Report as of FY2007 for 2006WA180G: "West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS"

Publications

- Articles in Refereed Scientific Journals:
    - Lettenmaier, D. P., A. W. Wood and K. Andreadis, 2006, A System for Real-time Prediction of Hydrological and Agricultural Drought over the Continental U.S., EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract G31A-07.
    - Wood, A. W., A. Steinemann, D. Alexander,and S. Shukla,2006, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract HC53-0648.
    - Fontaine, M. and A. C. Steinemann, Assessing Vulnerability to Natural Hazards: An Impact-based Method and Application to Drought in Washington State, ASCE Natural Hazards Review (in press).
    - Fontaine, M. M., A. C. Steinemann, and M. J. Hayes, State Drought Programs: Lessons and Recommendations from the Western U.S. ASCE Natural Hazards Review (in review).
    - Shukla, S. and A. W. Wood, 2007, Application of LDAS-era Land Surface Models for Drought Characterization and Prediction in Washington State (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H43A-0962. San Francisco, California.
    - Shukla, S., and A.W. Wood, 2008, Use of a Standardized Runoff Index for Characterizing Hydrologic Drought, Geophysical Research Letters, 35(L02405), doi:10.1029/2007GL032487.
    - Shi, X., A. W. Wood, and D. P. Lettenmaier, How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting?, Journal of Hydrometeorology (submitted).
    - Wang, A., T. J. Bohn, S. P. Mahanama, R. D. Koster, and D. P. Lettenmaier, Multimodel Reconstruction of Drought over the Continental United States, Journal of Climate (submitted).
    - Wood, A. W., and J. C. Schaake, 2008, Correcting Errors in Streamflow Forecast Ensemble Mean and Spread, Journal of Hydrometeorology, 9(1): 132-148, doi:10.1175/2007JHM862.1.
    - Vano, J. A., and A. C. Steinemann, 2007, Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington, USA, (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H24A-05. San Francisco, California.
    - Wood, A. W., S. Shukla, J. A. Vano, and A. C. Steinemann, 2007, Connecting Climate, Hydrologic and Drought predictions to Water Resources Management in Washington State (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement 88(52): Abstract H23F-1678. San Francisco, California.
- Other Publications:
    - Steinemann, A., 2007, Climate Forecasts for Drought Management, NOAA Climate Prediction Applications Science Workshop, Seattle, March 21, 2007.
    - Rosenberg, E., A. W. Wood, Q. Tang, A. Steinemann, B. Imam, S. Sorooshian, and D. P. Lettenmaier, 2007, Improving Water Resources Management in the Western United States through Use of Remote Sensing Data and Seasonal Climate Forecasts," Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop,Seattle, Washington, March 20-23, 2007.
    - Shukla, S., D. Alexander, A. Steinemann, and A. W. Wood, 2007, Applications of Medium

Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.

- Fontaine, M., and A. Steinemann, 2007, Assessing and Mitigating Drought in Washington State, Poster Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
- Shukla, S., D. Alexander, A. Steinemann A., and A. W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, Water Center Annual Review of Research, University of Washington, Seattle, Washington, February 14, 2007,
- Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
- Annual Review of Research: A Symposium of Water Research Hosted by the University of Washington Water Center. 2007. February 14, 2007. http://depts.washington.edu/cwws
- Andreadis, K., D. P. Lettenmaier, and A. W. Wood, 2007, Drought Identification and Recovery Prediction, Oral and Poster Presentations at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington. March 20-23, 2007.
- Shukla, S., and A. W. Wood, 2008, A Hydrologic Model-based Drought Monitoring System for Washington State, 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana, January 22-24, 2008.
- Shukla, S. and A. W. Wood, 2007, Drought Monitoring: An Evaluation of Drought Indicators Based on Climate and Hydrologic Variables, 2nd Annual Graduate Climate Conference, University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
- Vano, J. A., 2007, Challenges and Rewards of Translating Climate Change Science for Non-scientists: Two Case Studies on Drought, 2nd Annual Graduate Climate Conference University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
- Wood, A.W., 2007, Application of LDAS-era Land Surface Models to Drought Monitoring and Prediction, Oral Presentation at the 5th Annual U.S. Drought Monitor Forum, Portland, Oregon. October 10-11, 2007
- Wood, A.W., 2007, Drought-relevant Information Products Based on LDAS-era Hydrologic Modeling, Poster Presentation at the 6th Annual NOAA Climate Prediction Application Science Workshop, Chapel Hill, North Carolina. March 4-7, 2008.
- Wood, A. W., 2007, A System for Real-time Prediction of Hydrological Drought Over the Continental U.S., Oral Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-21, 2007.
- Wood, A.W., 2008, The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction, 88th American Meteorological Society Annual Meeting New Orleans, Louisiana. January 22-24, 2008.
- Wood, A.W., J. A. Vano, S. Shukla, and A.C. Steinemann, 2008, Applications of Climate Forecast Information in Water Resources Management: Opportunities and Challenges in the Yakima River Basin, Washington, Oral Presentation at the 6th Annual NOAA Climate Prediction Application Science Workshop, Chapel Hill, North Carolina. March 4-7, 2008.
- Wood, A., N. Voisin, and S. Shukla, 2008, Medium-range Ensemble Hydrologic Forecasting for Western Washington State, poster, 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana. January 22-24, 2008.
- Annual Review of Research, 2008, A Symposium of Water Research, hosted by the University of Washington Water Center, A. C. Steinemann, Director. USGS research conducted on Grant 06HQGR0190 was featured at this event. Seattle, Washington, February 14, 2008. http://depts.washington.edu/cwws/
- Bohn, T., Drought and model consensus: Reconstructing and Monitoring Drought in the U.S. with Multiple Models, Annual Review of Research, A Symposium of Water Research, hosted

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- Shukla, S., and A.W. Wood, Application of a Land Surface Model for Drought Monitoring and Prediction in Washington State, Annual Review of Research, A Symposium of Water Research, hosted by the University of Washington Water Center, A. C. Steinemann, Director. Seattle, Washington, February 14, 2008. http://depts.washington.edu/cwws/

Report Follows

PROBLEM AND RESEARCH OBJECTIVES

Drought is the costliest natural hazard in the U.S., averaging $6-8 billion in damages annually (FEMA, 2004). The 1988 central U.S. drought alone cost almost $62 billion (NCDC, 2006). Forecasts and real-time assessments of drought offer the potential to mitigate drought impacts. However, current drought monitoring systems for the western U.S. lack a predictive component for specific hydrologic indicators. Further, given that hydrologic impacts account for most drought losses, USGS data are essential to making drought forecasts useful.

We propose to develop a drought forecast and nowcast system for the western U.S., which will serve as a scientific framework for prediction and assessment of agricultural (soil moisture) and hydrologic (streamflow) drought in the region. This work, in collaboration with USGS personnel, will provide early warning capabilities and science-based indicators that are critical for the National Integrated Drought Information System (NIDIS), an effort of the Western Governors' Association (WGA), the National Drought Mitigation Center (NDMC), NOAA, the USGS, and other agencies. Our work will also contribute to the U.S. Drought Monitor, which currently uses our National Surface Water Monitor, by incorporating USGS data into methods to characterize and forecast drought conditions, persistence, and recovery. Further, the PIs and their students will work directly with water managers in selected states in the region (Washington, California, and others) to apply this forecast system to water resources decisions.

Our proposed drought forecasting system will build upon the University of Washington’s operational West-Wide Hydrologic Forecast System and National Surface Water Monitor. In doing so, we will extend the Variable Infiltration Capacity (VIC) macroscale hydrology model to utilize, via data assimilation methods, USGS hydrologic data in ways not currently exploited by prominent drought information services, such as the U.S. Drought Monitor.

Our specific objectives are to (1) implement a version of the VIC model that represents near-surface groundwater directly and thus can incorporate USGS well level data; (2) assimilate observations not presently used in the West-Wide system that are highly relevant to drought, such as USGS streamflow data from HCDN and similar stations, soil moisture information, and USGS well data; (3) produce probabilistic forecasts of drought persistence and recovery using ensemble prediction methods that incorporate climate forecasts out to one year; and (4) work with the WGA, the NDMC, and other users, such as state water agencies, to incorporate the resulting drought forecasts and nowcasts into drought information systems and water management decisions.

In addition to interactions with the WGA and the NDMC, we will work closely with Dr. Randall Hanson and Dr. Michael Dettinger of the USGS California Water Science Center in San Diego. Specifically, we will work with Drs. Hanson and Dettinger in (1) testing VIC predictions of well level anomalies at selected locations in California, (2) development of algorithms for assimilation of USGS well level and streamflow data, as well as other hydrologic data, into the drought forecasting system, (3) obtaining retrospective and real-time hydrologic data, and (4) validation of drought nowcasts and forecasts across the western U.S. study domain.

METHODOLOGY

The overall goal of the proposed project is to develop a drought forecast and nowcast system for the western U.S. (which we will define as the continental U.S. west of the Mississippi River), which can serve as a scientific framework for assessment and prediction of agricultural (soil moisture), and hydrologic (streamflow) drought in the region, and as the scientific core of NIDIS. The system will leverage the existing University of Washington WHFS and SWM. Our specific objectives are:

(1) To implement a version of the VIC model that represents near-surface groundwater (water table) directly, based on a simple groundwater model of Niu et al. (2007). This model will be capable of incorporating USGS well level observations via data assimilation in areas where there is strong connectivity between groundwater and surface water systems;

(2) To develop procedures for assimilating observations that are not presently incorporated in the WHFS but are highly relevant to drought, such as USGS well data, USGS streamflow data from HCDN and similar stations not greatly affected by water management, and soil moisture from such sources as the NRCS SCAN network and state networks where such data are available;

(3) To develop methods for producing probabilistic forecasts of drought persistence and recovery, using ensemble prediction methods that incorporate official NOAA CPC ensemble climate forecasts for lead times out to one year; and

(4) To work with the NDMC, the WGA, and other users (primarily state agencies in the western U.S.) to incorporate the resulting drought nowcasts and forecasts into water management decisions and into drought information systems such as the Drought Monitor/Outlook and NIDIS.

PRINCIPAL FINDINGS AND SIGNIFICANCE

A Washington statewide drought monitoring system has been implemented using the VIC hydrologic model at 1/16 degree (about 6 km grid mesh). This system provides real-time, daily updating analyses (maps, datasets, and time series of hydrologic variables) that characterize hydrologic conditions throughout the state, presented via a website (http://www.hydro.washington.edu/forecast/sarp/). It also presents a weekly update of the current drought status in terms of drought indices, including Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), Crop Moisture Index (CMI), and Z Index (ZIND), as well as a daily update of 1, 2, 3, 6, 9, 12, 24, and 36 month averaged values of Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI). Work has begun to prepare the statewide monitoring system with an embedded focus region of the Yakima River Basin as the initializing state for 2 week to 1 year lead hydrologic forecasts, from which it will be possible to obtain drought onset and recovery predictions. These will be based on both ensemble streamflow prediction (ESP) techniques advanced by the National Weather Service, and NCEP Climate Prediction Center seasonal outlooks. To this end, the Climate Prediction Center’s new consolidated forecast (not previously available to the public) has been obtained and is being evaluated in the Washington State domain. In addition, preliminary work to develop methods for forecast error reduction has resulted in a published paper (Wood and Schaake, 2008).

To supplement existing drought characterization methods, we developed a method known as the standardized runoff index (SRI), which is calculated as the unit standard normal deviate associated with the percentile of hydrologic runoff accumulated over a specific duration. This method is similar to the standardized precipitation index (SPI), but relates to a hydrologic variable, runoff, rather than a climatic variable, precipitation. Such an approach better accounts for the effects of seasonal lags in hydrologic response to climatology. For example, SPI does not account for the effects of decreased snowmelt on summer conditions. Maps of SPI and SRI, based on a rolling climatology, are updated daily for the continental U.S. at ½ degree spatial resolution as part of the U.W. Surface Water Monitor (Figure 1, http://www.hydro.washington.edu/forecast/monitor/indices/index.shtml). The development of this index and its comparison with SPI are presented in a published paper (Shukla and Wood, 2008).

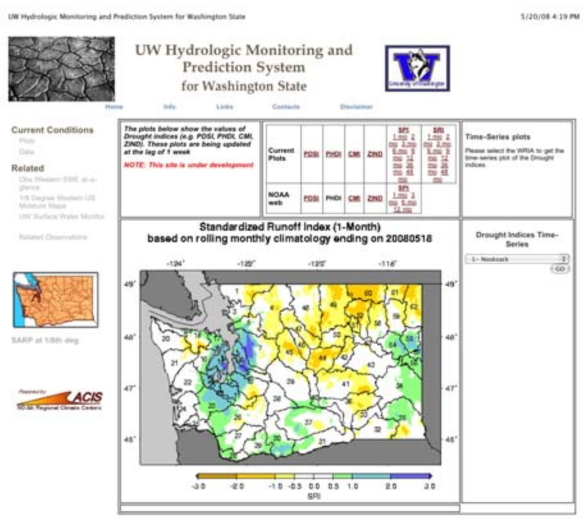

Figure 1. Screen shot of UW Hydrologic Monitoring and Prediction System for Washington State showing standardized runoff index (SRI, 1-month) using a rolling monthly climatology ending on May 18, 2008.

We have met with key stakeholders (e.g. federal, state, and regional water officials, irrigation district managers, farmers) in the Yakima River Basin, Washington, to assess their needs. We discussed current organizational decision processes, current uses of forecast information, needs for NOAA forecast products, barriers to forecast use, and potential net benefits of using the NOAA-CPC forecasts and the drought forecast information developed by this project. In this process, we identified four decision-making realms: (1) filling reservoirs without flooding in winter and spring; (2) maintaining flows for fish in fall; (3) week-to-week operations in summer; and (4) agricultural decisions in winter for irrigation season. The relevant decision timing relative to forecast timing for each of these operational periods were also assessed (Figure 2).

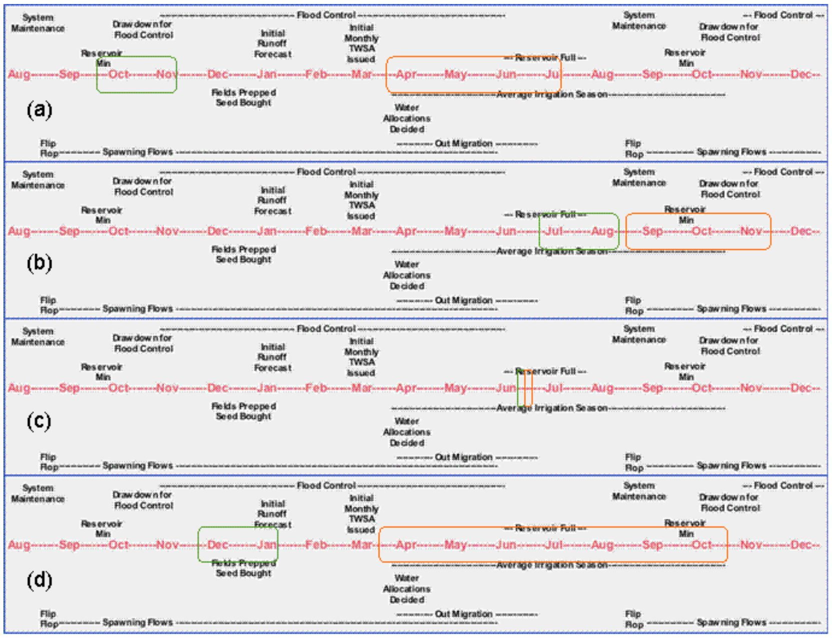

Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in summer, and (d) agricultural decisions in winter for irrigation season.

We have implemented and tested a drought recovery strategy, based on initializing VIC with current (soil moisture) conditions, and running forward in time with ensembles of future climate conditions. Maps of median forecast percentile and the forecast probability of conditions below the 20th percentile for soil moisture, SWE, and cumulative runoff for the continental United States are available at http://www.hydro.washington.edu/forecast/monitor/outlook/index.shtml. Ensemble Streamflow Prediction (ESP)-based and CPC outlook-based forecasts of daily streamflow volumes are made near the beginning of each month. These outputs are summarized as monthly hydrograph distribution plots available for several forecasting stations in the west-wide U.S. Region (Figure 3, http://www.hydro.washington.edu/forecast/westwide/sflow/). The ESP ensembles are drawn from sequences of past observations, whereas the CPC outlook ensembles are derived from the CPC's probability of exceedance (POE) forecasts for average monthly temperature and total precipitation in each of 102 climate divisions within the US. Probabilistic outcomes will be compared with nominal conditions (as simulated with the VIC model using the true forcings) for the retrospective period, and maps of the accuracy of climate recovery predictions will be produced as a function of season and lead-time. Figure 4 compares the ensembles of

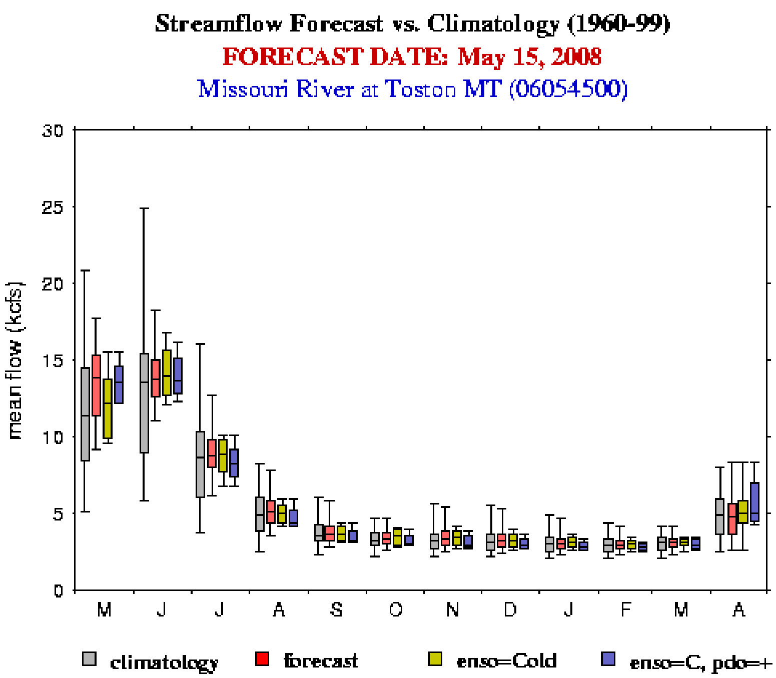

Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

predicted soil moisture, averaged over the Arizona-California portion of the drought, compared with "actual" (real-time) model soil moisture over the 6-month forecast period.

We have also implemented a drought nowcast system in real-time, and are in the process of implementing a drought forecasting system over the western U.S. domain, using methods similar to those illustrated in Figures 3 and 4, at one-quarter degree spatial resolution (our current Surface Water Monitor uses one-half degree resolution). We have recently implemented a drought identification system at the SW Monitor native ½ degree resolution. We summarize the method below.

The VIC hydrologic model produces near real-time, spatially and temporally continuous fields of drought-related variables such as soil moisture and streamflow (we focus here on soil moisture). Drought is defined locally at each model pixel using a thresholding method, i.e. whenever soil moisture or runoff are below a certain threshold value the pixel is classified as being "in drought". Instead of using the absolute values of soil moisture (or runoff), droughts are identified by expressing each pixel's soil moisture as percentiles of their 1915-2004 respective model climatology. This essentially normalizes the soil moisture and runoff time series to range of 0 to 1 across the domain. The threshold chosen here is 0.2, which corresponds to severe drought, with severity being calculated as the percentage remainder of the subtraction of the soil moisture (or runoff) percentile from unity.

Soil moisture and runoff spatial fields are estimated and used to produce weekly maps, which are then used in the drought identification procedure. In order to keep a certain temporal continuity in the areas identified as drought from one time step to the next, we have to apply some kind of temporal persistence constraint. This ensures that areas are classified as drought recovered relatively consistently, given that this is a near real-time application. Drought transition probabilities (probability that a pixel will recover if it was in drought the previous 1, 2 or 3 weeks) were calculated from the model climatology. These are then used after the first stage of drought identification (any pixel below the 20th percentile is classified as drought) to retain the temporal persistence in drought areas. The recovery probability threshold is set to 50%, but this can be adjusted accordingly.

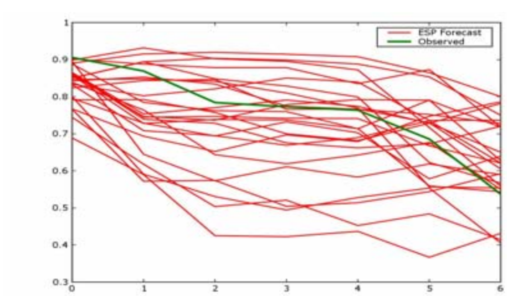

Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

The algorithm continues by applying a spatial median filter using a 5x5 window, in order to attain some spatial smoothing by minimally distorting the actual percentile values. The initial partitioning of the image then follows, by grouping adjacent pixels that are in drought into clusters. This fragmented image is then adjusted by merging clusters that are sufficiently close in terms of distance, and eliminating drought clusters that occupy less than the area of 20 model pixels. The final step includes the reclassification of pixels that are within larger drought areas as being in drought, by examining the neighborhood of each pixel not in drought within a radius of 3 model pixels. This procedure results in a map of drought areas, and also allows for their consistent tracking through time. Figure 5 shows results of application of the method over the continental U.S. starting in early May, 2007, as droughts were evolving in both the southeastern and southwestern U.S., and proceeding through the first week in June, 2007. The spatial limits of drought are updated once per

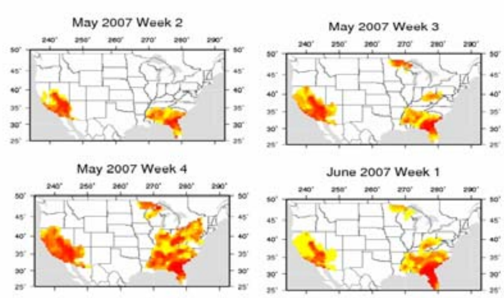

Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative

week. We are interacting with CPC personnel who are reviewing the method, but we believe that it has great promise for producing a more objective delineation of drought extent and severity that is currently possible in publications such as the National Drought Monitor.

In streamlining our implementation of the ESP approach to streamflow forecasting, we explored the necessity of calibration when applying an ESP approach to seasonal forecasts. This work looks at bias reduction via model calibration versus "training" a bias removal technique on retrospective simulation error statistics and removing bias during post-processing. Forecast error, as measured by the coefficient of prediction, of these two methods was found to be similar for each case, and in many cases, the reduction is greater for post-processing bias correction, by percentile mapping, at the seasonal scale. This work has been accepted for publication (Shi et al., 2007).

Since soil moisture in land surface models is dependent on model dynamics, we have investigated the use of multi-model ensembles. Tests of model-specific sensitivities in identifying and reconstructing drought events, based on model-predicted soil moisture, were conducted using six land surface/hydrology models over the continental United States for the period 1920-2003. We also applied two ensemble methods to combine results from all of the models. Combining models is thought to minimize any model errors. All models and the two ensembles identified the spatial patterns of major drought events. The spatial distribution of drought severity and duration was plausible for all models; however, models differed in these aspects. Differences between models were greater in the western U.S. than in the eastern U.S. due to precipitation differences. Deeper soil columns led to longer soil moisture memory. The multimodel ensembles have been implemented into the real-time drought nowcast system of the U.W. Surface Water Monitor. This work has been submitted for publication.

After further investigation into techniques for incorporating groundwater into large-scale land surface models, we have begun incorporating the simple groundwater model (SIMGM) developed for the Community Land Model (CLM) by Niu et al. (2007). This model is much more computationally efficient than the Liang et al. (2003) VIC-ground model, which we originally proposed implementing, and has been successfully run globally, with results that closely match water table levels derived from the Gravity Recovery and Climate Experiment. SIMGM includes a lumped-unconfined "aquifer" as a single integration element beneath the soil column. The hydraulic properties, including specific yield and exponentially decaying hydraulic conductivity, of this layer differ from those of the soil layers.

The basic concept behind SIMGM is a simple water balance, i.e. the change in water storage within an aquifer over time equals the difference between recharge into and subsurface flow out of the aquifer. Recharge is calculated using Darcy's law as a function of the depth to the water table and the matric potential and mid-element depth of the lowest unsaturated soil layer. The recharge estimate also accounts for an upward flux driven by capillary forces. The CLM implementation of SIMGM uses a simple TOPMODEL-based runoff model to calculate subsurface flow (baseflow) as an exponential function of water table depth. Unlike in TOPMODEL, Niu et al. (2007) estimate saturated hydraulic conductivity as a function of soil texture; in the aquifer, hydraulic conductivity exponentially decays with depth from that of the lowest soil layer. Water table depth is estimated from the resultant aquifer water storage scaled by the specific yield. Depth to the water table can be within the soil column, in which case the water table depth calculations differ slightly to account for differences in soil and aquifer properties. The water table can also be below the base of the lumped, unconfined aquifer element; hence, there is no prescribed total model depth.

The VIC implementation of SIMGM will differ from that of Niu et al. (2007) primarily in baseflow calculation. Whereas Niu et al. (2007) apply a TOPMODEL-based runoff scheme to parameterize lateral transport as an exponential function of water table depth, we will apply the ARNO baseflow formulation (Todini et al., 1996) to both the soil column and the aquifer, as in Liang et al. (2003). We will also explore the sensitivity of SIMGM to other baseflow formulations, such as those of Niu et al. (2007) and Huang et al. (2006, 2008). Also, the standard VIC model includes 3 soil layers, as opposed to the 10 layers of CLM. In order to improve the accuracy of water table depth estimates, we will use an approach similar to that of Wang et al. (2007) to map soil moisture from the standard VIC model to 10 smaller layers prior to performing groundwater calculations, and then to map the redistributed soil moisture back to the 3 VIC layers.