skillful in capturing the evolution of the droughts over both regions, especially during the first two months of each forecast. Since predictability decreases with lead time, as illustrated by Luo and Wood [2006], we expect that forecast skill will also decrease with lead time, which is supported by the increase in ensemble spread and with the mean forecasts approaching climatology. Therefore, when interpreting the prediction, we tend to trust the predictions more at the shorter lead times. The 200703 prediction made with the initial conditions on March 1, 2007 also captures the expansion of the drought over the West from March to June. According to the 200705 prediction, the drought over the West will persist while the Southeast will gradually recover from drought in the late summer and fall. The most recent forecast (200707) suggests that the drought over the Southeast will only recover slightly during the late summer, and may expand northward and become more severe during the fall (Figure 4).

4. Conclusions

[12] As shown in this study (including the results on our drought monitoring web site: <http://hydrology.princeton.edu/forecast/>), as well by Sheffield et al. [2004] and Andreadis and Lettenmaier [2006], model-based drought monitoring systems provide an accurate and quantitative measure of

land surface hydrological conditions, given that they are forced with high quality meteorological data. This study also demonstrates the feasibility of doing drought prediction using seasonal forecasts from dynamic climate models. Although forecasts from dynamic climate models have limited skill over the mid-latitudes in precipitation and temperature predictions, the drought prediction for the recent U.S. drought and hindcasts over the Ohio River basin (Luo and Wood, submitted manuscript, 2007) indicate the possibility of boosting forecast skills by statistically bias correcting and downscaling climate model forecasts via the Bayesian merging procedure. In the presented case, DMAPS was able to predict the onset of the current severe drought over the West with great confidence (small ensemble spread) several months in advance, and the spatial pattern and severity of the predicted drought correspond well with the subsequent realtime drought monitoring of ground conditions. In the Southeast, the system also predicted dry conditions, but the location, area and severity of the drought are not as accurate and the confidence is lower, as indicated by the spread of the ensemble distribution. This suggests that the ensemble spread is also informative when interpreting ensemble predictions.

[13] This paper only shows one successful case, and more drought cases are needed to show robustness of the results. We are in the process of analyzing a series of historical droughts in the US with the system and will report these results when the analysis is completed. A more comprehensive evaluation of the forecast skill of the seasonal hydrologic forecast system is shown by Luo and Wood (submitted manuscript, 2007).

[14] Our current drought forecast system uses the ensemble seasonal forecast from CFS within the Bayesian merging procedure, but the system can potentially use forecasts from multiple models. As illustrated by Luo et al. [2007], a multi-model Bayesian merging produces more reliable and skillful forecasts as compared with forecasts from one single dynamic model. Our expected implementation of this procedure with seasonal forecasts from multiple seasonal climate models will further improve the accuracy of the drought recovery estimates and should help the develop-

ment of National Integrated Drought Information System (NIDIS).

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