# Report as of FY2006 for 2006WA180G: "West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS"

## Publications

- Articles in Refereed Scientific Journals:
  - Wood, A.W. Correcting errors in streamflow forecast ensemble mean and spread. Submitted to Journal of Hydrometeorology (in review).
  - 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.
- 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

## 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 described by Liang et al. (2003) that represents near-surface groundwater (water table) directly, and hence 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 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 timeseries of hydrologic variables) that characterize hydrologic conditions throughout the state, presented via a website. Work has begun to prepare the statewide monitoring system with the embedded focus region 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 submitted paper (listed below).

We have implemented and tested a drought recovery strategy, based on initializing of VIC hydrology model with current (soil moisture) conditions, and running forward in time with ensembles of future climate conditions. We have performed initial testing of this method using the southwestern U.S. drought of winter 2005-6 as a case study, and using Ensemble Streamflow Prediction (ESP) methods, wherein the ensembles are drawn from sequences of past observations, as the ensembles (the method is easily generalized to utilize ensembles from other sources, such as the ensemble version of the CPC "official" forecasts that we use in our western U.S. streamflow forecasting. Figure 1 shows results from the winter 2005-6 case study. 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 2 compares the ensembles of 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 1 and 2, 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 timestep 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 $20^{th}$ 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.

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 3 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 (a few days before this report was written). The spatial limits of drought are updated once per 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.

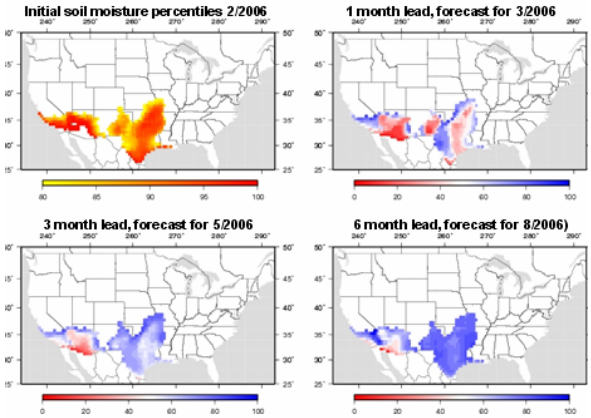


Figure 1: Projected progression of SW U.S. drought prediction beginning with observed soil moisture in February, 2006 (percentiles relative to 1915-2003 historical period). Subsequent plots show estimated probability of soil moisture exceeding 1915-2003 mean for lead times of 1, 3, and 6 months, beginning with February, 2006.

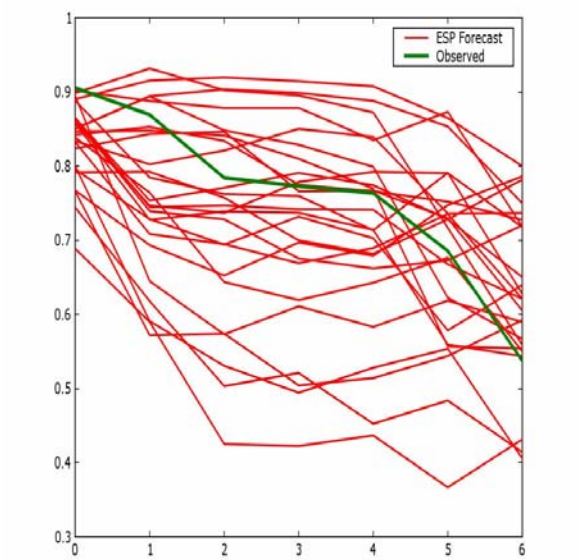


Figure 2: Spatial average soil moisture over AZ-CA portion of drought in Fig. 1 starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

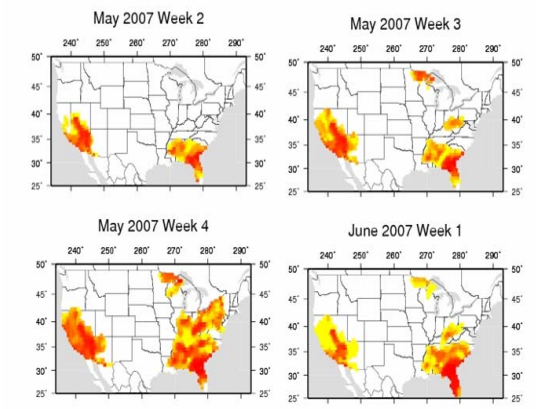


Figure 3: Estimated extend of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative to 1915-2004 climatology, color bar as in UW Surface Water Monitor