The University of Washington Surface Water Monitor: An experimental platform for national hydrologic assessment and prediction

Andrew W. Wood

ABSTRACT

Over the last decade, great strides have been made in land surface modeling at regional to continental scales. The North American Land Data Assimilation System has developed new approaches for estimating current land surface moisture conditions (e.g., soil moisture, snow and runoff) as well as retrospective reconstructions of the same variables. These science-based products were motivated by a need to improve initialization of numerical weather prediction models, but have many other potential applications both in research and operations. An experimental effort called the Surface Water Monitor (SWM) has melded these advances into a system serving both objectives in the area of water and potentially drought management. The SWM is a continental U.S. implementation of the Variable Infiltration Capacity hydrologic model that combines a retrospective daily analysis of over 90 years with real-time, daily-updating simulations of land surface climate and moisture conditions. The retrospective dataset provides a foundation for research toward understanding hydrologic trends and variability on a national scale since 1915. It also provides an unusually consistent statistical background for interpreting the real-time moisture estimates, enabling their depiction as anomalies or percentiles with respect to historical conditions. The real-time percentile maps and predictions have already become an input to national-scale operational drought management efforts such as the US Drought Monitor and the Climate Prediction Center Drought Outlook. The system is also used for prediction at seasonal lead times, enabling the production of operational hydrologic, drought-oriented forecasts that complement those currently available from operational centers.

[1]*Corresponding author address:* Andrew W. Wood, Civil and Environmental Engineering Dept., University of Washington, Seattle, WA 98115; aww@u.washington.edu; h2o.fcst@gmail.com

1. INTRODUCTION

This article demonstrates an experimental hydrologic analysis and prediction approach in the context of water management at the national scale. At such large scales, drought is a predominant concern because severe events can grow to affect as many as half the states in the U.S. at once. The largest floods, such as on the Mississippi River in 1993 and the Missouri River in 2007, are also generated by abnormally wet conditions spanning a number of states. There are few water management-oriented modern operational, national scale systems for characterizing such large scale hydrologic events, however. Although recent research at the NOAA National Centers for Environmental Prediction (NCEP) is promising, federal and state drought management efforts, for example, still rely on inputs such as the Palmer Drought Severity Index, which is only weakly related to physical land surface factors, or the NOAA Climate Prediction Center's (CPC) soil moisture model (Huang et al. 1996), which lacks a snow component.

Many indicators now used to describe drought are derived from analyses of climate variables such as precipitation and temperature, although the agricultural, hydrological and societal impacts of drought (Wilhite and Glantz, 1985) depend on other factors in addition to climate. The current state-of-the-practice US drought analysis, the US Drought Monitor (USDM; Svoboda et al., 2002), and drought prediction product, the CPC Drought Outlook (DO), are subjectively assembled from such climate-based indices and from observed streamflow percentiles and SWE anomalies, CPC soil moisture percentiles, and other land surface descriptors, together with climate forecasts for various lead times. It is not likely that the characterization and prediction of drought will ever be purely objective, but various central, physical aspects of drought, such as the severity of precipitation deficit (as related to area and duration), or the cumulative departure of streamflow or soil moisture from normal conditions over a given period, can be both estimated and predicted objectively with varying levels of accuracy. Hydrologic models have an important role to play toward this objective because of their ability to synthesize the effects of climate on land surface conditions, thus providing a systematic, physically-based framework for connecting meteorological drought to agricultural drought (related to soil moisture) and hydrological drought (related to runoff).

Fortunately, modern, sophisticated land surface simulation schemes have evolved over the last decade with the primary aim of improving the representation of land surface physics in numerical weather prediction and climate models. “Macroscale hydrologic” models of this class contain physical water and energy balances of the major components of the top 1-2 meters of the land surface, run at between an hourly and daily timestep, and at horizontal grid resolutions that are finer than the county level. Among the most successful of the modeling efforts in the US is the NOAA Land Data Assimilation Project (NLDAS; Mitchell et al., 2004), which has helped lead the development of four land surface schemes over much of North America at 1/8 degree spatial resolution.

The NLDAS-type models offer great potential for substantial improvements in the operational assessment and prediction of large (regional to national scale) hydrologic events. The University of Washington Surface Water Monitor (SWM) is a real-time hydrologic monitoring and prediction system for the continental U.S. that demonstrates this potential, using an NLDAS model to produce real-time information products based on simulated soil moisture, runoff and snow water equivalence (SWE). The SWM was introduced in 2005 to facilitate water management, particularly in the context of drought, at the national scale. The operational products from the SWM are increasingly used as input to federal drought analysis efforts (e.g., at the CPC and the National Drought Mitigation Center) at a time when drought has become a paramount concern to climate scientists, hydrologists, water and energy managers and policymakers throughout the country. Current initiatives such as NOAA’s “Coping with Drought” and the interagency National Integrated Drought Information System are evidence of the high priority now placed on understanding, characterizing and predicting drought, which since 2000 has afflicted nearly all parts of the western U.S. at one time or another, and is the cause of a current water management crisis in the southeastern US.

In contrast to other real-time hydrologic simulation efforts, the SWM emphasizes an approach which maintains consistency between the real-time and long (greater than 50 year) retrospective simulations, thus legitimizing the examination of current model conditions in the context of the model’s historical climatology. A primary objective of the SWM is to serve as an operational demonstration project (“test-bed”) for model-based information products. As a result, the interactions with and feedback from the operational and management focusing on system and product development are a critical part of the SWM effort. The SWM system, products, and interactions are described in the following sections.

2. THE UNIVERSITY OF WASHINGTON SURFACE WATER MONITOR SYSTEM

The SWM generates both a daily, real-time snapshot of hydrologic conditions throughout the US and seasonal lead forecasts of those conditions, and also provides a monthly archive of similar assessments extending back to 1915. The following subsections describe various aspects of the system, including the hydrologic model, the model forcing approach, the meteorological station dataset, the computational details, and the website.

2.1 VIC model implementation

The SWM to date has been based on the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 1994). The VIC model was developed with NOAA and NASA support during the early 1990s, and was one of four physically based, semi-distributed macroscale hydrologic (water and energy balance) models investigated and implemented as part of the NLDAS project (Mitchell et al., 2004). The NLDAS modeling domain spans 25N to 53N, 67W to 125W, and the modeling grid is 1/8th degree longitude by latitude. In the SWM, VIC is applied at a daily time step (hourly for the embedded snowpack model) and run in water balance mode. VIC physics and parameterization approaches account for sub-grid scale variations in vegetation, elevation, and infiltration processes. For each grid cell in the simulation domain, the simulation produces daily estimates of soil moisture and snow water equivalent (SWE), evaporation, surface runoff, baseflow and other water and energy balance variables. Although surface runoff and baseflow can be routed through a stream network to produce streamflow and locations of interest, the SWM has not to date produced routed streamflows.

The ½ degree VIC model parameters used in the SWM (for vegetation, soils, elevation and snowbands) are the same as those used in Andreadis et al. (2005) for a retrospective analysis of CONUS drought. Those parameters in turn were aggregated from the models described in Maurer et al. (2002), with the exception of the snow bands, which were redeveloped using elevation zones of 500m or less, up to a limit of 9 zones per cell. The model soil layers have variable depth, with the top and middle layers typically being 10 and 30 cm respectively, and the bottom layer varying between 70 and 200 cm. The current SWM model has 3322 grid cells. The references provided above provide greater detail on the VIC model physics and calibration strategies. Note that the 1/8 degree streamflow calibrations performed for Maurer et al. (2002) will not necessarily hold for the Andreadis et al. (2005) or SWM implementations.

Using the index station forcings described in section 2.3, the SWM VIC model was cold started and run from 1 January 1915 to 31 December 2004. The final hydrologic state was saved and the real-time forcing and simulation code version was used to advance the state file until the (then) current date in May 2005, and since then for subsequent real-time updates. Each day, a 1 to 2 month spin-up run is made to generate current hydrologic conditions. This real-time run carries forward the state information from the end of the previous run, thus the current hydrologic state is the end result of the continuous simulation starting in 1915.

2.2 Real-time meteorological station dataset

As described in section 2.3, the SW Monitor forcings are constructed from a gridded climatology and a real-time meteorological station dataset. The real-time data are automatically downloaded from the NOAA Applied Climate Information System (ACIS). The UW access to ACIS is free (courtesy of a Memorandum of Agreement between the UW and the NRCS). To be suitable for the index station forcing approach, these stations have both long term records and report reliably in real time. For the current version of the SWM, the station dataset includes only first order National Climatic Data Center (NCDC) Cooperative Observer (Co-op) stations at 2130 locations within the CONUS region. All index stations have periods of record that are at least 45 years long, and at least 80% coverage of their record. Despite the consequence that the resulting station density diminishes before 1960 (**Figure 1**), this choice of period was made to include a greater number of stations in the index dataset. Future implementations of the SW Monitor should make a correction for station dataset inhomogeneity effects before 1960 – one possibility is to use the approach suggested in Hamlet and Lettenmaier (2005).

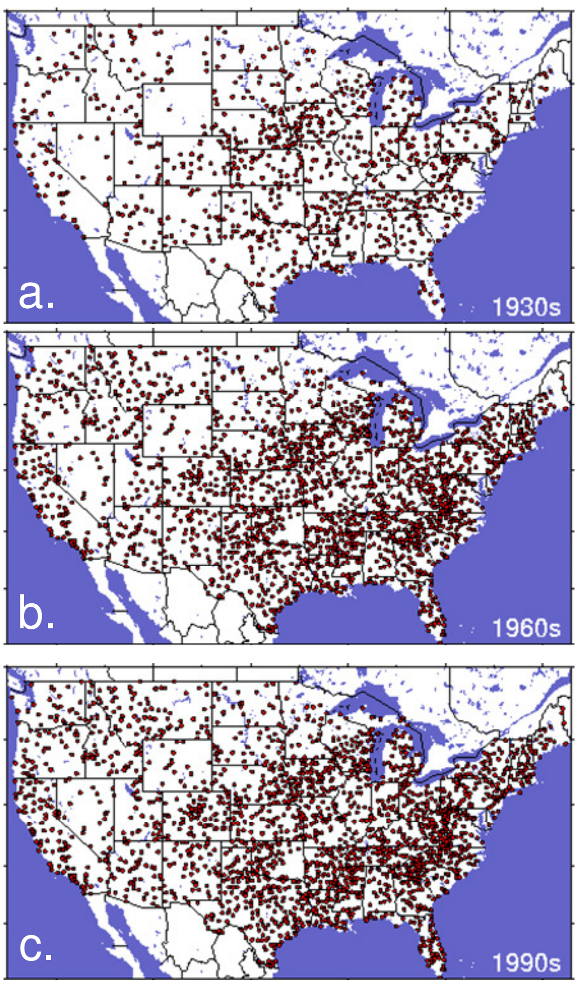

Figure 1. SWM index station dataset in (a) 1930s, (b) 1960s and (c) 1990s.

2.3 Index station forcing approach

The typical implementation of hydrologic models for real-time analyses or prediction involves the development of a model forcing dataset that can support simulation both in a retrospective period and in real-time. The VIC model forcings include daily precipitation (P), temperature minima and maxima (Tmax and Tmin) and wind speed that are analyzed to the model grid, although the model can also be run with additional humidity and radiation forcings, which is more characteristic of operational land surface models. Hydrologic models used for water management objectives are calibrated and validated during the retrospective period to reproduce streamflow at an hourly to monthly time step. In regional or larger scale applications such as NLDAS (Mitchell et al., 2004), validation efforts focus equally on vertical fluxes of energy and moisture, since such models may form boundary conditions for coupled land-atmosphere schemes.

In either case, the construct of using retrospective simulations to validate and provide statistical context for interpreting real-time results is challenged by the discrepancy between the network of meteorological observations that are available retrospectively and that which is available in real time. The need to process and quality control the observations causes lags between measurement and availability to modelers of months or more for many stations. Consequently, the real time forcings are potentially biased relative to those with which the models have been calibrated – i.e., those which drive the retrospective simulations that define the model climatology. The potential manifestation of real-time forcing biases in the real time hydrologic simulations calls into question the accuracy of simulated real-time anomalies that are critical for hazard, water and energy management.

One of the major considerations in the design of the SW Monitor forcing approach, therefore, was to minimize potential real-time forcing biases by eliminating the discrepancy between real-time and retrospective station datasets. In this regard, which is not without drawbacks, the SWM is unique among the existing real-time land surface hydrology simulations. Stations used in retrospective simulation are limited to those available in real-time, as described in section 2.2, and these are termed "*index stations*".

The SWM implementation of VIC uses only daily P, Tmax, Tmin, and long term average wind speed to force the hydrologic response of each grid cell. In calculating forcings for a gridded model, station data are commonly interpolated to estimate a mean forcing over a grid cell, and this step may be combined with or followed by a rescaling or lapsing to account for terrain (e.g, orographic) influences on precipitation, temperature and other variables. Because the index station dataset includes only a maximum of 2130 stations, which is sparse compared to the number that are available retrospectively, such simple or scaled interpolation methods would produce gridded fields that are spatially smooth compared to those produced by a greater (i.e., retrospectively available) density of stations. The author designed and implemented alternative approach – called the ***index station method*** – that involves interpolating the percentiles (for precipitation) or anomalies (for temperature) of the observations, rather than the observations themselves. The values matching the percentiles or anomalies at each grid cell are then extracted from the grid-cell specific climatological distributions for the associated variable. The method relies on the fact that the synoptic conditions that govern weather impart spatial coherence to meteorological observations within a neighborhood of stations such that from the perspective of rank, the meteorological observations at these stations behave similarly (i.e., have a high Spearman correlation). This approach is more robust in the face of missing observations, and reduces the biases associated with retrospective versus real time dataset inconsistencies. A description and evaluation of the approach for precipitation is given in Tang et al. (2008).

The application of the method differs for temperature and precipitation. For temperature, the Co-op station daily Tmax and Tmin anomalies (additive) from the long term mean are interpolated to each grid cell, and the daily grid cell values are calculated by adding the grid cell long term means for each variable to the interpolated station anomalies. The grid cell long term mean and distribution data for temperature, as for precipitation, are taken from the Maurer et al., 2002) gridded dataset, which relied on a denser Co-op station dataset that is available retrospectively.

Precipitation is an intermittent variable, hence the observed distribution of daily precipitation often contains more zeros than non-zero values, which complicates the estimation of the rank or percentile of a precipitation observation. The proportion of zero precipitation events within the distribution diminishes as the timestep of the event increases in length, e.g., from days to a week, month, or longer. For this reason, percentiles are calculated for precipitation accumulated over a period no shorter than 21 days. This period slides forward in time together with the current update. Station percentiles for the period are estimated, interpolated to the grid cell, and the period values are extracted from the grid cell climatology. The period values are then disaggregated back to a daily timestep by calculating the daily fractions of precipitation within the period from spatially interpolated daily station precipitation observations, and multiplying them by the period total.

The application of the percentile-based approach described above reassesses precipitation estimates over the entire period used for percentile calculation. One advantage of the reassessment is that preliminary station data that are later changed within the period due to quality controls or reported late will automatically become part of the analysis. A major disadvantage is that the analyses for the period change every day, rather than becoming fixed as the update day moves forward. The second major disadvantage is that short-record, real-time stations, radar and other precipitation products are not used to make the forcings.

2.4 Computational description

The SW Monitor runs on a single CPU of a Linux workstation (CentOS on AMD Athlon MP, 2133 MHz x2 CPUs, 1G RAM, 850 Tb RAID storage array) and takes about 2.5 hours from meteorological data download to website update. At approximately 8:30 a.m. PST, station data are downloaded from ACIS and processed into VIC forcings. The daily spin-up simulation takes approximately one hour, from about 9 a.m. to 10 a.m., and the post-processing of results and map preparation takes approximately one hour, so that the SW Monitor website updates daily at approximately 11:00 a.m. PST.

A number of types of computer code are incorporated in the SWM. A Perl script that runs as a cron job controls the sequencing of steps, starting with a Python script that performs the ACIS data download. The codes that process the station data into VIC forcings are a mixture of UNIX C shell scripts, a FORTRAN interpolation program, and Perl scripts. The VIC model is written in C language. A mixture of C shell and Perl scripts that call Generic Mapping Tools (GMT) plotting commands post-processes the simulation results and generates all the graphical products of the system.

The software for real-time VIC forcing generation was written by the author in support of the NOAA supported project focused on the development of the West-wide Seasonal Hydrologic Forecasting System (WSHFS; Wood and Lettenmair, 2006; http://www.hydro.washington.edu/forecast/westwide/). The author later wrote the software for automated daily updating of these forcings and subsequent hydrologic spin-up and ensemble forecasting as part of an independent consulting contract to migrate a component of the WSHFS to a private firm). The resulting software scheme was then applied to the ½ degree CONUS model from the Andreadis et al. (200X) implementation. After building the SWM website (http://www.hydro.washington.edu/forecast/monitor/), the author launched the SWM in May, 2005 (Wood et

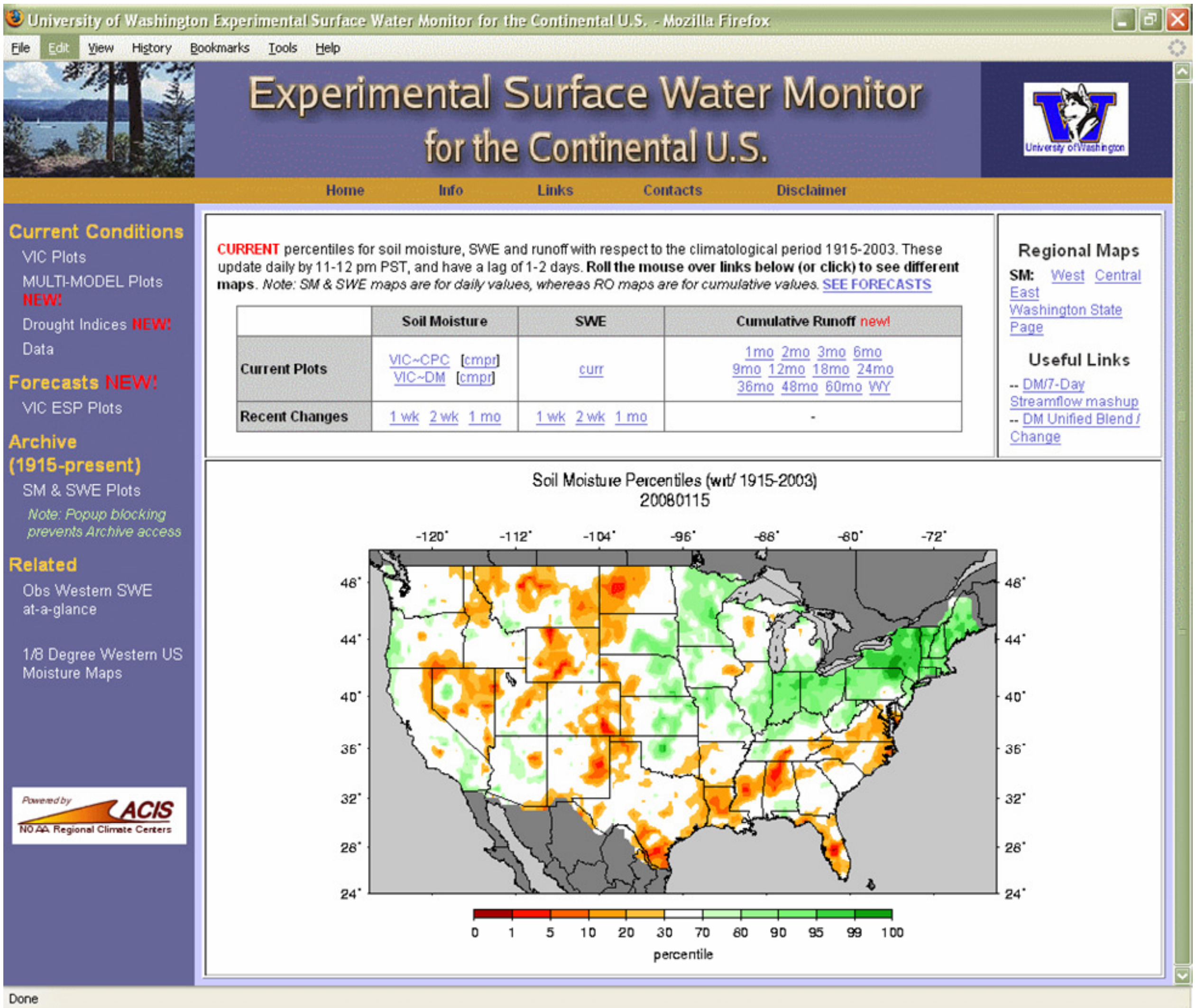

Figure 2. Surface Water Monitor website (http://www.hydro.washington.edu/forecast/monitor/)

al., 2005). More recently, the automated code was adopted as the core of the WSHFS when that system transitioned onto a Linux cluster at UW in 2006, and also became the core of a spinoff system focused on Washington State (http://www.hydro.washington.edu/forecast/sarp/).

2.5 SWM Website

The main design principal of the SWM website (**Figure 2**) is to present a single central graphic that is viewable on the main page, while making related content easily accessible in the same format. Borrowing from the CPC's home page, the table of links at the top of the page allows the user to switch between the central graphic – soil moisture percentiles – and others, such as SWE, cumulative runoff, or change in condition plots, simply by moving the mouse pointer over the link. This main page table contains links for all the VIC current water balance variable plots, which currently focus on soil moisture, SWE and runoff.

Links on the left side navigation bar of the site lead the user to other types of content. The primary types of data content are grouped under the headings "Current Conditions" and "Forecasts". Under current conditions, one link leads to maps of drought indices derived from the VIC model variables; another leads to data associated with the maps; and a third leads to a page showing current conditions from other land surface models, an area that is being developed via the collaborative efforts of Dennis Lettenmaier and Ted Bohn (both at UW) and facilitated by the SW Monitor system. The forecast (rather than current conditions) link leads to VIC-based ensemble prediction plots. These and other products are described in more detail below.

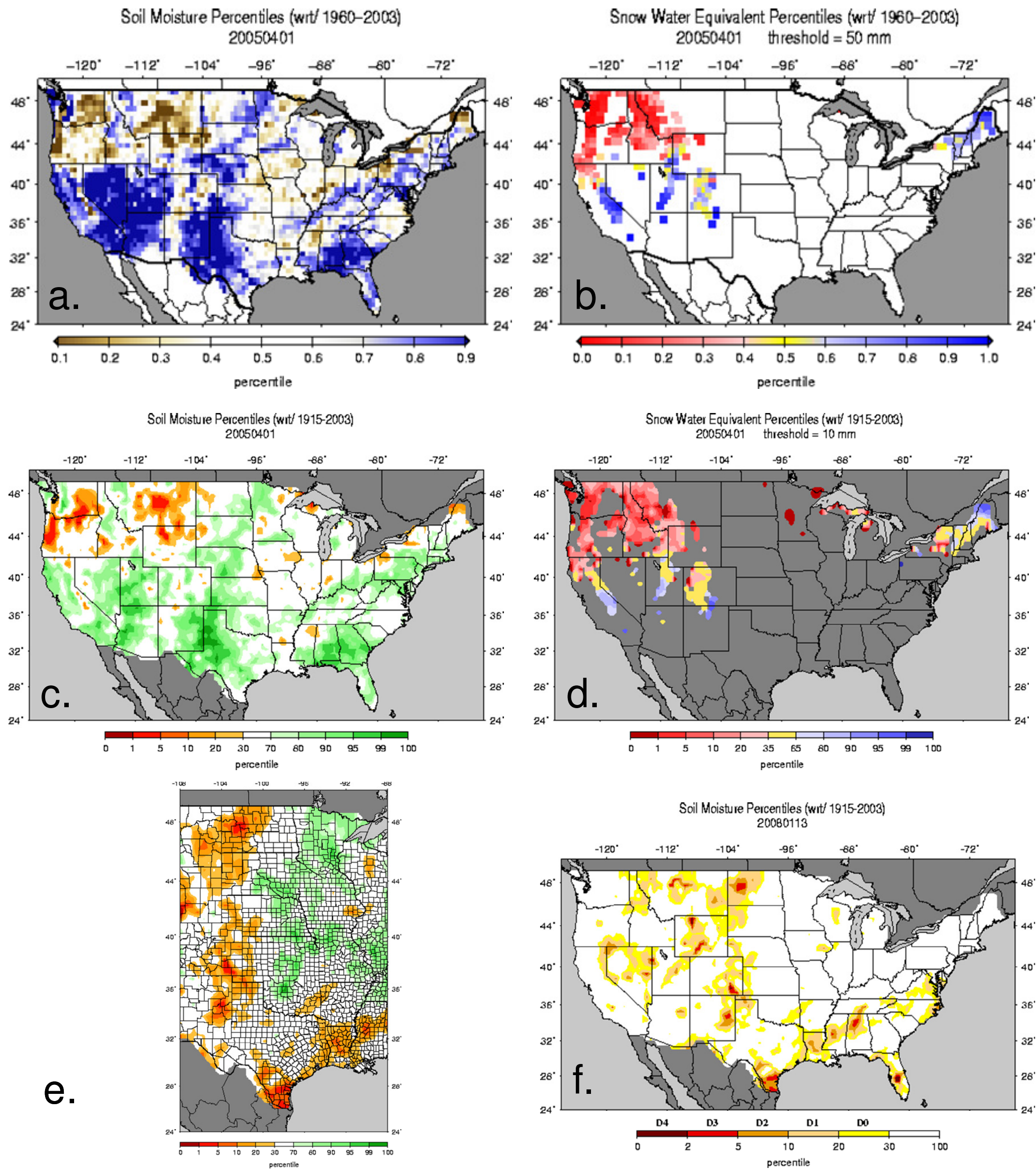

Figure 3. (a-b) Original SWM soil moisture and SWE plots; (c-d) current soil moisture and percentiles plots showing CPC color scheme and smoothing; (e) county level blowup plot; and (f) Drought Monitor color scheme plot of soil moisture percentiles. Note that plots represent conditions on different dates.

3. SWM PRODUCTS

The current suite of hydrologic analysis products have been developed in the context of an informal interaction during 2005-2008 between the author and members of the hydrologic research community and drought- or water resources-focused operational groups. The author's participation in the CPC Drought Outlook (DO) panel during this time has facilitated the dissemination of experimental SWM products and exchange of feedback leading to their improvement or development of new information products. For example, when it was launched in 2005, the SW monitor contained only real-time daily maps of SM and SWE percentiles, taken with respect to the historical period 1960-2003 (**Figure 3a-b**). On suggestions from CPC, the primary color scheme of the SM maps was changed to match that of the CPC SM percentile maps (**Figure 3c**), for easier comparison of the two. SW Monitor map data were spatially smoothed, yielding a non-pixelated data presentation (**Figures 3c-f**) but one that also obscures the model grid (and resolution). Blow-ups of the maps were created to show county delineations (**Figure 3e**), and a version of the SM map was duplicated in the colors of the DM drought categories (**Figure 3f**). At times, skeptical feedback on the SWM results has led to the discovery and correction of various coding bugs, and in that regard was equally essential to product suggestions in the development of the current system.

3.1 CURRENT CONDITIONS AND RECENT CHANGES.

In addition to the soil moisture and SWE plots, which analyze the final day of simulation update, cumulative runoff percentile plots are also viewable on the main page. Runoff from the VIC model is treated as the sum of surface runoff and baseflow, for each grid cell. The volatility of daily runoff is such that the cumulative runoff over a month or longer period is less noisy and has greater relevance for drought considerations. Percentiles are plotted for cumulative periods of 1, 2, 3, 6, 9, 12, 18, 24, 36, 48 and 60 months prior to the current date (two examples shown in **Figure 4**).

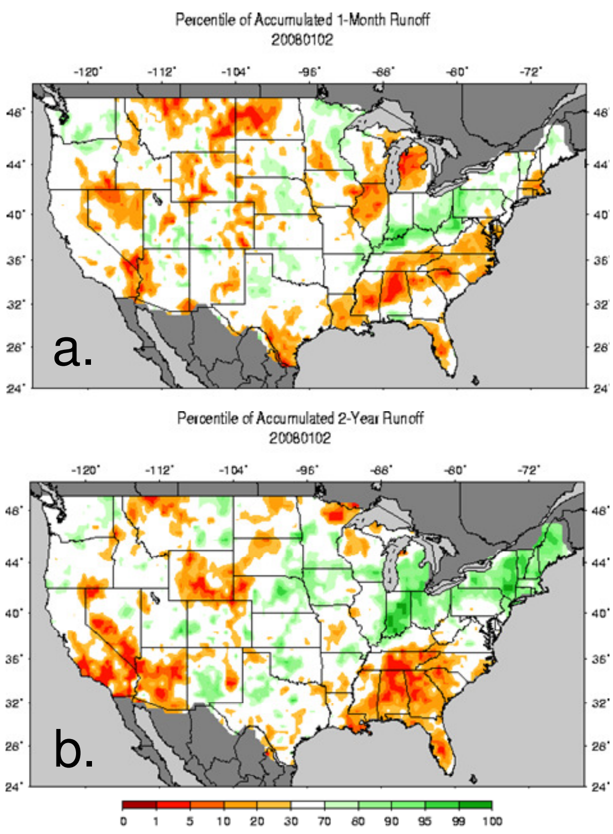

Figure 4. Cumulative runoff percentile maps for (a) 2 month runoff and (b) 24-month runoff.

The percentile of water year (WY) runoff (i.e., runoff since October 1) is also presented. For one month accumulations, but the soil moisture and runoff percentiles are highly correlated, the ability of accumulated runoff to describe deficits over longer drought periods may be better than that of soil moisture, a model's representation of which, unlike accumulated runoff, is constrained by the model's soil capacity.

Along with the nowcast maps described above, plots showing the changes in percentiles for the prior week, two weeks and month (**Figure 5**) are also updated daily. This information helps to convey the recent trends in conditions, and can be particularly useful for activities such as the DO, in which authors would like to ensure that updates to each outlook are consistent with changes in conditions since the prior outlook.

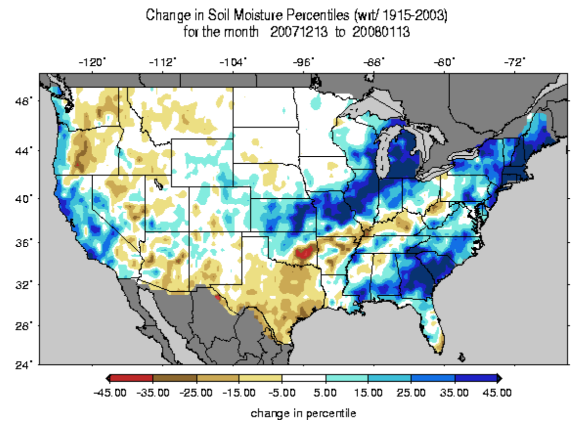

Figure 5. Changes in soil moisture conditions for the month leading up to the current day.

3.2 RETROSPECTIVE ANALYSIS ARCHIVE

The SWM's retrospective component – an archive of these variables extending back to 1915 that is being used by researchers around the U.S. – yields insight into major drought (and flood) events in U.S. history. The retrospective simulations are also useful in providing a historical perspective on current conditions. To this end, percentile analyses of soil moisture and snow water equivalent on the first day of every month in the record are plotted and made available via a search tool linked to the website (**Figure 6**). For example, **Figure 7** shows soil moisture analyses from (a) July 1934, during the Dust Bowl drought; (b) August 1993, during the Mississippi River floods; and (c) snow water equivalent from May 1997, when record snowpacks were recorded in the US Pacific Northwest. The raw data to accompany the retrospective analysis is made available online and upon request (for larger data volumes); and real-time simulation raw data are also staged online.

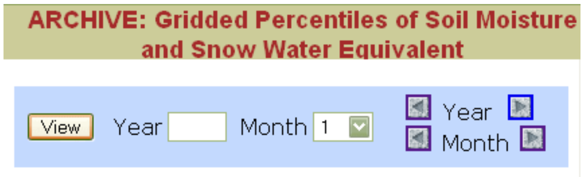

Figure 6. Search bar for accessing retrospective plots of soil moisture and snow water equivalent.

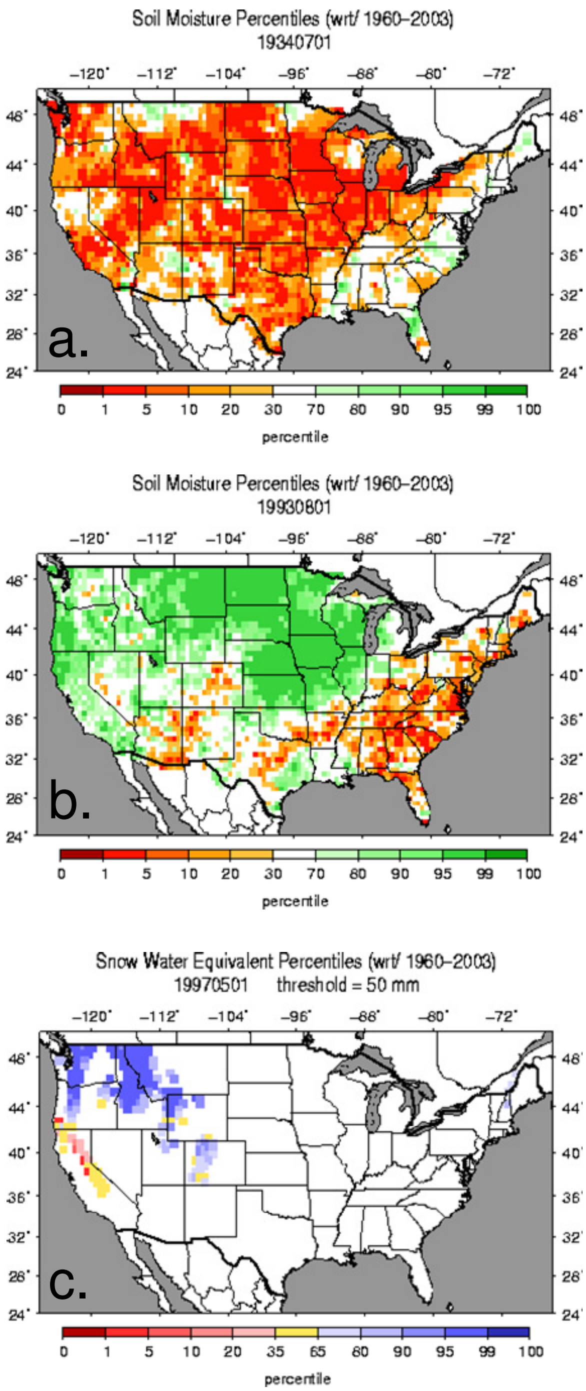

Figure 7. Retrospective analyses of soil moisture in (a) 1934, (b) 1993; and of SWE in (c) 1997.

3.3 FORECASTS

In operational agencies such as the NOAA National Weather Service (NWS), hydrologic models are used to make hydrologic ensemble predictions at lead times from hours to seasons. The primary approach in NWS is Ensemble Streamflow Prediction (ESP; Twedt et al., 1977), which uses a hydrology model to estimate the current land surface moisture conditions, after which the model states are forced into the future using sequences of weather observations taken from different years in the historical record of the forecast period. The term ***climatological*** **ESP** signifies that the sequences are taken from all the years of a past period (e.g, 1971-2000) with equal weighting given to each year.

Because the forecasts are initialized using current hydrologic states (primarily soil moisture and SWE), the forecast results merge persistence in the anomalies of these states with climatological uncertainty about future weather. A strength of the physically-based modeling framework is that the effects of seasonality are taken into account in the model physics (which is important because phenomena such as shifts in the timing of snowmelt runoff can otherwise confound recovery estimates).

ESP predictions were added to the SWM in August 2007, and the predictions are updated weekly. The SWM ensemble forecast framework is depicted in **Figure 8**, which shows schematically how, starting from a spatial drought nowcast map for a hypothetical ongoing drought (the spatial extent is taken from analysis of the 1930s drought), one can generate maps of the probability that soil moisture for each grid cell within the drought region will return to or exceed its long-term median value for various lead times, e.g., 4, 8 and 12 months. These recovery (or conversely persistence) probabilities could be calculated for either the entire soil column, or for model layer moistures separately (the different layers have different variability characteristics). The probabilities are derived from the ensemble soil moisture trace outcomes simulated for each grid cell, where the ensembles are taken from both climatological ESP and a conditional ESP. Currently in the SWM, an ENSO-conditioned ensemble is formed by including only the ESP ensemble members created from historical meteorological traces from years in which the ENSO state (La Nina, Neutral, El Nino) was similar to the current state.

The current climatological period for the SWM ESP forecasts is 1955-2002, and the forecast lead time is 3 months, which is also the lead time of the DO. Forecast-based products, which are shown for lead times of 1, 2 and 3 months, for both climatological and ENSO-subset forecasts, currently include the following:

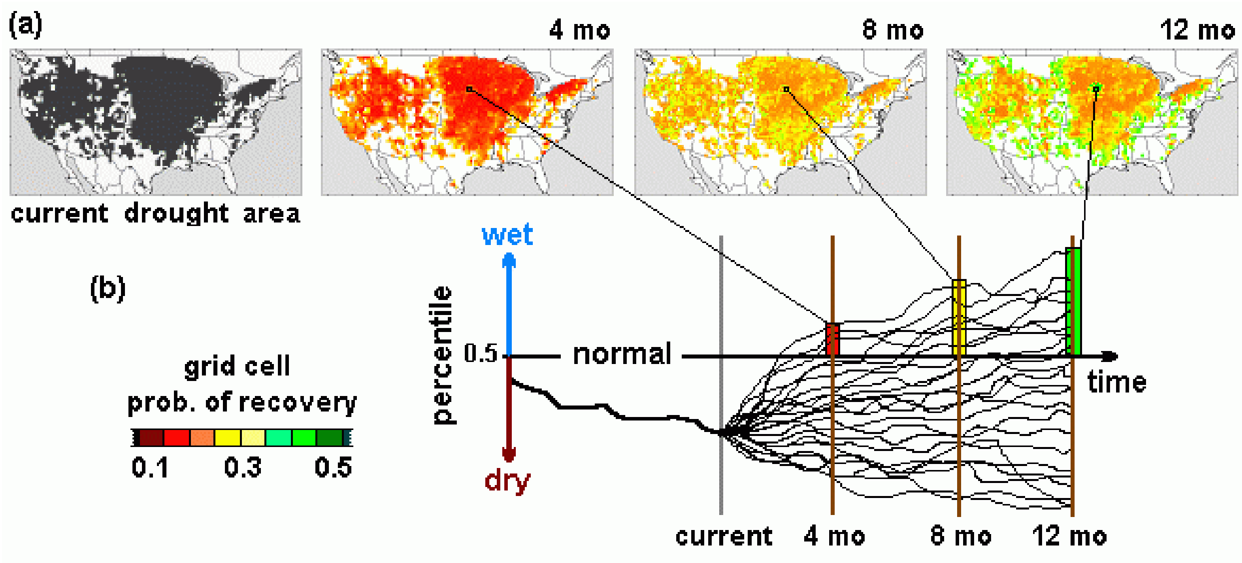

Figure 8. Illustration of ensemble forecast approach of the SWM, as applied to drought prediction. (a) Current drought area (based on August 1933); and for different lead times, maps showing the probability (in each grid cell experiencing drought) that soil moisture percentiles will recover. (b) The grid cell-specific recovery probabilities are derived from real-time soil moisture simulations up to the current date, after which simulations are driven by ensemble climate forecasts.

- the percentiles of the ensemble median soil moisture and 3-month runoff (**Figures 9a-b**, which show the ENSO-subset ESP results)
- the probability of future soil moisture and 3-month runoff being in the lowest quintile (i.e., lower than 20th percentile) of the historical range for the forecast date (current date + lead time) (**Figures 9c, d)**

The lowest quintile (i.e., 20th percentile and below) range of hydrologic variation is used in the drought monitoring community as a boundary between drought and non-drought. This boundary was suggested by CPC after the author initially tested a tercile-based product.

3.5 Drought Indices (SRI, SPI)

The SWM water balance variables can be used as a basis for deriving drought indices other than the variable percentiles. The first of such indices to be added to the SWM are the standardized precipitation index (SPI; McKee et al., 1993) and the standardized runoff index (SRI; Shukla and Wood, 2008; Mo, 2008). Each of these indices is defined as the unit standard normal deviate associated with the percentile of the accumulated precipitation over different accumulation periods. The percentile can be estimated from the empirical distributions of these variables, or from fitted distributions. McKee et al. (1993) use the Gamma distribution; and while the initial SWM SRI implementation (for reasons of expediency) also used the Gamma distribution, Shukla and Wood (2008) note that the selection of other distributions such as the 3-parameter log-normal and Generalized Extreme Value may be warranted for runoff instead. The SPI and SRI maps are calculated for 1, 2, 3, 6, 9, 12, 18, 14, 36 and 48 months (**Figure 10** shows, e.g., 6-month plots), and viewable using mouse-over links as on the main nowcast page.

One advantage of the index framework over the percentile framework in conveying anomalies for applications in which extremes matter is that the index units are non-linearly related to percentiles, so that the index scale gives greater resolution to the extreme ranges that matter most from the perspective of the application.

At present, the SWM has the only real-time (quasi-operational) SRI product, but an operational version at CPC (as described in Mo, 2008) is under development. The SWM SPI (and SRI) products represent an advance over current operational SPI products in several other regards. Current operational products tend to be at a far coarser scale both in space (i.e., the climate division or county level, as compared to the SWM's ½ degree grid) and in time (i.e., monthly or weekly at best). The SWM employs a rolling climatology to allow for daily updates to the SPI and SRI values. This requires a calculation based on a monthly time-step averaging of the retrospective to current simulation outputs that slides forward one day at a time.

The different accumulation periods have different significance in different regions and sectors due to the varying seasonality of runoff and the varying storage capacity of water management systems. For example, 1-3 month precipitation and runoff deficits

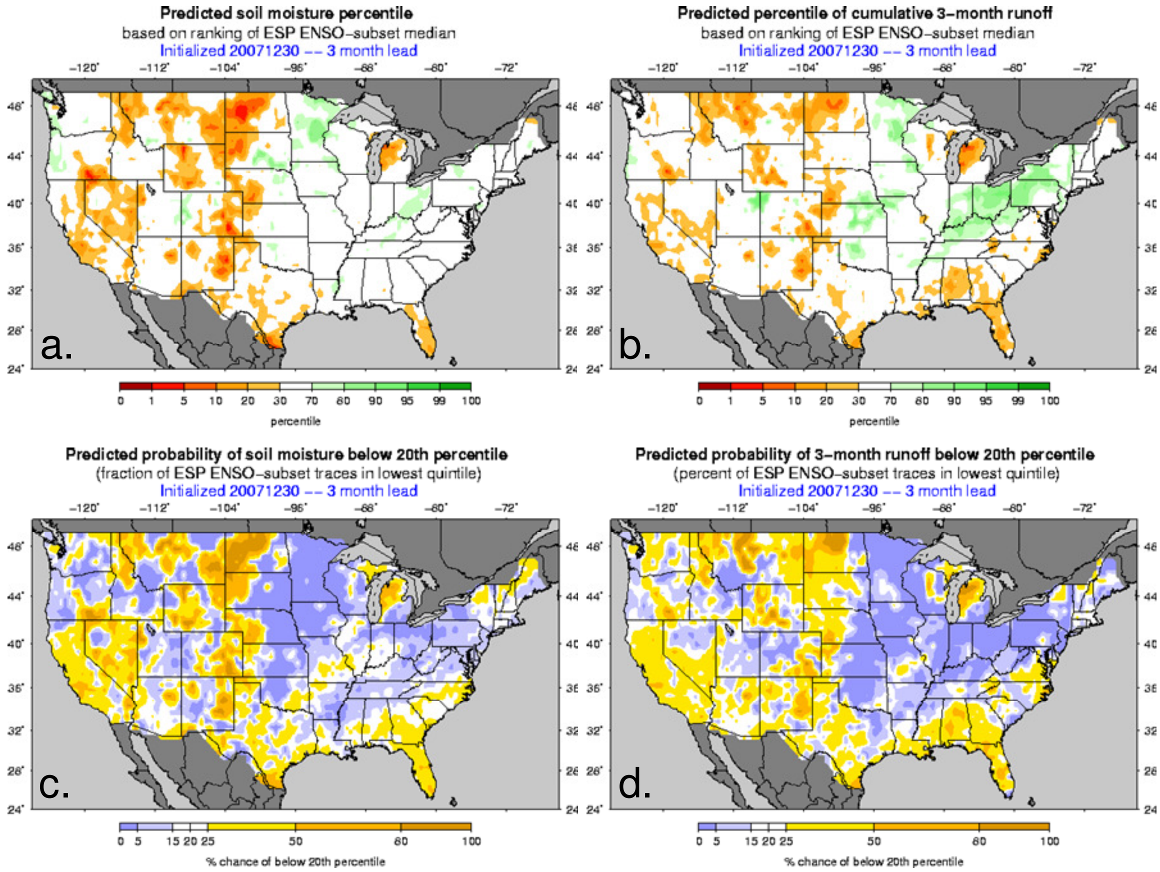

Figure 9. ENSO-subset (La Nina) ESP predictions of median (a) soil moisture and (b) 3-month runoff; and of probability that lowest quintile (c) soil moisture and (d) 3-month runoff will persist. Predictions are for 3 month lead times.

are important in areas with small reservoir systems, whereas in the Colorado R. basin, which has 4 years of capacity on the mainstem of the river, water management concerns are driven longer accumulation deficits. The differing behavior of the indices for different accumulation periods is shown in the example (for SRI) **Figure 11**. The monthly timeseries extending back to the 1950s of SPI and SRI values in each two degree area of the map are accessible by clicking on the map in the desired area. This visualization helps link spatial and temporal information about the extent of drought (or surplus moisture) in a way that is, at this time, fairly unique for an online, real-time analysis system.

3.6 TIMESERIES WATER BALANCE ANALYSIS PRODUCTS

In viewing a drought condition or the sudden amelioration of drought, it's helpful to be able to address the question: "How did this situation occur?". The author's interaction with the DO panel has led on a number of occasions to the need for diagnostics of the type shown in **Figure 12**. The plot shows, for a given area (in this case a small grid cell, but it could also be an areal average over a basin), the evolution of precipitation, temperature, SWE, soil moisture, and 5-day runoff during the prior five water year, as compared with the boundaries and quartiles of the historical climatology. This temporal analysis perspective, when merged with spatial analysis products, is a very powerful way to diagnose the causes of current conditions for an arbitrary region, to see where they are likely to lead, and also to estimate their similarity to surrounding regions. To date, however, the water balance analysis has been provided on demand by the author rather than maintained as part of the automated system.

4. DISCUSSION

The current implementation of the SWM has clear strengths. On a cosmetic level, the website appears to be an effective means of dissemination of the SWM products, and has helped to foster a range of collaborations and interactions that generated feedback that has aided the system's development. The primary strength, in the author's view, is that the approach for forcing the model offers a unique level of consistency between real-time and retrospective simulations not present in other operational land surface simulations that offer similar long term retrospectives, at least for the post-1950 period. This consistency minimizes the potential for biases in the estimation of real-time variable anomalies and percentiles arising merely from the change in observing system between real-time and retrospective periods. A related, major strength is the provision of a searchable long-term retrospective archive of soil moisture and SWE, and associated hydrologic datasets that, at least back to the 1950s, are thought to be consistent with the real-time simulations. The complete automation of the system from the gathering of observations to the update of the website with real-time products, and the manageable computational requirements of the coarse-scale system (relative to NLDAS), have facilitated both the development of new products and the repair of faulty simulations when bugs have been discovered. As a result, the SW Monitor currently offers an array of simulation products and data of comparable breadth to operational efforts supported by larger resources.

Some of these strengths, however, result from methodological choices that also have drawbacks. For instance, the coarse scale (1/2 degree) resolution that makes the system manageable also limits its spatial specificity from the perspective of many, local-scale applications. One minor deficiency worth noting is that several CONUS domain grid cells in the state of Maine are missing, and should be replaced in the next version. More seriously, the choice to use only index station forcings to maintain past-present-future consistency also requires excluding many observations that, but for their short periods of record, could provide additional information for the real-time simulations. The consistency objective also precluded the potential for data assimilation of other short record products, such as from satellites, to correct for simulation errors. The use of a single land surface model, VIC, that has not been directly calibrated for streamflow simulation (i.e., in its ½ degree implementation) also means that the SWM biases in soil moisture, SWE and runoff simulation products are unknown. It might be argued that individual model biases may be circumvented to some degree by interpreting model outputs in anomaly or percentile-space, but the validity of this argument has not been formally examined. Lastly, no correction is made at present for station dataset inhomogeneities that clearly affect the index station dataset before 1950, hence the same confidence in real-time to retrospective consistency for the post-1950 simulations cannot be extended to the pre-1950 results. Many of these criticisms can likely be levied against most other operational datasets (excluding those noted earlier). Nonetheless, to the extent that these deficiencies result from development capacity limitations rather than deliberate choices, the author hopes that these drawbacks in the current, initial version of the SWM will be corrected in future implementations either at UW or elsewhere.

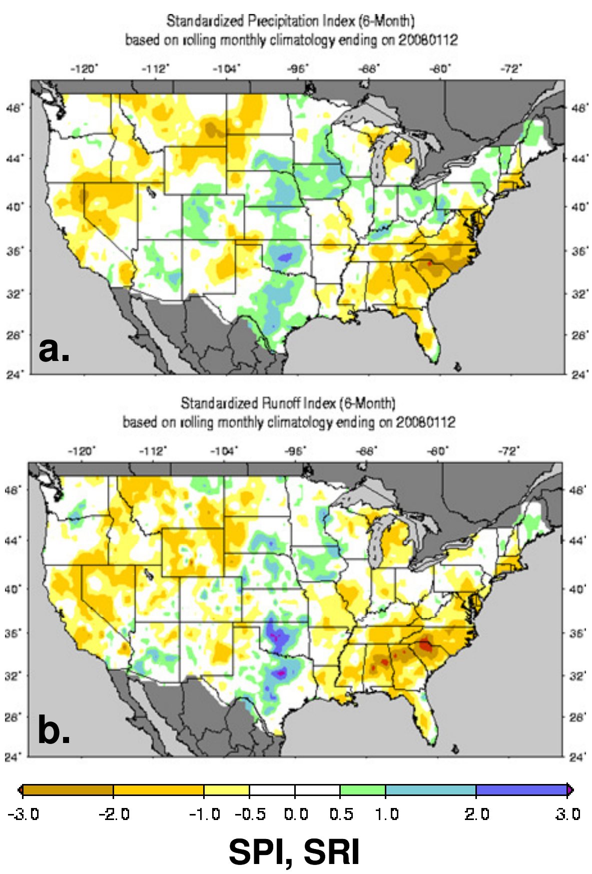

Figure 10. Daily-updating (a) standardized precipitation index (SPI) and (b) standardized runoff index (SRI) maps for 6-month accumulations.

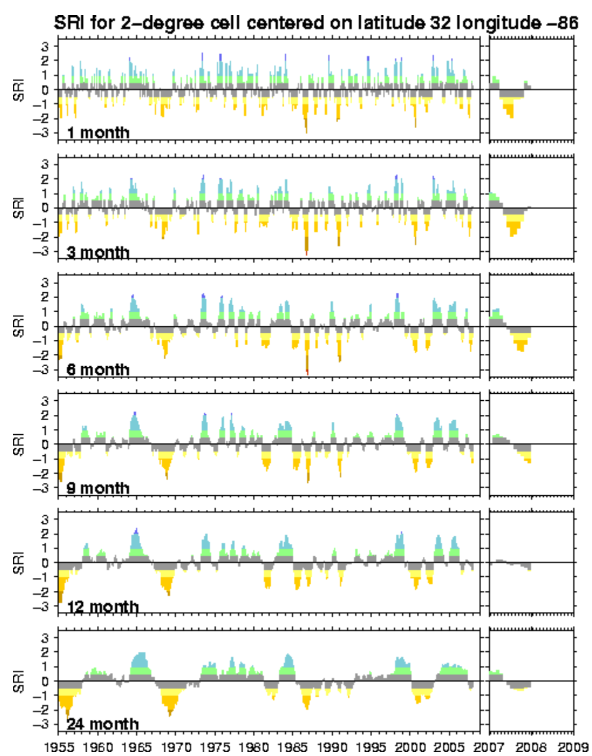

Figure 11. Timeseries of SRI averaged from values in a 2-degree area of the southeastern US, for various accumulation periods. The anomalies in SRI are colored to match the categories also shown on the corresponding spatial plots (in Figure 10).

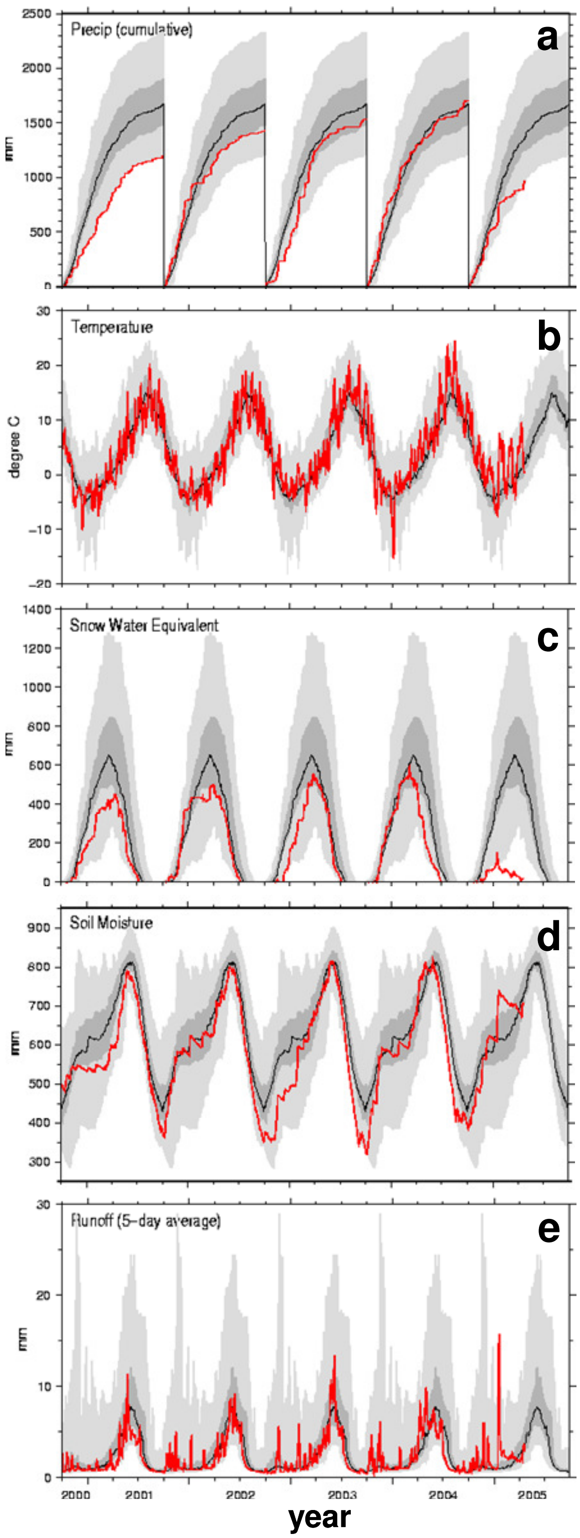

Figure 12. Timeseries of current conditions (red) vs historical climatology (gray) for (a) precipitation, (b) temperature, (c) SWE, (d) soil moisture, (e) runoff.

ACKNOWLEDGEMENTS

With the exception of the VIC model, the ACIS related code, and the archive retrieval script, the SWM as described herein has been conceived, created, developed and run by the author. This effort, however, owes a very large debt to the insightful feedback and interest of Doug LeComte, Victor Murphy, Mark Svoboda, Kelly Redmond, Rich Tinker, NRCS NWCC, Ken Mitchell and Kingtse Mo; to the technical assistance of Ali Akanda, Kaiyuan Lee, Kathy Devlin and George Thomas; to ACIS and particularly David Sathiarj; and to collegial support from Ed Maurer, Tom Pagano, Bart Nijssen and Phil Mote. The author is also grateful for funding to the UW from the NOAA Climate Diagnostics and Experimental Prediction, Climate Prediction Program for the Americas (under PI Dennis Lettenmaier, who provided financial support for the author when the SWM was initially implemented), and particularly from the NOAA Transition of Research Applications to Climate Services programs; and lastly for independent contract support to the author from 3Tier Group, Seattle, Washington, USA.

REFERENCES

Andreadis, K.M., E.A. Clark, A.W. Wood, A.F. Hamlet, and D.P. Lettenmaier (2005), 20th Century Drought in the Conterminous United States, J. Hydrometeor., 6(6): 985-1001.

Hamlet A.F., Lettenmaier D.P., 2005, Production of temporally consistent gridded precipitation and temperature fields for the continental U.S., J. of Hydrometeorology, 6(3), 330-336

Huang, J., H. M. Van den Dool, and K. P. Georgakakos (1996), Analysis of model-calculated soil moisture over the United States (1931-1999) and applications to long-range temperature forecasts. J. Climate, 9, 1350-1362.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs. J. Geophys. Res., 99(D7), 14,415-14,428.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier and B. Nijssen, 2002. A long-term hydrologically-based data set of land surface fluxes and states for conterminous United States, J. Clim. 15(22), 3237-51.

McKee, T. B., N. J. Doesken, and J. Kleist, (1993), The relationship of drought frequency and duration to timescales. 8th Conference on Applied Climatology, Anaheim, Calif., 17– 22 Jan.

Mitchell, K. E., and many authors (2004), The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributedhydrological modeling system. J. Geophys. Res., 109, D07S90, doi:10.1029/2003JD003823.

Mo, K., 2008, Model-based drought indices over the United States, *J. Hydrometeorology* (submitted).

Shukla, S., and Andrew W. Wood, 2008. Use of a standardized runoff index for characterizing hydrologic drought, Geophys. Res. Lett., 35,LXXXXX, doi:10.1029/2007GL032487.

Svoboda, M., and many authors (2002), The Drought Monitor. Bull. Amer. Meteor. Soc., 83, 1181–1190.

Tang, Q., A.W. Wood, D.P. Lettenmaier, 2008, Real-time precipitation estimation based on index station percentiles. *J. Hydrometeorology* (submitted).

Wilhite, D.A.; and M.H. Glantz. 1985. Understanding the drought phenomenon: The role of definitions. Water International 10:111–120.

Wood, A.W., Akanda, A.S., and Lettenmaier, D.P., 2005. An Experimental Surface Water Monitoring System for the Continental US. Poster presented at NASA Workshop: Predicting Drought on Seasonal to Decadal Timescales (College Park, Maryland), May 17-19.

Wood, A.W. and D.P. Lettenmaier, 2006, A testbed for new seasonal hydrologic forecasting approaches in the western U.S., Bulletin of the American Meteorological Society **87**:12, DOI:10.1175/BAMS-87-12-1699, 1699-1712..