A TEST BED FOR NEW SEASONAL HYDROLOGIC FORECASTING APPROACHES IN THE WESTERN UNITED STATES

BY ANDREW W. WOOD AND DENNIS P. LETTENMAIER

An experimental forecast system based on modern hydrologic models facilitates the evaluation of data assimilation methods, ensemble climate forecasts, and dissemination of visual nowcast and forecast products in ways not possible with current operational methods.

Hydrologic extremes are costly to the nation. Annual U.S. drought and flood damages over the last decade have averaged between $6–$8 and $2 billion, respectively (FEMA 1995). Losses associated with the four-year 2000s drought in the western United States are likely to be in the tens of billions of dollars. To the extent that floods and droughts can be mitigated by management of water stored in reservoirs, improved streamflow prediction can help to reduce these losses. Potential economic benefits result from accurate hydrologic forecasts in years that are not hydrologically extreme as well. For instance, Yao and Georgakakos (2001) and Hamlet et al. (2002) have shown how hydropower revenues can be increased through incorporation of climate information in hydrologic forecasts, while Brumbelow and Georgakakos (2001) have shown the benefits of improved hydrologic forecasts to management of agricultural water supply.

Despite the potential benefits of improved hydrologic forecasts, most operational hydrologic prediction at seasonal lead times and related water and energy management decisions are based on methods and data sources that have been in place for almost half a century. In particular, the primary operational method of seasonal and subseasonal streamflow forecasting in the western United States is regression of seasonal streamflow volume on indicator variables, primarily point observations of snow-water equivalent. This is especially the case for long-lead (e.g., monthly to seasonal) hydrologic forecasts that are the basis for hydropower and water supply management

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in the western United States. Nonetheless, a recent analysis by Pagano et al. (2004) showed that the skill of western U.S. seasonal streamflow forecasts has generally not improved since the 1960s, in part due to an increase in climate variability in recent decades (Pagano and Garen 2005a; Jain et al. 2005) and to changes in the observing system. Incorporation of new sources of data (e.g., satellite observations of the extent of snow cover) and methods (e.g., data assimilation) within the regression framework is difficult, in part because the forecast models require "training" using long time series of observations. Furthermore, regression-based approaches may be ill suited to a hydroclimatic setting in which the underlying relationships between the climatic and hydrologic predictors and the predictand (streamflow) appear to be changing in time (e.g., Hamlet et al. 2005; Mote et al. 2005; Cayan et al. 2001).

While hydrologic forecast accuracy has shown little improvement in recent decades, climate and weather forecast skill has clearly improved over the same period (e.g., Goddard et al. 2001), in part due to a combination of computing advances, increased model (spatial and temporal) resolution, improved dynamics, and improved observing capabilities for boundary model forcings such as sea surface temperature. In hydrology, forecast improvements have been more difficult to achieve, arguably at least in part because the physical processes that control runoff and streamflow production are much more spatially heterogeneous than those that control weather and climate. While forecast accuracy improvements would likely result from observing system densification, the need for long data records in regression-based methods like those on which the Pagano et al. (2004) results are based dictates that associated forecast accuracy improvements would take decades to realize (ignoring the further complicating effects of a changing climate). We believe that a more promising pathway lies in the development of methods for assimilating new sources of observational data (for parameters and land surface states) into land surface energy and water balance models, which can then be forced with modern climate and weather forecasts. Such a strategy is inherent in the National Weather Service's (NWS's) Advanced Hydrologic Prediction System (AHPS; McEnery et al. 2005), and a similar strategy is being adopted by the National Water and Climate Center (NWCC) of the National Resources Conservation Service (NRCS). NWS and NRCS are the two U.S. Federal agencies with primary responsibility for seasonal streamflow forecasting in the western United States.

While regression-based seasonal streamflow forecasts still form the backbone of the NWS and NWCC operational systems, a variety of alternative approaches have been (and are being) tested and implemented at the federal and state levels. Foremost among these is an approach now known as ensemble streamflow prediction (ESP) that was developed in the late 1970s (Twedt et al. 1977; Day 1985), wherein ensembles of past observations (primarily of precipitation and surface air temperature) are used to force a dynamic hydrologic (or land surface) model. This historic resampling approach can be adapted to reflect a selected range of climate conditions [e.g., depending on the phase of El Niño–Southern Oscillation (ENSO)], and this approach is now being explored, at least at shorter lead times, by some NWS River Forecast Centers (Werner et al. 2005).

Notwithstanding practical complications that in some cases can constrain the forecast accuracy of ESP methods (see, e.g., Lettenmaier 1984; Day 1985, for a discussion), there is an ongoing trend away from the traditional regression-based forecasts for some of the reasons noted above. The NWS AHPS initiative has motivated implementation of ESP for seasonal streamflow forecasts at an expanded set of forecast points in the western U.S. RFCs. The NWCC has adopted principal component analysis techniques (Garen 1992), and for some locations has implemented modifications to their regression approach that incorporate external climate forecast information, such as predictions of ENSO phase (Pagano and Garen 2005b) or the Trans-Niño Index (Trenberth and Stepaniak 2001). NWCC has also dramatically improved the online visualization methods for their forecast-related observational data and analyses, increased forecast frequency, and is investigating the use of hydrologic models to complement their statistical forecasting operations (Pagano 2006). Other efforts, such as the Hydrologic Ensemble Prediction Experiment (HEPEX; see Franz et al. 2005) and the Distributed Model Intercomparison Project (Smith et al. 1999), both of which are led by NWS, are also relevant.

In the forecast user community, experimental efforts to improve forecasts are also underway. The U.S. Bureau of Reclamation (USBR) is collaborating with the U.S. Geologic Survey (USGS) and university researchers to explore alternative streamflow forecast methods for a number of small western U.S. basins (Grantz et al. 2005; Mastin and Vaccaro 2002). One of the most mature existing efforts to operationalize alternative streamflow-forecasting methods and incorporate them into water resources management is a model-based, interagency (state and federal) collaboration known as INFORM (the Integrated Forecast and Reservoir Management Project; Georgakakos et al. 2005). INFORM focuses on at least four major reservoirs and their drainage basins in northern California.

Recent climate extremes (such as the extreme high snowfalls in the southwestern United States, and drought in the Pacific Northwest in winter 2004/05) have renewed interest in alternative operational approaches that exploit new sources of observations and data assimilation methods for seasonal hydrologic prediction. This interest has also been fostered in part by expanded academic research devoted to the subject (e.g., Clark and Hay 2004; Wood et al. 2002, 2005; Perica et al. 2000; Grantz et al. 2005) and by the experiences of the operational agencies noted above.

We describe herein the development of an experimental West-wide seasonal forecast system that is intended to serve as a test bed for seasonal hydrologic forecasting methods and hydrologic data assimilation approaches for the western United States. The system presently focuses on monthly to seasonal lead times and runs in an operational (real time) mode at the University of Washington (UW). Development of the system began in the spring of 2000 and focused on predicting drought conditions in the eastern United States. It was initially intended as a vehicle to incorporate global seasonal (6-month lead) climate forecasts from the National Centers for Environmental Prediction (NCEP) Global Spectral Model (Wood et al. 2002, 2005) and to resolve challenges related to downscaling the climate ensembles (then about 2.8° latitude × 2.8° longitude) to the much finer spatial resolution (1/8°) of the hydrologic model.

In January 2001, the system was transplanted to the Pacific Northwest and forecasts were made for the summer flow of the Columbia River at The Dalles, Oregon (a key index location for management of the Columbia River reservoir system), during what became one of the region's driest years on record. In water year 2002, the system was expanded to include climate forecast ensembles from other sources and methods. These included ESP, ESP with ENSO-conditioned, and Pacific Decadal Oscillation (PDO)-conditioned interpretations (Hamlet and Lettenmaier 2000), and the National Aeronautics and Space Administration (NASA) Seasonal to Interannual Prediction Project (NSIPP; Bacmeister et al. 2000) model ensembles. In water year 2003, the forecast domain was expanded to include all of the United States west of the Continental Divide, the Climate Prediction Center (CPC) seasonal outlooks were added as a climate forecast source, and a hydrologic model assimilation of point snow-water equivalent observations was implemented. This evolution has culminated in the current UW West-wide Seasonal Hydrologic Forecast System (henceforth referred to as the "West-wide system"), which generates monthly spatially distributed nowcasts and forecasts of hydrologic conditions (soil moisture, snowpack, runoff) across the western United States and associated ensemble streamflow forecasts of numerous locations.

COMPONENTS OF THE NOWCAST AND FORECAST SYSTEM.

Most of the elements of the system are evolving, by design. This section describes the components of West-wide system as it is presently implemented.

Hydrologic model. The forecast system is currently based on the variable infiltration capacity (VIC) macroscale hydrology model (Liang et al. 1994; Cherkauer et al. 2003, among others); our eventual intent, however, is to utilize multimodel ensemble methods (Kirshnamurti et al. 2000) that will make the specifics of the VIC model less relevant. VIC is a semidistributed grid-based model that is typical of the land surface schemes now used in most numerical weather prediction and climate models (Mitchell et al. 2004). For offline simulations such as those used in the West-wide system, the VIC model is forced with daily precipitation, maximum and minimum temperature, and daily averaged wind speed, which are taken from gridded observations prior to the forecast date (model spinup), and from a variety of other sources (described below) during the forecast period. Grid cell runoff is routed to produce streamflow at forecast points (currently about 90) within the simulation domain (Fig. 1). The VIC model implementation is consistent with that described in Maurer et al. (2002).

The forecast system utilizes three types of VIC model runs. The first is a daily retrospective simulation from 1949 to 2000, driven by observations from the NOAA Cooperative Observer (Co-Op) network [online National Climatic Data Center (NCDC) Summary of the Day dataset] and processed into model forcing grids as described in Maurer et al. (2002). This retrospective run yields the climatology or "normal" used to interpret real-time nowcasts and forecasts as anomalies or percentiles. These data were also used to calibrate and validate streamflow simulation results at the forecast points. The second type of VIC run is a shorter spinup simulation "warm

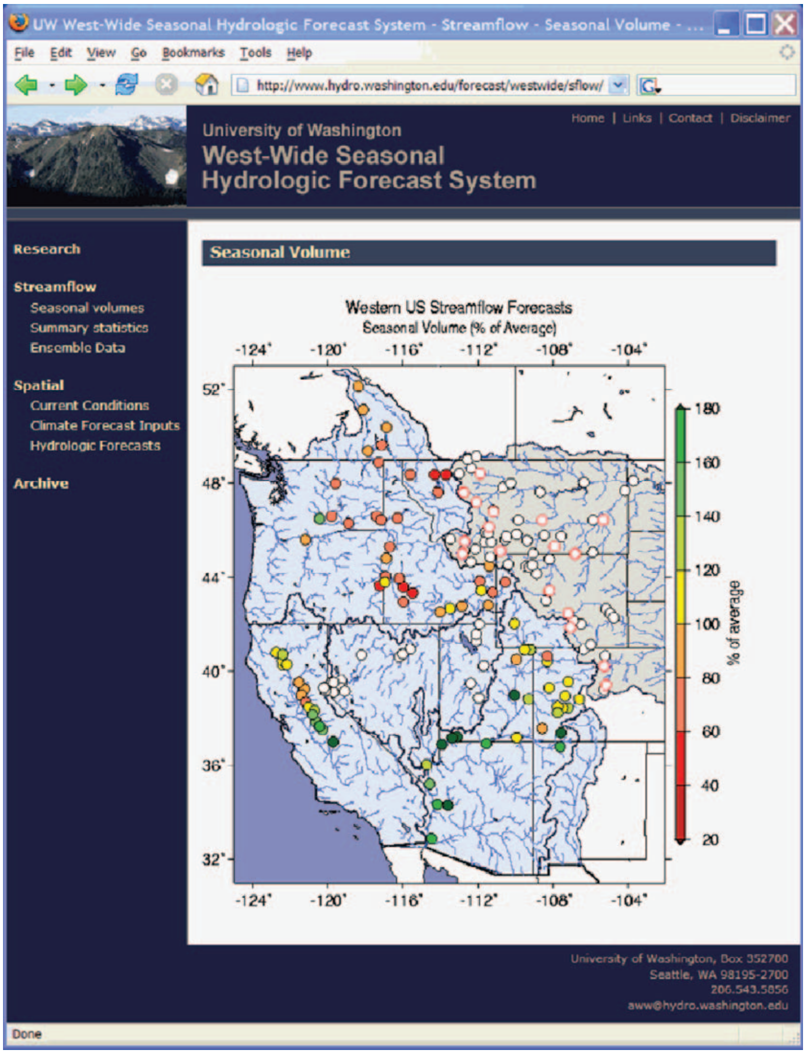


Fig. 1. A current forecasting system Web site display, showing a map with existing (colored) and in-development (white) streamflow-forecasting locations.

started" from the end of the retrospective simulation, extending to the forecast start date. This simulation produces the nowcast of hydrologic state (primarily soil moisture and snow-water content) that initializes the forecasts. The spinup simulation is also driven by gridded Co-Op station observations, with a slight variation described in the next section. The third type of run is the hydrologic forecast, which is warm-started by the hydrologic state from the spinup simulations. Figure 2 summarizes the information flow in the forecast system.

Hydrologic spinup approach. Depending on the time of year and location, the evolution of hydrologic state during the forecast period depends in varying degrees on the initial hydrologic conditions and on the climate inputs during the forecast period. A major complicating factor in providing model forcings during the spinup period is that many of the observations used for retrospective simulations are only available with a time lag of several months or longer. Prior to the most recent 3 months (the approximate lag for release of Co-Op station data from NCDC), the Maurer et al. (2002) methods are used, after which we employ an index station method that combines information from a sparser network of real-time reporting stations (a subset of the more spatially detailed long-term retrospective stations) with climatological information from the retrospective dataset. We currently use 261 index stations (15 of which are in British Columbia, Canada), selected according to the reliability of real-time reporting and the length of retrospective record. The index station data are spatially interpolated, expressed in terms of anomalies (for temperature) and percentiles (for precipitation), and are used to extract corresponding temperature and precipitation values from the 1/8° retrospective climatology [which incorporates orographic effects that are important in the western United States, using methods described in detail by Maurer et al. (2002)]. The resulting 1/8° daily temperature and precipitation data reflect the coarser index station–based climate signal over the finer-resolution variability that would be present if the denser network were available in real time. The effectiveness of the index station approach is owed in part to the fact that streamflow in most of the forecast domain is derived from snowmelt runoff, which is dominated by the effects of large-scale frontal storm systems that have sufficient spatial coherence to be reasonably well described by a relatively sparse (compared with the network available at a 3-month lag) index station network.

Observed SWE assimilation in initial state estimation. Because winter snow-water equivalent (SWE) is the primary source of moisture storage over much of the forecast system domain in water and spring, the potential exists to update the model's initial snow state with observations. The U.S. Department of Agriculture (USDA)/NRCS snow telemetry (SNOTEL) network includes over 600 sites within the forecast domain. In addition, there are about a dozen Automated Snow Pillow (ASP) stations in the Canadian (British Columbia) portion of the domain, operated by Environment Canada (see Fig. 3). We use a one-time assimilation routine that blends the observed station SWE anomalies at the time of forecast with the SWE anomalies predicted by the hydrologic model to create the initial state used in the forecasts. Observed SWE values generally are inconsistent with model estimates due to the differences in observation (point) and model prediction (areal average) scales, among other biases. SWE anomalies (or percentiles) relative to the observed or modeled climatology can be useful in bridging the scale gap. Therefore, observed station anomalies (relative to 1990–2000 observed averages) on the forecast date are interpolated to the hydrologic model grid. Stations that average less than 10 cm of SWE on the date of the update are not used. The interpolated station anomalies are used to adjust each model grid cell's simulated mean for the same period, for each model elevation partition ("snowband"). The adjusted SWE values are then merged with the model's original simulated SWE values for the forecast start date using weightings based on a combination of a) distance from the grid cell center to the station, b) elevation difference between the station and the grid cell elevation band, and c) the possible contributions of other stations in the area. Radii of station influence over nearby model grid cells range from 50 km (with a linear decrease in influence away from the station location) to 150 km (for the sparser stations in Canada); and the weighting for elevation also drops off linearly from the station elevation. For example, a station located at a grid-cell center at the central elevation of an elevation band, outside the range of all other stations, would have a weighting of 1, while the simulated value in that band would be weighted 0. This relatively simple assimilation approach, although apparently successful in improving the forecast initial conditions, depends

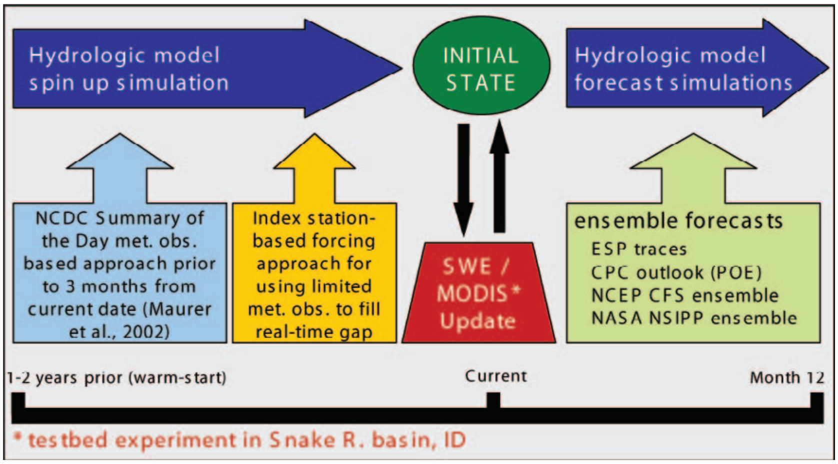


FIG. 2. The configuration of the current seasonal streamflow-forecasting system.

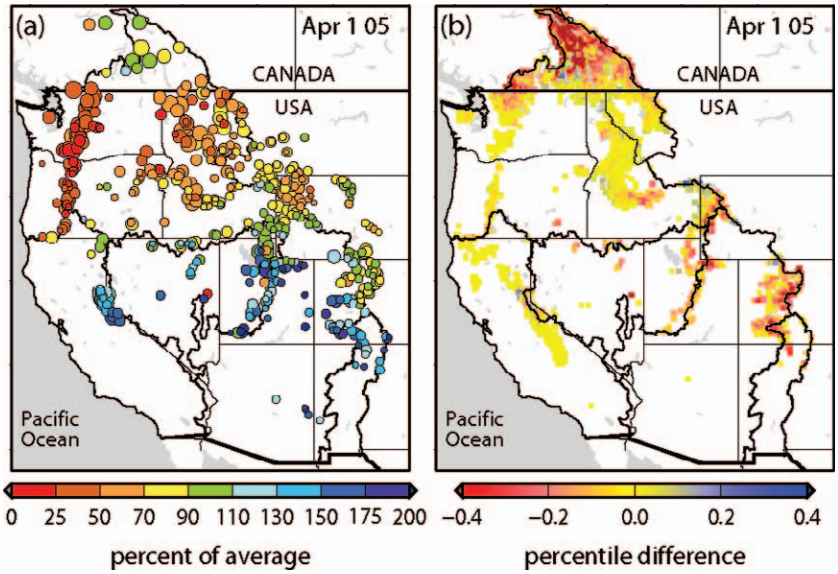


FIG. 3. Snow assimilation is effected by merging, at forecast initiation time, (a) the measured SWE anomalies at NRCS SNOTEL and Environment Canada snow pillow stations with the modeled SWE anomalies, resulting in (b) varying adjustments to the model-only snow-water equivalent, as reflected by the change in SWE percentile.

for now on several arbitrary inputs that affect the weightings. In parallel, we have also used the Westwide system to explore more sophisticated methods of incorporating both station and satellite estimates of snow-water equivalent and areal extent in the model predictions (Andreadis and Lettenmaier 2006; McGuire et al. 2005), and snow data assimilation remains an area of active development.

Climate forecast approaches. ENSEMBLE STREAMFLOW PREDICTION. The ESP forecasts are based on ensembles of daily hydrologic model outputs resulting from driving the VIC model with climate sequences resampled from previous years (in the current implementation, these sequences are drawn from the period of 1960–99), beginning on the same day that the forecast is initialized and extending for one year. The resulting unconditional ensemble of forecasts reflects the assumption that the daily weather during the forecast period could mirror that of previous years for the same calendar period. Two conditional forecast results are also created, formed by a) restricting the pool from which past years are drawn to those previous years sharing the current ENSO state, and b) restricting the pool to those previous years sharing the current ENSO and PDO states. The (unconditional) ESP approach provides a baseline forecast because it is the least experimental of the approaches employed.

CLIMATE MODEL–BASED APPROACHES. The climate model–based approaches have focused on the NASA NSIPP and NOAA/NCEP models (now the Coupled Forecast System; Saha et al. 2006). As noted above, a key issue is downscaling from the relatively coarse climate model domain of the 1/8° grid mesh used by the forecast system. A statistical bias correction and downscaling procedure is used to transform the climate model outputs, which are temporally aggregated (at the respective climate modeling centers) to monthly mean temperature and total precipitation, to the spatial and temporal resolution of the hydrology model. The downscaling procedure (detailed in Wood et al. 2002) is applied to each climate model forecast ensemble member in the following steps:

- bias correction of monthly climate model forecast outputs at the climate model scale using a probability-mapping approach (illustrated in Fig. 4);
- spatial disaggregation: a) linear interpolation of monthly forecast anomalies from the climate model to the 1/8° hydrologic model scale, and b) adjustment of 1/8° climatological monthly means by 1/8° anomalies to produce monthly 1/8° precipitation and temperature values, and
- temporal disaggregation of monthly values to a daily time step by randomly resampling 1-month-long observed 1/8° patterns of daily precipitation and temperature, followed by rescaling (precipitation) and shifting (temperature) to preserve the monthly forecast values.

The climate model output datasets differ in a number of ways, such as the number of ensemble members, grid resolution, and the type of model climatology that is available, but the general downscaling framework is applicable to both. We note that the approach we use is but one method of addressing the general problem of how best to incorporate ensemble weather and climate predictions into a hydrologic prediction context, a problem that will be addressed in detail by the Hydrologic Ensemble Prediction Experiment (HEPEX) effort.

CPC OUTLOOK-BASED APPROACH. CPC probability-of-exceedance forecasts for average monthly temperature and total precipitation in each of 102 climate divisions within the United States are translated into a 30-member ensemble of monthly climate division temperature and precipitation, using a statistical method called the Schaake shuffle (Clark et al. 2004). The Schaake shuffle generates (through resampling to create an ensemble of historical temperature and precipitation sequences) a monthly time-step spatial and temporal rank structure for the forecast variables that is consistent with observations. The rank structure is then imposed on the unranked and unassociated CPC temperature and precipitation forecast distribution values, which preserve the forecast ensemble signal while creating historically justified temporal and spatial associations between temperature and precipitation for each ensemble member. The resulting forecast ensemble is downscaled (spatially and temporally disaggregated) using the same procedure applied to the climate model outputs, creating 1/8° daily time-step forcings for hydrologic forecast simulations.

FORECAST SYSTEM PRODUCTS AND ACTIVITIES.

Examples of the products that the nowcast/forecast system currently provides are drawn from the water year 2005 (WY2005) forecasting season (from October 2004 to June 2005), during which remarkable spatial contrasts evolved in hydrologic conditions over the western United States.

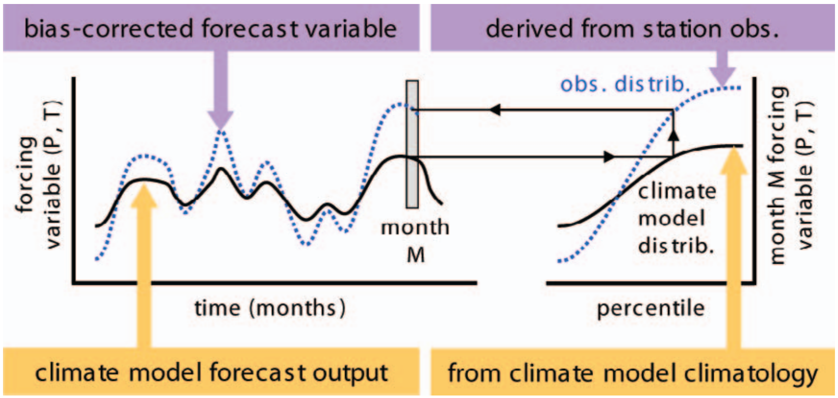


Fig. 4. The bias correction approach (a transformation described in Panofsky and Brier 1968) used to adjust the climate model forecast outputs before downscaling.

Snow-water equivalent and soil moisture nowcasts. An important feature of the Westwide system is the spatially distributed nowcast (of, e.g., snow-water equivalent and soil moisture) that the system produces. The daily time step, spatial unit (approximately 18,000 grid cells), and vertical resolution (associated with elevation bands) afford the opportunity to characterize and visualize hydrologic response in much greater geographic and temporal detail than is provided by point observations and forecasts alone. Such spatial detail is illustrated in Fig. 5, which shows the evolution of land surface conditions in the forecast system during WY2005. Precipitation forcings and system nowcasts of soil moisture and SWE are expressed as (nonexceedance) percentiles with respect to a 40-yr retrospective climatology. As Fig. 5 indicates, WY2005 (starting 1 October 2004) began with soil moisture deficits in California, the Great Basin, the lower Colorado basin, and the Pacific Northwest, particularly at high elevations. An anomalously wet October over much of the West alleviated these deficits, but November then arrived as the first of four consecutive months with below- and above-normal precipitation in the Pacific Northwest the the Southwest, respectively. The Northwest–Southwest divergence in conditions was striking in February, after which precipitation was closer to normal in most of the domain. Soil moisture deficits recovered in the Southwest and worsened in the Pacific Northwest, particularly in western Oregon and Washington.

Land surface water balance diagnosis and prediction. As is illustrated in Fig. 5, one characteristic of the system (for the forecasts as well as the nowcasts) is the ability to examine model fields in the context of the historical climatology. Because the procedure for initializing the forecasts is consistent with that used to produce the model climatology, and because bias in the climate forecasts is removed, the nowcasts and forecasts can be directly compared to the climatology, that is, in terms of anomalies or percentiles, or as analogs to previous years. For the purposes of water management, this capability is essential because it allows managers to review the current hydrologic status and operational options in light of prior experiences. Examples of forecast products that utilize this capability are the nowcast and forecast maps of SWE, soil moisture and runoff, and the forecasts of streamflow in various formats (e.g., monthly hydrographs, and seasonal volumes in percentages of average that can be compared to current operational forecasts).

Figure 6 shows how 1 April 2005 SWE (shown in Fig. 6a) was predicted based on forecast ensemble medians from the CPC ensembles, and by the CPC ensembles in comparison to the ESP ensembles. The CPC forecast used in January (Fig. 6b taken from the 16 December 2004 outlook) correctly identified the drier-/wetter-than-normal conditions in the Pacific Northwest/Southwest for January and February that contributed to the Northwest–Southwest SWE disparity. Even so, the 1 January CPC-based SWE forecasts (Fig. 6c) overestimated 1 April SWE percentiles in the PNW and underestimated them in the Southwest, with diminishing errors in the 1 February and 1 March forecasts. Nonetheless, the errors in the CPC-based SWE forecast were lower, particularly in the PNW, than those in the ESP-based SWE forecast (Fig. 6d). As might be expected, the largest differences were in January. As the season progressed, the initial conditions began to dominate the forecast signal, and differences between CPC and ESP forecasts diminished.

Figure 7 illustrates the diagnostic capabilities of the forecast system using the Yakima River basin above Parker, Washington, one of the hardest hit areas in the 2005 drought in Washington State. The current water year simulations (i.e., the spinup and forecast ensemble) cast against a historical backdrop provide insight into the daily evolution and likely future development of the hydrologic state of a basin, relative to the range of conditions that might be expected. In this case, the two major rain events (Fig. 7b) of the winter coincided with anomalously warm temperatures (Fig. 7c), so that instead of

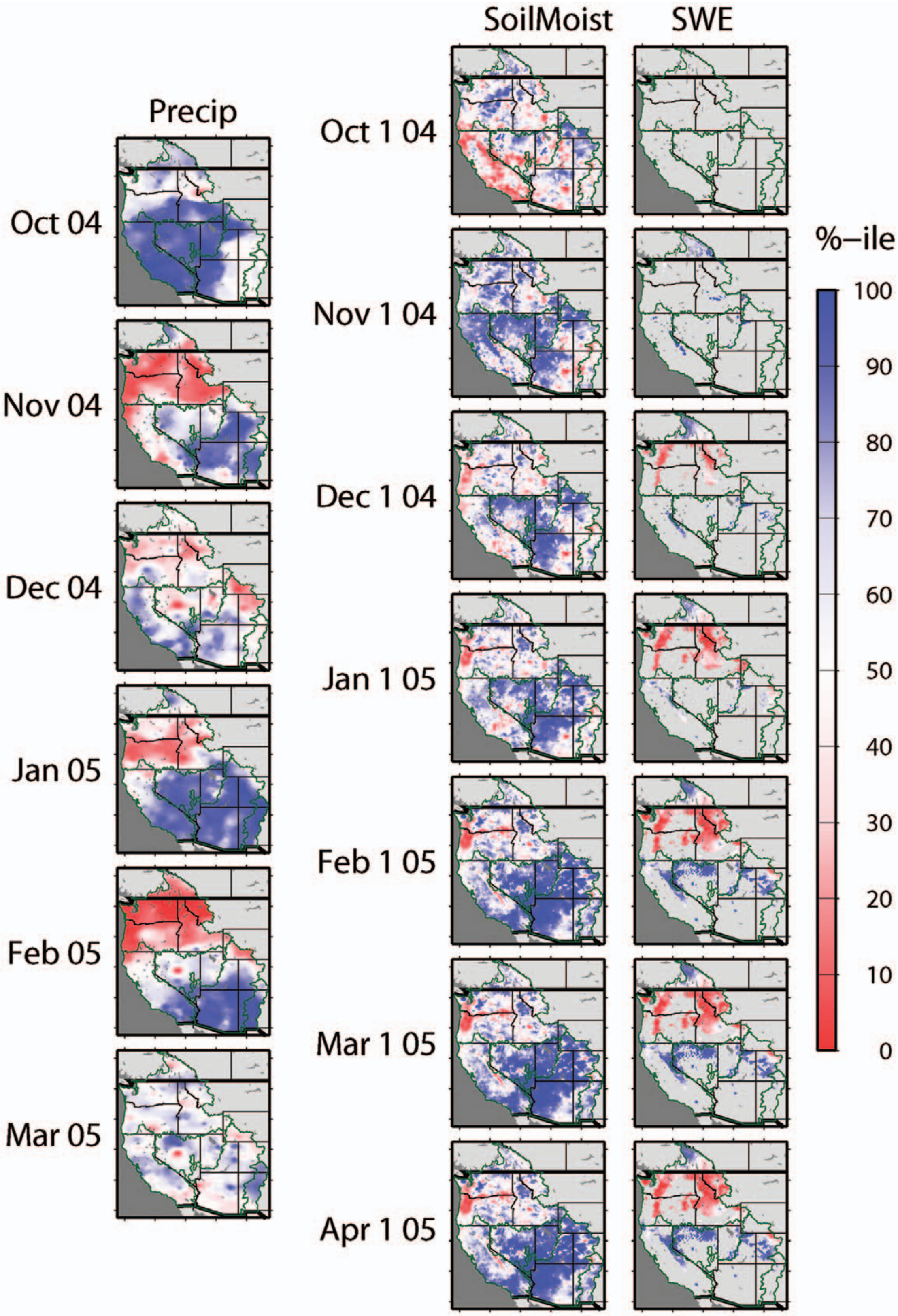


Fig. 5. **Evolution of the nowcast (forecast initial conditions) during the 2005 winter. Monthly precipitation percentiles reflect the dominant climate input to the system between the snapshots of soil moisture and snow-water equivalent (on day 1 of each month) that are used to initiate the hydrologic forecasts.**

building snowpack (Fig. 7e), they recharged soil moisture (Fig. 7d). As a result, the current conditions depicted for mid-April showed slightly higher runoff (Fig. 7f) and soil moisture than climatology, but the outlook for the critical summer period was for severe deficits in both as a result of very low snowpack, and the prospects for much below runoff later in the year. The striking insight from the analysis was that the snowpack was lower than at any point in the recent historical record (including the drought year of 1977).

This type of water balance diagnosis and prediction is possible in spatially lumped forecast models used in NWS operational activities (e.g., AHPS), and is now being offered on a limited, experimental basis by NWCC as well. However, the continuous spatial extent of the grid-based forecasting system is unique in that it also facilitates the analysis of conditions over any arbitrary part (and elevation range) of the domain, enabling conditions at particular forecast points to be related to alternative regional information.

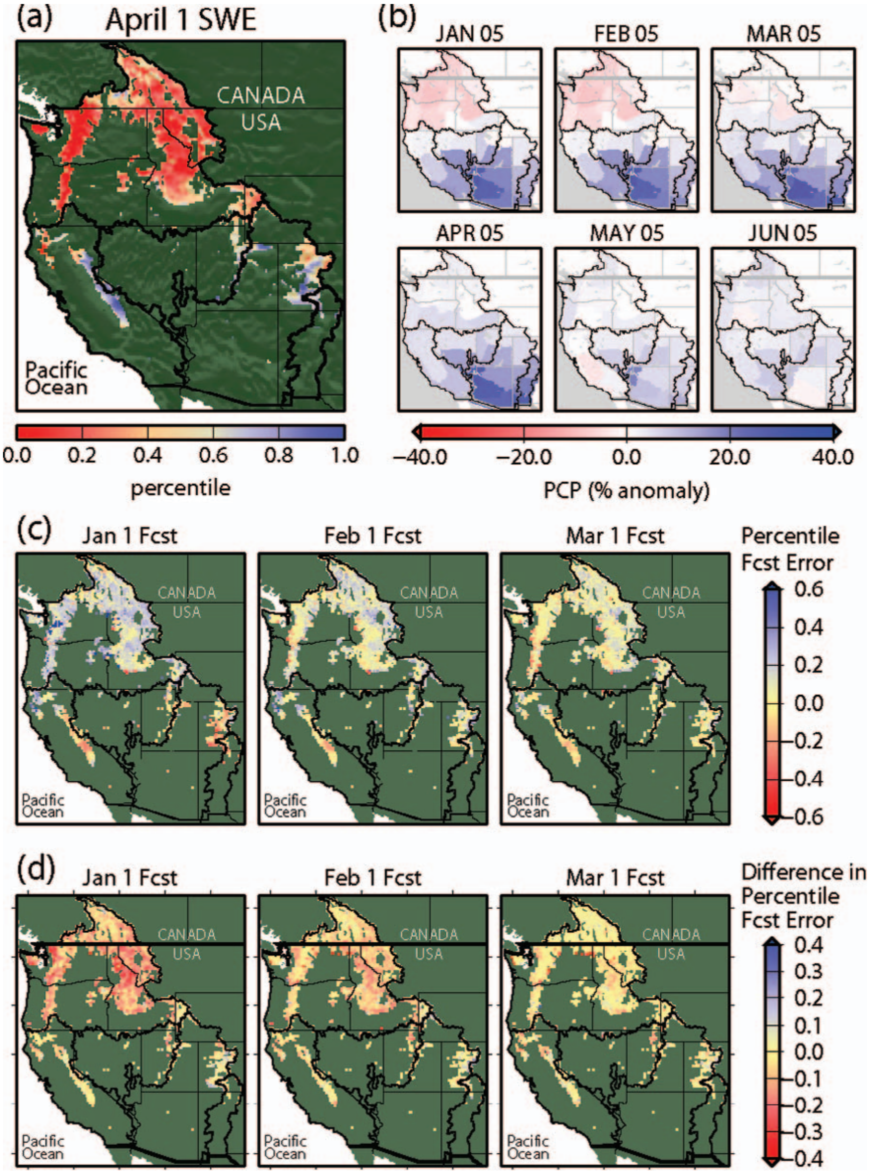


FIG. 6. (a) 1 Apr 2005 SWE percentile from real-time nowcast; (b) CPC precipitation forecast (16 Dec) used in 1 Jan 2005 hydrologic forecast; (c) percentile error in CPC-based mean forecast of 1 Apr 2005 SWE percentile for leads of 1–3 months; and (d) difference in CPC-based forecast percentile absolute error from ESP-based forecast percentile absolute error (negative for lower CPC errors).

Ensemble streamflow prediction. The West-wide system produces monthly time-step hydrographs for all climate forecast ensembles from which the ensemble distributions of streamflow relative to climatology can be interpreted. Figure 8 shows an example of such results for the Columbia River at The Dalles (a location of major importance for energy markets) at the end of the snow accumulation season in 2004. The late-January forecast only partially anticipated the summer flow deficits, with the ESP and CPC forecasts in this case outperforming the others. The five climate forecast ensembles differ more from the climatology than from each other, reflecting the sensitivity of future streamflow to initial conditions at this point in the season. In Fig. 9, a sequence of streamflow forecasts initialized in winter–spring 2005 for the same location, and for the Colorado River at Lees Ferry, Arizona, illustrates the influence of the snow accumulation season on the forecast as well as the divergence in outlooks between the PNW and the Southwest. The 1 January streamflow forecast ensembles (ESP- and CPC-based forecasts

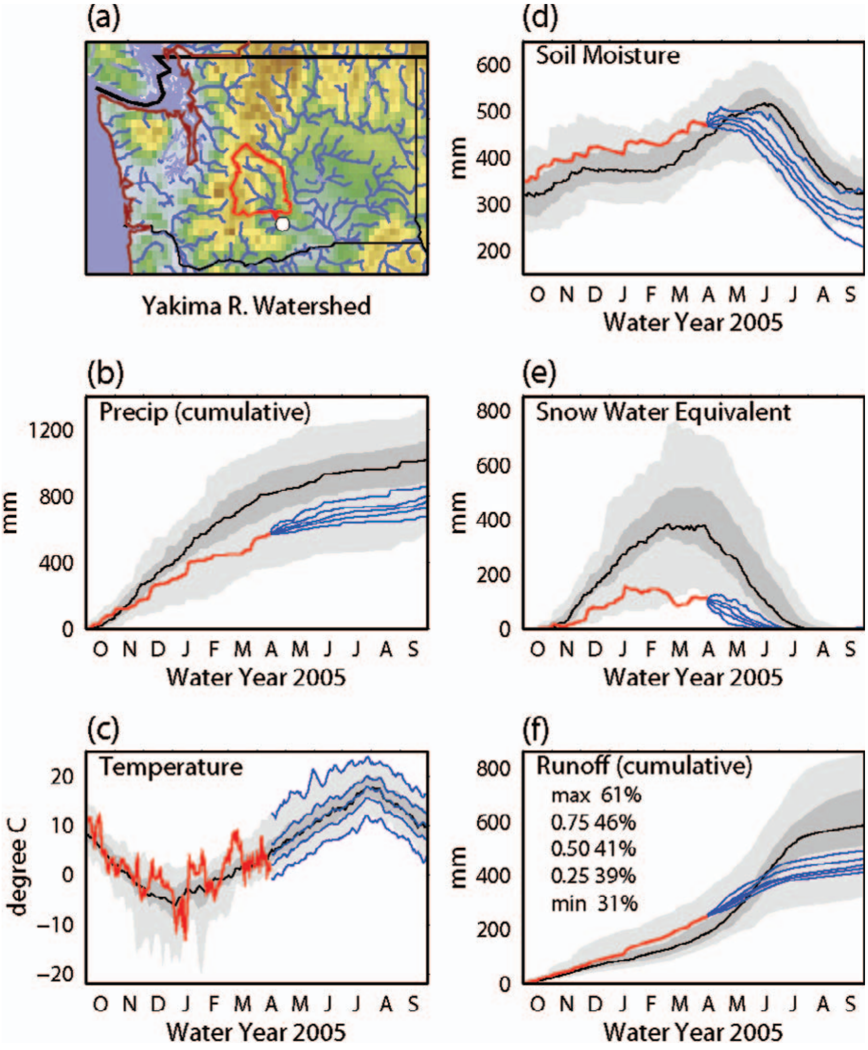
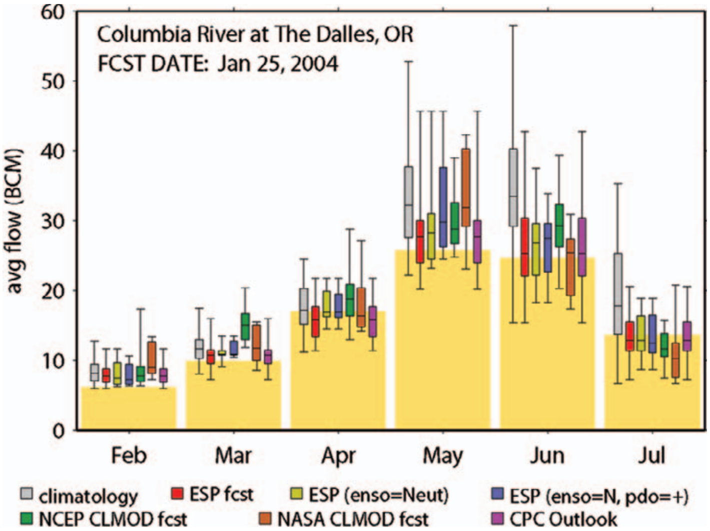


Fig. 7. (a) A basin-averaged hydrologic nowcast and forecast perspective for the Yakima River basin above Parker, WA, calculated on 15 Apr 2005. The current condition (red) and mid-April forecast range (blue) is shown against the 1971–2000 distribution (gray), for (b) cumulative precipitation, (c) temperature, (d) soil moisture, (e) snow-water equivalent, and (f) cumulative runoff, for which the calculated summer forecast anomalies at different percentiles are also shown (inset).

shown) were relatively close to climatology, with only a slight tendency (especially in the CPC forecast) toward the anomalies that later occurred. The 1 February forecasts, however, clearly responded to the anomalous snow conditions in both river basins; in the Colorado, the forecast distributions were already centered on the observations, while in the Columbia, the flows continued to drop in the 1 March forecasts. Little change occurred between March and April, because the bulk of the snow accumulation season had passed.

In addition to monthly forecast ensemble hydrographs, the West-wide system also produces forecasts of spring and summer streamflow averaged over a peak runoff period (April–July in the Southwest and California, and April–September in the PNW), which allows comparison with regression-based water supply forecasts produced by the NWCC and River Forecast Centers (RFCs). The West-wide system products, including streamflow forecasts, are objective in the sense that they are not adjusted subjectively after calculation by the forecasting methodology, as is the case for the official (NRCS and NWS) volume forecasts. While such adjustments may increase forecast accuracy by correcting for errors that may arise from, for example, data deficiencies and other operational irregularities, they complicate the objective evaluation and management of a forecast system. All of the streamflow products are for naturalized streamflow and do not take into account any human alteration of the water balance, such as by irrigation or reservoir system operation. Many of the forecast points in the Columbia, Colorado, and the Sacramento–San Joaquin River basins match the inflow locations for reservoir management models that we have developed for other purposes (see Hamlet and Lettenmaier 2000; Christensen et al. 2004; and Van Rheenen et al. 2004, for details). These management models can, in principle, be used to produce ensembles of reservoir storage during the forecast period, as illustrated by McGuire et al. (2005).

Interaction with agencies, water managers, and the public. Although the forecast system was developed as an experimental tool to facilitate evaluation of strategies for utilizing modern, experimental data sources and methods, an effort has been made to share ongoing research results with the general public (in settings such as an annual water outlook meeting sponsored by the UW Climate Impacts Group) and with agency groups. In WY2005, a "Memorandum of Understanding" was signed between the UW and NWCC, leading to a regular but informal interaction in which UW forecast system hydrologic analyses, nowcast, and/or forecast products (tailored where possible to NWCC forecast points) are provided to NWCC. In turn, NWCC has provided access to forecast-related data, and feedback on the design of the forecast products and on forecast performance. The authors are also exploring collaborations with RFCs in the western United States, mostly centering on the implementation of the grid-based Sacramento, California, soil moisture accounting model (Burnash et al. 1973; an element of the operational NWS River Forecast System) in parallel with the VIC model in several forecast locations. In addition, forecast system results targeted at local regions



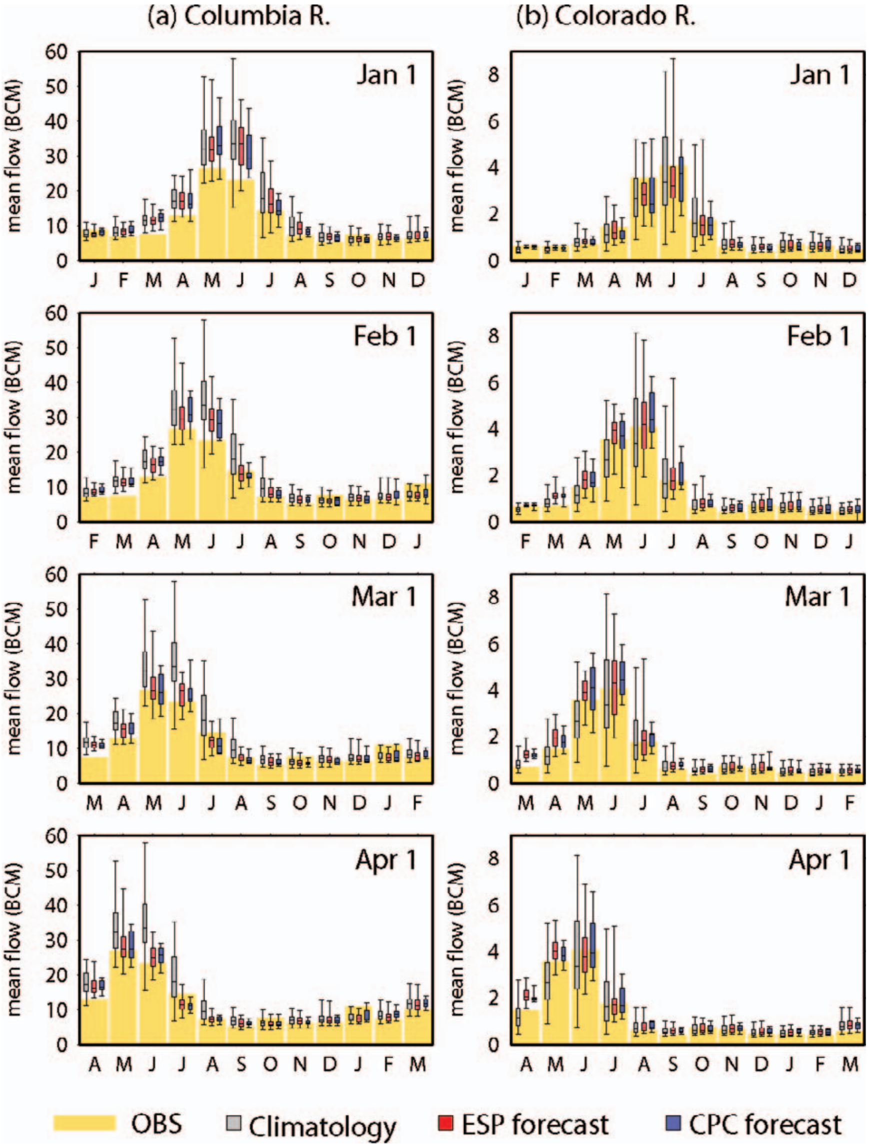


Fig. 8 (top right). Typical streamflow forecast issued each month, showing ensembles based on ESP, ESP with conditioning for ENSO and PDO, the NOAA NCEP and NASA (NSIPP) climate models, and the NCEP CPC outlooks.

Fig. 9 (bottom right). Monthly flow forecast ensembles for major forecasting locations in the U.S. Pacific Northwest and Southwest: (a) the Columbia River at The Dalles, OR, and (b) the Colorado River at Lees Ferry, AZ, respectively. The outlooks (ESP in red and CPC in blue) are shifted away from normal (gray) only slightly in the 1 January forecast, but diverge thereafter until they closely match the observed flows (low in the Southwest, high in the PNW) by 1 April.

in Washington State (Puget Sound and the Yakima River basin) have been presented at meetings attended by water management officials, and at a State of Washington water committee meeting, as the potential for drought in the state increased. Finally, forecast system results are discussed on an informal basis via e-mail and phone conversations with interested parties from private companies and the general public. These interactions have been valuable in providing direct feedback on product development and potential use, and similar outreach and development will become even more targeted in coming seasons as a result of slated research projects in the Klamath and Yakima River basins and in California. We have found such academic–operational connections to be critical to supporting continued development and diagnosis of the forecasting system "operation" over a sustained period that is (and we believe must be) considerably longer than the typical 3-yr life span of most research projects.

DISCUSSION AND FUTURE DIRECTIONS.

The West-wide system generates hydrologic nowcasts and forecasts on an operational schedule, and our experiences have suggested that a number of the streamflow forecasts and associated diagnostic products are useful in their current state. The broader goal of the West-wide system, however, is to serve as a test bed for investigation and evaluation of new methods and data sources that are intended for eventual adoption in operational centers. To this end, conducting the research in real time and with results made publicly available has yielded valuable insight into the constraints faced in operational settings, such as the relative scarcity of real-time quality-controlled observations, the computational requirements for timely forecast production, the challenges of automation, the varying reliability of forecast system inputs, and even the ramifications of airing a forecast "bust." Primary examples of research using the test bed to date are investigations of the use of experimental and official climate forecasts for hydrologic prediction and the assimilation of in situ and satellite-based snow products (McGuire et al. 2005; Andreadis and Lettenmaier 2006). The West-wide system also forms a key component of the HEPEX "Western Basins" test bed effort. Another current effort, motivated by drought monitoring and prediction applications, is the expansion of the forecast system domain eastward to the Mississippi River. In the future, research plans include the use of shorter lead (out to 15 day) weather forecasts to produce hydrologic ensembles, a change that will require more frequent (probably daily) nowcast updates, and allow us to address the merging of short and long lead climate forecasts as they are downscaled to produce hydrologic forecasts. We also intend to explore more advanced data assimilation methods for snow (e.g., Day 1990; Sun et al. 2004; Andreadis and Lettenmaier 2006) and other variables than we presently employ.

Finally, as noted earlier, we are moving toward a multimodel hydrologic forecast system. It will initially incorporate two hydrology models other than VIC—the NCEP land surface scheme Noah now used in the Eta Model and the NCEP Global Forecast System, and the grid-based version of the Sacramento model. There are many challenges in producing multimodel ensembles for hydrologic purposes, not the least of which are removal of bias and production of reliable probabilistic information (see Smith et al. 1992, for early ideas on this topic). Nonetheless, we hope that this change exemplifies activities that may help to draw the field away from what one operational forecaster terms the "one-method syndrome" (i.e., each forecasting entity considers primarily, if not exclusively, forecast products from internally developed models and tools). This practice differs notably from operational weather predictions, which are formulated from a suite of predictions and diagnostics from models run at different centers (both academic and governmental). The practice is also taking root in seasonal climate prediction, where the consolidation of both statistical and dynamical predictions into consensus products illustrates that physical models need not supplant statistical ones, rather, the objective is to combine the strengths of all approaches while circumventing their weaknesses. There are both good and bad reasons for the prevalence of the one-method syndrome in operational hydrologic forecasting, ranging from simple technical issues (e.g., software related) to institutional constraints to significant differences in the spatial scales that control climate in contrast to hydrologic processes. We believe that the reasons are less important than the resulting opportunity loss. Our intention is that hydrologic forecasting test beds such as the one described here will provide an avenue for advancing operational hydrologic prediction through a partnership between operational and research entities, and we encourage the involvement of both sectors in doing so.

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