Long-range climate forecasting and its use for water management in the Pacific Northwest region of North America

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ABSTRACT

Ongoing research by the Climate Impacts Group at the University of Washington focuses on the use of recent advances in climate research to improve streamflow forecasts at seasonal-to-interannual, decadal, and longer time scales. Seasonal-to-interannual climate forecasting capabilities have advanced significantly in the past several years, primarily because of improvements in the understanding of, and an ability to forecast, El Niño/Southern Oscillation (ENSO) at seasonal/interannual time scales, and because of better understanding of longer time scale climate phenomena like the Pacific Decadal Oscillation (PDO). These phenomena exert strong controls on climate variability along the Pacific Coast of North America.

The streamflow forecasting techniques we have developed for Pacific Northwest (PNW) rivers are based on climate forecasts that facilitate longer lead times (as much as a year) than the methods that are traditionally used for water management (maximum forecast lead times of a few months). At interannual time scales, the simplest of these techniques involves resampling meteorological data from previous years identified to be in similar climate categories as are forecast for the coming year. These data are then used to drive a hydrology model, which produces an ensemble of streamflow forecasts that are analogous to those from the well-known Extended Streamflow Prediction (ESP) method. This technique is a relatively simple, but effective, way of incorporating long-lead climate information into streamflow forecasts. It faithfully captures the history of observed climate variability. Its main limitation is that the sample size of observed events for some climate categories is small because of the length of the historic record. Furthermore, it is unable to capture important aspects of global change, which may interact with shorter term variations through changes in climate phenomena like ENSO and PDO. An alternative to the resampling method is to use nested regional climate models to produce the long-lead climate forecasts. Success using this approach has been hindered to some degree by the bias that is inherent in climate models, even when downscaled using regional nested modeling approaches. Adjustment or correction for this bias is central to the use of climate model output for hydrologic forecasting purposes. Approaches for dealing with climate model bias in the context of global and meso-scale are presently an area of active research. We illustrate an experimental application of the nested climate modeling approach for the Columbia River Basin, and compare it with the simpler resampling method.

At much longer time scales, changes in Columbia River flows that might be associated with global climate change are of considerable concern in the PNW, given recent Endangered Species Act listing of certain salmonid species, and the increase in water demand that is expected to follow increases in human population in the region. Many of the same general challenges associated with the spatial downscaling of climate forecasts are present in these long-range investigations. Additional uncertainties exist in the ability of climate models to predict the effects of changing greenhouse gas concentrations. These uncertainties tend to dominate the results, and lead us to use relatively simple
methods of downscaling seasonal temperature and precipitation to interpret the implications of alternative climate scenarios on PNW water resources.

Key words | climate forecasting, climate modeling, downscaling, ENSO, hydrologic modeling, PDO, streamflow forecasting, water resources management

INTRODUCTION AND BACKGROUND

Water is an intensely managed resource in the Pacific Northwest (PNW),1 and in most of the Western United States. Much of the region is endowed with what once must have seemed like a limitless supply of fresh water, most of which originates as snowmelt in Cascade and Rocky Mountain headwater streams. This water has fueled urban growth in the Seattle–Portland corridor west of the Cascade Mountains, where the primary demand is for municipal water supply, and in the interior of the Columbia River Basin, where millions of irrigated acres are sustained by the flow of the river, as is the generation of an annual average of over 18,000 MW of hydropower (Bonneville Power Administration 1991). The Columbia River (see Figure 1) also sustains navigation as far upstream as Lewiston, Idaho, as well as lake and river recreation, and provides flood control for the cities of Vancouver, WA, and Portland, OR, as well as numerous smaller cities along its path. This development has, however, come at the expense of once enormous runs of salmon, which have been in decline over much of the 20th century, with some runs now in danger of extinction.

The response and performance of a water resources system is a complex function of the timing and quantity of inflows to reservoirs and river reaches, the physical characteristics of the water resources system (e.g. storage), the timing and quantity of the demands placed upon the system, and the specific constraints imposed by the operating policies for the dams and reservoirs. The control and prediction of changing demand for water over a range of time scales is an important consideration in water management, but advance knowledge of supply is equally important, particularly in the context of interannual management decisions when demand is largely prescribed.

The potential for improving forecasts of future runoff has long been recognized as a means of more effectively managing water resources (see, e.g., Maass et al. 1962; Jackson 1977; Yeh et al. 1982; Johnson et al. 1991). Streamflow forecasts are used at various lead times in the operation of reservoirs in the PNW, both in Columbia River system and the myriad of smaller streams that drain the west slopes of the Cascade Mountains. For flood control, streamflow forecasts with lead times of several hours to several months (the latter largely for evacuation of flood storage ahead of time) are required, while for water supply planning longer lead time forecasts of cumulative flows over seasonal or annual time scales are needed. The time scale in this case is a function of the

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1The Pacific Northwest is defined here as the states of Washington, Oregon and Idaho in the United States and the greater Columbia River Basin, some of which is in Canada (Figure 1).

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Figure 1 | The PNW study area with the Columbia River Basin (shaded), major storage dams (triangles), and run-of-river dams (circles), and major rivers within the Columbia Basin (in white).
length of reservoir storage cycles. For long-term planning, estimates of streamflow variability at seasonal and annual time scales are needed to test the performance of various management alternatives. Under current practice, such estimates are extracted from long term streamflow observation records.

Much of the annual runoff in PNW rivers (generally over 70%) originates as snowmelt. In many cases, quite accurate forecasts of seasonal runoff in snowmelt-dominated rivers can be made at or near the time of maximum snow accumulation in early spring (see, e.g., Lettenmaier & Garen 1979). Seasonal runoff forecasts based on observations of mountain snowpack have been used in streamflow forecasts as far back as the 1930s and 1940s. The limitation of these methods is that, prior to the beginning of winter snow accumulation (e.g. about December), their accuracy is no better than climatology. The reservoir operating system for the Columbia River Basin has evolved over time to make use of forecasts of this kind to determine flood control and hydropower reservoir rule curves, which largely determine the releases of storage from reservoirs under the current operating policies (Bonneville Power Administration 1991). However, for the reasons indicated above, the forecasts are not used before January 1, prior to which reservoir operations are based on a critical period analysis using historic streamflow data. Recently advances in long-term climate prediction provide the potential for making streamflow forecasts with lead times of 12 months or longer. These forecasts exploit information about future climate that results from teleconnections related to thermal inertia of the oceans (see, e.g., Barnston et al. 1994) that strongly affect the climate of the west coast of North America, and the PNW in particular. The El Niño/Southern Oscillation (ENSO) is the best studied and understood of these phenomena, but other teleconnections have the potential to be incorporated in so-called ‘end-to-end’ forecast schemes that could have implications for water management.

Climate (as opposed to weather) information is probably most useful for streamflow forecasting at hydrologic time scales longer than a month. That is because it is still (and may well always be) impossible to predict individual storm events at time scales longer than a few days. On the other hand, climate, which is essentially the integral of the effects of multiple storm sequences, can be predicted at longer lead times and integration periods. A monthly time scale (e.g. for accumulated runoff) is often useful for water resources management, and particularly for the management of small water supply systems, the seasonal reservoir storage for which often has a characteristic response time of several months to a season. Two of the streamflow forecasting techniques that will be examined here use seasonal-to-interannual climate forecasts as the primary drivers for experimental seasonal streamflow forecasts that would be useful in this context.

At a much longer time scale, water resources planning studies usually use the historic record of streamflows, typically over periods of multiple decades, as a quantitative representation of the variability of supply to the water resources system. In a relatively stationary climate this practice is probably adequate for long-term planning (which must, in any case, deal with many uncertainties about future conditions). However in situations where climate is not stationary from decade to decade, using even long streamflow records as a proxy for future streamflow variability is problematic at best, and presents a serious obstacle to effective long-term planning. How best to conduct long range water planning in the face of potentially rapid future changes in climate is very much an open question at present. We describe an approach that involves streamflow scenarios, which describe the potential effects of global warming simulated by climate models on the variability of streamflow with lead times of 10–100 yr.

The Climate Impacts Group (CIG) at the University of Washington is an interdisciplinary research team affiliated with the Joint Institute for the Study of Atmosphere and Oceans (JISAO), the School of Marine Affairs (SMA), and several University departments. One of the primary tasks of the CIG is to conduct research related to the effects of climate variability and change on the PNW, and to evaluate the utility of a planned ‘climate service’ for the PNW. In particular, the CIG is charged with evaluating the potential linkages between climate information and impacts to PNW forests, fisheries, coastal areas, and regional hydrology/water resources. This paper reports on some key findings of the Hydrology and Water Resources sector of the CIG. In each of the three studies discussed here, practical methods of incorporating climate
information in hydrologic forecasts have been devised and tested. In developing these methods, a number of technical obstacles to the use of climate information are examined in detail, and some specific techniques for circumventing these problems are presented. By providing an overview of currently available climate information and methods for incorporating it in experimental streamflow forecasts for the PNW, we hope to facilitate extension of similar techniques in other contexts or regions.

PATTERNS OF PACIFIC NORTHWEST CLIMATE AND STREAMFLOW

Precipitation in the PNW is strongly winter-dominant, and mostly occurs in the period from October to March. Much of the precipitation during that period falls as snow at higher elevations. Especially east of the Cascade Mountains, where the lowlands are quite dry even in winter, streamflow is strongly dominated by spring snowmelt. Snow storage is a substantial component of the annual hydrologic cycle in most of the streams draining the interior of the Columbia River Basin, and many of the major west-flowing streams as well. In such river catchments, winter climate and the resulting storage of snow is a key determinant of spring and summer runoff.

Two global-scale climate phenomena are closely linked to winter climate, mountain snowpack, and summer streamflow in the PNW. These are the El Niño/Southern Oscillation (ENSO) (see, e.g., Battisti & Sarachik 1995) and the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997). ENSO is driven by conditions in the tropical Pacific Ocean (especially anomalies in sea surface temperature and the resulting location of convection in the tropics) and has a characteristic period of approximately seven years, with individual events typically lasting 1–2 yr. Warm-phase ENSO (El Niño) tends to produce warmer and dryer than average winters in the PNW, while cool-phase ENSO (La Niña) tends to produce cool and wet winters (see, e.g., Dettinger et al. 1998; Cayan et al. 1999). The PDO is a climate phenomenon that has a characteristic sea surface temperature (SST) signature similar to ENSO, although the effects are more pronounced in the North Pacific (Mantua et al. 1997). The PDO produces effects on PNW winter climate that are similar to ENSO, but at much longer time scales. The PDO has a characteristic frequency of approximately 50 yr, and an individual dominant phase of the PDO will typically persist for about 25 yr. The effects of PDO and ENSO are at least partially independent of each other in their effects to PNW climate, and the two phenomena can strongly reinforce each other when they are ‘in phase’. Cool PDO/La Niña winters, for example, are strongly associated with cooler temperatures, and above-average precipitation and snowpack. Warm PDO/El Niño winters, on the other hand, are associated with warmer temperatures and below-average precipitation and snowpack. In other combinations ENSO and PDO climate signals tend to negatively interfere and effects are less pronounced (see, e.g., Dettinger et al. 1998; Gershunov & Barnett 1998; McCabe & Dettinger 1999; Hamlet & Lettenmaier 1999a). Summer streamflows in snowmelt-dominated and transient basins (the latter having an elevation range such that the lower part of the basin is rainfall-dominated, while the upper elevations are snowmelt-dominated) follow these patterns due to the influence of winter climate on the cumulative spring snowpack (Hamlet & Lettenmaier 1999a).

Climate categories for streamflow forecasting

For the investigations reported here, inter-annual variation in the numerical PDO index (see Mantua et al. (1997) for details) is not considered because it cannot currently be forecast with appreciable skill. Instead, the observed phase of the PDO is defined as a persistent, bimodal, epochal function. It is defined to be in cold-phase from 1900–1924 and from 1947–1976, and in warm-phase from 1925–1946 and from 1977 to about 19962 (Mantua et al. 1997). ENSO phase, however, varies from year to year and is defined retrospectively by the NINO3.4 index of Trenberth (1997) averaged from December–February. A water year (October–September) associated with a

2There is considerable debate at present as to whether the climate regime associated with the PDO shifted from warm-phase to cold-phase in about 1996 or 1997. We believe there is evidence, based on the observed regional climate and the streamflow record of the Columbia River, that such a transition probably occurred before 1997, and for forecast purposes we assume cold-phase for water years 1998 to present.
winter index value (Dec–Feb mean) more than 0.5 standard deviations above the long-term mean for the period 1900–1996 is defined as warm-phase (El Niño). A year associated with a winter index value (Dec–Feb mean) more than 0.5 standard deviations below the long-term mean value is defined as cold-phase (La Niña). All other years are defined as ENSO neutral. Table 1 shows the climate categories for each water year from 1900 through

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<tr>
<th>Climate Category</th>
<th>Warm PDO Warm ENSO</th>
<th>Warm PDO Neut. ENSO</th>
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1995, the period on which subsequent analyses are based.

Because of the strong linkage between PNW winter climate and spring–summer streamflows via snowpack, PNW streamflows are strongly related to PDO and ENSO. Figure 2 shows streamflows simulated using the Variable Infiltration Capacity (VIC) hydrology model (see the following section on the VIC model for references) for the years in each of the Table 1 climate categories from 1948–1997. Figure 3 shows naturalized spring–summer average streamflow in the Columbia River segregated according to the Table 1 PDO epochs. These effects on spring–summer streamflow are quite consistent for the PNW. Figure 4 shows composite monthly average streamflow for the Columbia River at The Dalles, OR, inflows to Chester Morse Lake (which provides about 70% of Seattle's water supply), and Snake River flows at Milner (see Figure 1 for locations). Note that, despite considerably different basin sizes, hydrologic characteristics (snowmelt-dominated runoff for the Columbia and Snake River locations, and transient snow for the Chester Morse inflows) and a wide geographic range within the region,
there is a consistent regional signal for winter climate and summer streamflow associated with PDO and ENSO. Note in particular the pronounced effects in all cases when PDO and ENSO are in phase.

**IMPROVEMENTS IN CLIMATE FORECASTING**

Dramatic improvements in the ability to monitor, forecast, and interpret ENSO events have resulted from a number of recent developments within the climate prediction community. Among the recent advances are...
the implementation of NOAA's TOGA-TAO program (see, e.g., Trenberth et al. 1998; McPhaden et al. 1998), general improvements in ocean/atmosphere simulation models that have improved simulations of the evolution of ENSO, and better interpretation of the resulting climate forecasts at the regional scale (see, e.g., Mason et al. 1996; Barnston et al. 1994). One result of the TOGA-TAO program has been the installation of an array of observational buoys in the tropical Pacific. This has been an important addition to the suite of tools used to forecast ENSO, because it allows numerical ocean/atmosphere models to be initialized relatively accurately in real time, enhancing the skill of the resulting sea surface temperature (SST) forecasts. Validation of the forecast improvements resulting from implementation of the combined TAO observing system and state-of-the-art ocean/atmosphere simulation models is complicated by the short post-TAO period of record. However, for at least the past three years it has been possible to correctly forecast the ENSO state (warm, neutral, cool) for the coming winter by June 1 preceding the water year. More retrospective ENSO forecast studies are needed to assess the skill of these state-of-the-art forecasting methods over a longer time period. However, the excellent results in the past several years and earlier studies evaluating the general improvements in ENSO prediction skill (see, e.g., Latif et al. 1994) suggest that lead times for categorical winter ENSO forecasts (warm, neutral, cool) on the order of six months are now feasible. Because of the linkages between winter climate and summer

Figure 4 | (b) Observed variability of naturalized streamflow associated with PDO and ENSO for three PNW river basins: (b) inflow to Chester Morse Lake from the Cedar and Rex Rivers.
streamflow, a June 1 ENSO forecast yields a lead time of approximately 12 months from forecast to peak summer flows in PNW snowmelt-dominated basins.

Although the PDO is very important in the context of forecasting PNW streamflow (see Figures 3 and 4), the physical dynamics of the PDO are poorly understood in comparison with ENSO, and PDO cannot currently be predicted on an interannual basis (Mantua & Hare 2000). However, because the PDO tends to persist for several decades, it can still be used effectively in climate forecasts. The primary challenge is the identification of transitions in real time. Methods for identifying PDO regime shifts based on thresholds of summer streamflow (Figure 3) are reported in Hamlet & Lettenmaier (1999a). While empirical prediction methods are difficult to validate due to the time scales involved (there have only been three generally acknowledged PDO regime shifts in the historic record), these methods show some apparent skill over the observational record (about 100 yr). Presumably empirical prediction techniques of this type will become unnecessary as the physics of the PDO become better understood.

In addition, there are currently proposals to instrument the North Pacific in a manner similar to the TAO array in the tropics. Such an observing system could be used to identify, in real time, the interannual signature of the PDO, which frequently persists on time scales of several months. The effects on PNW streamflow associated with the interannual PDO index are very similar to those shown in Figure 4 for the PDO epochs, which suggests that such a forecasting scheme could work well in

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**Figure 4** (c) Observed variability of naturalized streamflow associated with PDO and ENSO for three PNW river basins: (c) Snake River at Milner.
practice. Perhaps more importantly, instrumenting the North Pacific would greatly improve the availability of data that could eventually lead to numerical forecasts of the PDO using ocean/atmosphere models.

STREAMFLOW FORECASTING MODELS AND METHODS

Macro-scale hydrologic model

The Variable Infiltration Capacity (VIC) hydrology model (Liang et al. 1994) has been implemented over the Columbia Basin at both a coarse spatial resolution of one degree (Nijssen et al. 1997), and more recently at 1/4 degree resolution (Mattheussen et al. 2000) and 1/8 degree resolution (Hamlet & Lettenmaier 1999b). The details of the model, as well as previous implementations for the Columbia at the coarse resolution (Nijssen et al. 1997), and 1/4 and 1/8 degree resolution (Mattheussen et al. 2000) have been described in these papers and these details are omitted here. The results discussed here are based on both the coarse one degree, and the most recent high resolution implementation of the VIC model. The VIC model has been widely used for simulation of the water and energy balance of various continental-scale watersheds in North America (see, e.g., Abdulla et al. 1996), Europe (see, e.g., Lohmann et al. 1998), and globally (Nijssen et al. 2000a,b). Figure 5 shows schematically the physical processes simulated in the VIC model, and Figure 6 shows the modeled channel network for the
Columbia River Basin as represented at 1/8 degree spatial resolution. The driving data for the model are derived from interpolated station data for the period 1948–1997, rescaled to long-term monthly means produced by a statistical/topographic precipitation and temperature model (Daly et al. 1984).

**Seasonal/interannual streamflow forecasts**

Two basic methods for producing seasonal/interannual streamflow forecasts based on long-lead climate forecasts of the type mentioned in the previous section will be discussed here. The first, and most general, is an off-line linking of ensemble forecasts generated by a fully coupled land/ocean/atmosphere climate model to force a hydrology model, which in turn produces streamflow forecasts that are routed through a water resources management model (see Figure 7). This approach has the advantage that it can produce an arbitrary number of ensemble members that is limited only by computer resources, hence in principal the precision (if not the accuracy) of the results can be controlled. Furthermore, it is not limited by the variability or spatial coverage of the surface observations, and it is, in theory, fully responsive to observable initial conditions (e.g. sea surface temperatures, sea ice, snow cover extent, and soil moisture). In practice, however, such a fully linked forecast system is difficult to implement. Climate models, and particularly high resolution climate models appropriate to the regional scale at which water resources management decisions are made, are computationally intensive. Furthermore, and perhaps more importantly, model bias and/or lack of ability to reproduce observed regional climate patterns with sufficient accuracy for meaningful hydrologic simulations have plagued attempts to implement these types of forecast systems simply by coupling existing climate and hydrologic models (see, e.g., Doherty & Mearns 1999). Finally, although the latest generation of climate models simulate ocean/atmosphere interactions that at least resemble actual ENSO and PDO cycles (see, e.g., Latif and Barnett 1994; Röchner et al. 1996; Walland et al. 2000) the actual regional climate signals associated with ENSO and PDO variability are not necessarily reproduced by climate models with sufficient accuracy for streamflow prediction. Experiments to validate and improve ensemble climate forecasts for particular regions have been a major focus of hydroclimatic research in recent years. Regional experiments for the PNW conducted by Leung et al. (1999), have shown promise, and are discussed in some detail later in this paper.

A second approach to seasonal/interannual forecasts that utilizes climate forecast information is based on resampling from the historical climate record. The approach is outlined in Figure 8. Hydrologic models are used in the same way as in the ensemble climate forecast approach (Figure 7), but the climate data used to drive the hydrologic model are resampled from the historic record, rather than being generated by a climate model. Specific periods in the historic record are associated with recurrent climate patterns, and this information is used to select or ‘resample’ data from the historic record, and to produce real-time climate forecasts. The advantages of this methodology are largely practical in nature. Because
observed driving data used for resampling contain realistic representations of observed climate variability for the region of interest, the simulations tend to be quite realistic, and cumulative bias is limited because only the relatively small bias inherent in the hydrology model predictions is present. Computer resources required for this forecasting method are quite modest in comparison with the more sophisticated ensemble climate forecast approach described in the previous section. Problems with this method are that the ensemble forecasts are constrained in their range and statistical properties by the historical record and thus conditions unlike those experienced in the historic record (e.g. unusual natural variability or climate change) are not represented in the forecasts.

Climate change scenarios
Streamflow scenarios associated with climate change predictions use essentially the same modeling structure depicted in Figure 7, except that the climate model simulations are derived from transient GCM simulations that reflect changing concentrations of CO₂ and other atmospheric greenhouse gases. A key issue in developing streamflow scenarios corresponding to alternative climate
change scenarios is the scale mismatch between the GCMs that produce the climate scenarios, and the hydrological models used for streamflow simulation. For instance, most GCMs used for long-term climate simulations (e.g. for periods of at least a century) are implemented at spatial resolutions of around 5 degrees latitude by longitude, with the highest resolution models operating at about half that scale, e.g. around 2.5 degrees by 2.5 degrees. In contrast, the VIC hydrological model used in our Columbia River work is implemented at 1/8 degree resolution, which represents a scale mismatch of over three orders of magnitude in area. Particularly in mountainous regions like the PNW, these differences in scale can be quite significant in terms of the spatial distribution of temperature and precipitation and the resulting spatial variability of water cycles.

Various methods have been used to downscale GCM results to hydrologically relevant spatial scales. The most theoretically appealing method uses a nested regional climate model, which is forced at the boundary by the GCM, and resolves within its domain spatial scales relevant to the hydrological model. The problem with this approach is that it is extremely computationally intensive, and the results inherit biases not only from the global GCM, but also from the regional climate model. A cursory review of the GCM model results (without downscaling) for current climate (Doherty & Mearns 1999) shows that precipitation and temperature, which are the primary hydrologic drivers, are not accurately reproduced for the current climate by most GCMs, even at very large continental scales for seasonal means. The end result is invariably that the climate model output, whether or not it is downscaled, has to be adjusted so that a 'base case' scenario, meant to represent the current climate, does in fact have the same statistical characteristics as the historical climate observations, and results in reasonable hydrologic simulations, relative to which alternative climate scenarios can be interpreted. We have tested various downscaling methods ranging from very simple interpolations (e.g. Lettenmaier & Gan 1990) to rather complicated methods that are based on stochastic representation of the evolution of daily weather patterns, and their relationship to daily precipitation and temperature (Hughes et al. 1993). We conclude, as the result of a number of studies using both simple and complex downscaling methods, that the simple methods are preferred at present. Such methods impose the seasonal cycle of GCM-predicted average changes in temperature and precipitation on observations of the same variables. This approach results in hydrologic predictions that are most easily interpreted, and that are most consistent with the useful information present in the GCM runs. As GCMs improve, however, these simple methods may become less appropriate, and particularly in the context of assessing changing interannual climate variability, downscaling techniques based solely on adjustments to long-term seasonal means are probably insufficiently detailed to address the problem.

**EXAMPLE APPLICATIONS**

**Ensemble climate forecasting experiments**

Leung et al. (1999) used a meso-scale regional climate model (RCM) nested within the National Center for Environmental Prediction’s (NCEP) global medium range forecasting model (MRF) to produce two sets of 24-member ensemble climate simulations for the month of January. The ensemble sets represented normal and
anomalously warm tropical Pacific sea surface temperatures typical of El Niño conditions. These January ensembles were subsequently inserted into a repeating 1960 water year temperature and precipitation time series (observed data) and used to drive the one-degree VIC hydrologic model for the Columbia River Basin. The study showed that the climate simulations were not sufficiently accurate in their raw state to produce usable streamflow forecasts. However, after application of a simple bias correction scheme which preserved the spatial signals of the climate model, the simulated forecasts were able to reproduce the effects of January climate variability on the following spring and summer’s streamflows reasonably well (Figure 9). Furthermore, the simulated forecasts were able to capture mean warm SST streamflow signals at The Dalles (warm SST ensemble mean minus normal SST ensemble mean) quite realistically after bias correction (Figure 10). These results are encouraging in two respects. First, they demonstrate that climate models can successfully simulate ENSO teleconnections that produce the warm ENSO climate signal in the PNW from first principles. Second, the bias-corrected streamflow simulations based on the climate simulations were consistent with historical streamflow observations, and they accurately represented the streamflow anomalies associated with warm ENSO.

An ongoing extension of the Leung et al. (1999) study has evaluated six month simulations (October–March) for normal SST using the same simulation and bias correction...
tools. The results in this case were not as good as those produced by the January experiments. While the hydrologic simulations (after bias correcting the climate simulations) were within reasonable bounds, their statistical characteristics were clearly different from those of the historical October–March streamflow sequences. These problems are probably attributable both to the relatively simple bias correction scheme used in the earlier study, and to problems with the spatial distribution and seasonality of precipitation signals produced by the climate models. Resolution of these problems will require an identification and characterization of the different kinds of bias to which the hydrologic simulations are sensitive, and refinement of the climate models and bias correction schemes to remove these undesirable aspects of the climate simulations. Despite the relatively early stage of development, the experiments do suggest that there is promise of eventually bringing nested ensemble climate forecast methods into an operational context to guide water management decision processes.

It is also worth noting that the distinction between large scale and meso-scale climate models is largely a practical one associated with available computer resources, and global climate models may ultimately achieve higher spatial resolution than that of current meso-scale models. Global models with variable spectral grid spacing are also being developed, and these may provide a means of increasing the spatial resolution in areas where it is needed without simulating the entire globe at this resolution.

**Resampling forecast experiments**

Hamlet & Lettenmaier (1999a) describe a ‘shortcut’ approach to producing ensemble climate, and associated streamflow, forecasts. The method is based on resampling, from the historic record, precipitation and temperature sequences associated with the climate category (PDO/ENSO) predicted for the forecast period. Forecasts for the Columbia Basin for water years 1998–2000 were produced in real time on about June 1 preceding the water year (i.e. with about 12 month lead time for peak streamflows in June). Figure 11 shows forecasts of naturalized flow (flows that would have occurred in the absence of reservoirs and diversions) at The Dalles on the Columbia River that were produced for water year 1999. Figure 10 shows the approximate upper and lower bounds for expected streamflows, estimated from the envelope of the highest and lowest simulated flows for each month simulated by the hydrologic model for the period 1948–1988 (heavy black dashed lines). Also shown are forecast ensembles (gray lines) produced by the VIC model initialized with soil moisture taken from a surrogate for the preceding water year (1952 in this case), and the observed naturalized streamflow (dashed line). 1998–2000 were all assumed to be cold-phase PDO for reasons discussed by Hamlet & Lettenmaier (1999a). 1998 was forecast as an El Niño year, and 1999 and 2000 were forecast as La Niña. Hamlet & Lettenmaier (1999a) also retrospectively forecast 10 water years not shown here, and discussed some potential uses of long-lead forecasts of this type for water resources management in the Columbia River Basin.

**Climate change experiments**

Hamlet & Lettenmaier (1999b) describe an assessment of the possible impact of climate change in the Columbia River Basin, using methods similar to those described in the preceding section for ensemble climate prediction. In the climate change experiments, two representative GCM scenarios from the Hadley Centre (HC) and Max Planck Institute (MPI) were used to estimate monthly average, regional-scale changes to precipitation and temperature.
over the Columbia River Basin for future decades centered on 2025, 2045, and 2095. These simulated changes were then applied to observed daily-time-step driving data for 1961–1997, which in turn were used to drive the 1/8 degree resolution VIC model (Mattheusen et al. 2000). The experiments assume that the natural variability of temperature and precipitation over the PNW within each month are similar to those occurring from 1961–1997, but that the long-term monthly means are different. Thus the mean monthly values and the resulting seasonality of the driving data are altered in a consistent manner for the entire time series in each case. Figure 12 shows the changes in average March 1 snow extent simulated by the VIC model for the different GCMs and future decades. Figure 13 shows the corresponding changes in streamflow at The Dalles, OR (see Figure 1 for location) for the same simulations. Figure 14 shows the changes in reliability (probability of successfully meeting the objective) of several important water resources objectives in the Columbia Basin as simulated by the ColSim reservoir model (see Hamlet & Lettenmaier (1999b) for details) for the base case and climate scenarios.

Despite the fact that these results are quite uncertain in a quantitative sense (due primarily to the uncertainties in the large scale climate simulations of precipitation), they are useful for interpreting the implications of the climate scenarios for water resources. By evaluating the hydrologic and water resources impacts over a range of climate scenarios, a picture of the hydrologic and water resources sensitivities begins to emerge. For instance, although there is considerably variability among the climate scenarios, they all predict a warmer climate, which would have the effect of reducing winter snow cover extent, and moving the period of peak runoff earlier in the year. Winter flows would in general be higher, and summer flows lower. This in turn has profound implications for the operation of the water resources system for its multiple objectives, and particularly for those

![Figure 11](https://iwaponline.com/jh/article-pdf/2/3/163/392083/163.pdf)
objectives that are most sensitive to declines in summer streamflows (e.g. irrigation, urban water supply, fish flows). There is less similarity among the climate scenarios in their predicted precipitation changes, but Mote et al. (1999) note that for the PNW, most of the models predict somewhat increased precipitation. Annual water cycles are not strongly affected by summer precipitation in the PNW, but increased winter precipitation could have two important implications. First, it would tend to increase annual streamflows, and second, it would compound a late winter flood problem that would already be exacerbated by the shift in the runoff peak earlier in the year due to warming. This effect would be most severe for lower elevation catchments in the Columbia interior, which would become transient, rather than snowmelt-dominant. A slightly different situation would occur for west slope streams, where early winter floods, often enhanced by rain-on-snow, would likely be increased.

CONCLUSIONS

Considerable progress has been made in the past several years in producing accurate long range ENSO forecasts, in understanding the natural climate variability in the PNW at longer time scales, and in developing appropriate streamflow forecasting methods that capitalize on this information. More detailed retrospective forecasting studies are required to assess fully the overall skill of state-of-the-art ENSO forecasting techniques. However, it appears from recent forecasts and earlier retrospective assessments of ENSO forecasting techniques that the ability to forecast winter ENSO in one of three broad categories (warm, neutral, cool) is generally feasible with lead times of about six months. These interannual ENSO forecasts provide forecast lead times on the order of 12 months for seasonal/interannual forecasts of summer streamflow in snowmelt-dominated catchments in the PNW.

In the long term, seasonal-to-interannual forecasting methods that make use of climate models as the primary drivers for hydrologic simulation tools are preferred for creating the basis for effective and useful hydrologic forecasts. One important reason for this preference is the issue of potentially rapid changes in future climate, which cannot be encompassed by other methods. Such techniques can rely either on nested meso-scale models or statistical downscaling of large scale climate simulations in the near future. As computer resources improve, however, the use of nested model structures may be superseded by high-resolution global models, perhaps with variable grid spacing to provide higher spatial resolution in regions of particular interest. In the short term, however, practical and conceptual problems with these more sophisticated forecasting methods may make semi-empirical methods such as the retrospective resampling method, which makes use of a 50 yr observed meteorological driving data set and a hydrology model, more effective for interannual streamflow forecasting.

Investigations of the long-range hydrologic implications of climate change are currently most strongly influenced by uncertainties in GCM precipitation simulations. For this reason, issues regarding downscaling may be regarded as secondary for the time being. In this context, simple downscaling methods are adequate to allow interpretation of the hydrologic implications of the

Figure 12 | Average March 1 Columbia basin snow extent associated with the Max Planck Institute (MPI) and Hadley Centre (HC) climate change scenarios.
primary information from the global simulations. As GCMs continue to develop and more consistent and detailed simulations begin to emerge, the issues surrounding appropriate translation from the global to regional scale may become more significant. To answer questions regarding potential changes in interannual and decadal scale variability associated with climate change, for example, the simple downscaling techniques described here will eventually become inadequate.

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