Simulations of the ENSO Hydroclimate Signals in the Pacific Northwest Columbia River Basin

L. Ruby Leung,* Alan F. Hamlet,† Dennis P. Lettenmaier,‡ and Arun Kumar*

ABSTRACT

Natural fluctuations in the atmosphere–ocean system related to the El Niño–Southern Oscillation (ENSO) induce climate variability over many parts of the world that is potentially predictable with lead times from seasons to decades. This study examines the potential of using a model nesting approach to provide seasonal climate and streamflow forecasts suitable for water resources management. Two ensembles of perpetual January simulations were performed with a regional climate model driven by a general circulation model (GCM), using observed climatological sea surface temperature (SST) and the mean SST of the warm ENSO years between 1950 and 1994. The climate simulations were then used to drive a macroscale hydrology model to simulate streamflow. The differences between the two ensembles of simulations are defined as the warm ENSO signals.

The simulated hydroclimate signals were compared with observations. The analyses focus on the Columbia River basin in the Pacific Northwest. Results show that the global and regional models simulated a warming over the Pacific Northwest that is quite close to the observations. The models also correctly captured the strong wet signal over California and the weak dry signal over the Pacific Northwest during warm ENSO years. The regional climate model consistently performed better than the GCM in simulating the spatial distribution of regional climate and climate signals. When the climate simulations were used to drive a macroscale hydrology model at the Columbia River basin, the simulated streamflow signal resembles that derived from hydrological simulations driven by observed climate. The streamflow simulations were considerably improved when a simple bias correction scheme was applied to the climate simulations. The coupled regional climate and macroscale hydrologic simulations demonstrate the prospect for generating and utilizing seasonal climate forecasts for managing reservoirs.

1. Introduction

Natural fluctuations in the ocean–atmosphere system related to the El Niño–Southern Oscillation (ENSO) induce climate variability over many parts of the world. While evidence for predictability in the Tropics has long been demonstrated (e.g., WCRP 1992), quantitative assessment of the prediction skill that can be achieved over the extratropics has only been recently reported (e.g., Brankovic et al. 1994; Kumar and Hoerling 1995). These studies suggest that although atmospheric variability in the extratropics is often dominated by chaotic dynamics associated with atmospheric flows, there is certain skill in predicting seasonal variability. This skill depends on the season and strength of the ENSO events, and varies geographically.

Advances in the understanding and technique for long-range forecasting has led the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center to issue routine seasonal climate forecasts for the United States with lead times of up to a year. These forecasts are made primarily using linear empirical methods (Huang et al. 1996; Barnston 1994) that relate spatial anomalies of sea surface temperature (SST), Northern Hemisphere large-scale circulation, and the U.S. surface climate, and are expressed as probabilities of air temperature and precipitation falling within certain preselected categories.
Recently, Livezey et al. (1996) analyzed the prediction skill of climate forecasts in the Pacific–North America region made by dynamical models (Ji et al. 1994) using a two-tiered approach (Bengtsson et al. 1993; Graham and Barnett 1995). The dynamical method uses a coupled ocean–atmosphere general circulation model to forecast the global SST, which is then used to drive an atmospheric general circulation model (AGCM) to provide an ensemble of seasonal atmospheric forecasts. Their study indicates that the prediction skill associated with these dynamical forecasts is comparable to, if not higher than, the corresponding official forecasts produced mainly by statistical models. Over specific regions, however, it is not clear if GCMs can provide better seasonal climate forecasts than statistical methods. Dynamical forecasting methods are less prone to problems associated with the availability of historical data that is needed by statistical forecasting methods to identify ENSO signals for different SST conditions, and they can incorporate possible nonlinearity between SSTs and the atmospheric responses (e.g., Hoerling et al. 1997). Therefore, dynamical forecasting techniques should be further explored to determine their full potential for providing useful seasonal climate forecasts.

Despite the efforts of ongoing research to improve AGCMs for refining the skill of climate predictions, limitations in the physical representations and the coarse spatial resolution used by AGCMs still present a serious problem when the models are put to practical use. One central issue relates to the specificity of the dynamical seasonal climate forecasts, that is, are they provided with enough accuracy and spatial resolution to be of value in managing natural resources? For example, can climate forecasts be applied directly to drive operational hydrology models for water resources planning?

This paper examines the use of dynamical downscaling with a regional modeling system consisting of a regional climate model driven by an AGCM and a macroscale hydrology model to determine the degree to which the ENSO hydroclimate signals can be simulated. Numerous studies using regional climate models (e.g., Giorgi et al. 1994; Leung and Ghan 1999) showed that by using higher spatial resolution to represent local effects of surface topography, vegetation, land–sea contrast, and mesoscale circulation, regional climate models produce simulations of precipitation and surface temperature that resemble the observations more than the driving large-scale simulations. However, several recent studies discussed some important issues on the use of dynamical downscaling. For example, Leung et al. (1999) performed an intercomparison of regional climate models and showed that regional simulations are very sensitive to the parameterizations of clouds and cloud-radiation feedback. Warner et al. (1997) discussed several measures that can provide good guidance on how model domain and lateral boundary conditions could be determined to avoid erroneous growth of error in using mesoscale models for weather forecasting. Seth and Giorgi (1998) also discussed the sensitivity of regional climate simulations to domain size and suggested that larger domains are important for studies of climate sensitivity to internal forcings. This study followed the methodology (domain size, selection of physical parameterizations, method of applying lateral boundary conditions, etc.) previously adopted by Leung and Ghan (1995, 1998, 1999) for successful applications of a regional climate model over the Pacific Northwest. Furthermore, Leung et al. (1996) and Miller and Kim (1997) have examined the use of dynamical downscaling using regional climate and hydrology models over the Pacific Northwest and California and found that these models are useful for studying climate impacts on water resources.

Our numerical experiments and analyses will focus on the Pacific Northwest and, in particular, the Columbia River basin. The Columbia River basin drains parts of British Columbia and seven different states in the U.S. Pacific Northwest, covering a total area of 567 000 km². Winter snow accumulation and spring snowmelt dominate runoff production within the basin. The river system is highly managed for electric power generation, flood control, irrigation, flow enhancement, fishery and wildlife protection, navigation, and recreation. There are more than 250 reservoirs and 100 hydroelectric projects in the river system. Observational data analyses (e.g., Livezey et al. 1997; Cayan 1994; Kahya and Dracup 1993) have already shown that there are statistically significant and coherent hydroclimate signals over the Pacific Northwest associated with the ENSO. Under warm SST conditions in the tropical Pacific, the Pacific Northwest winter is warmer and dryer than the climatological mean condition, and the trend is generally reversed for the cold SST conditions. As a result, the mean annual streamflow and the timing of streamflow in the Columbia River basin are affected by the ENSO events. The use of seasonal climate forecasts can potentially benefit the management of water resources in the river system, which is already under increasing stress due
to the growing demand for water and changing water use priorities in the region.

Historical records show that interannual variability is very strong over the Columbia River basin. Even among warm ENSO years, one event can differ quite significantly from another. In order to obtain a larger signal-to-noise ratio, we have opted to use a larger ensemble but limit the study to the ENSO climate effects of January alone rather than to perform a few seasonal simulations. Therefore, as a first step to determine the potential of dynamical seasonal climate forecasts for reservoir management, we performed two 24-member ensembles of perpetual January simulations with an AGCM driven by climatological mean SST and mean SST for the warm ENSO years between 1950 and 1994. The difference between the two simulations is defined as the simulated warm ENSO signal. The AGCM simulations are used to drive a regional climate model, which then provides meteorological data to drive a macroscale hydrology model over the Columbia River basin. This study investigates the prospects of using this suite of nested models to provide seasonal climate forecasts of surface temperature, precipitation, and streamflow in association with the ENSO events.

Although most water resource management problems are local in nature, and the hydrology model is capable of simulating streamflow at a number of locations within the basin with high accuracy (Nijssen et al. 1997), for this preliminary study we only analyze the streamflow simulations at The Dalles, which essentially represent the runoff integrated over the entire Columbia River basin. Furthermore, our method is limited by the climate simulations that are only available for January. Although we performed hydrological simulations over the entire annual cycle using a repeating meteorological sequence, the streamflow signals calculated only indicate how surface hydrology changes propagate throughout the year as a result of climate perturbations in January. They do not reflect the true ENSO impacts integrated over the seasonal cycle. As a demonstration of how climate simulations might be made more useful for streamflow forecasting, we have also applied a simple bias correction scheme to the climate simulations and determined the improvements that can be achieved in the streamflow simulations. In what follows, section 2 describes the models, the simulation approach, and datasets that are used in the numerical experiments. Section 3 describes the evaluation of the climate simulations, and section 4 discusses the analysis and evaluation of the hydrological simulation results and the application and impact of the bias correction scheme. Finally, section 5 summarizes the results and conclusions.

2. Methods

a. Model description

Three numerical models are used to simulate the warm ENSO hydroclimate signals. First the National Centers for Environmental Prediction (NCEP) Medium-Range Forecast (MRF) model (Ji et al. 1994; Kumar et al. 1996) is used to simulate large-scale atmospheric conditions. The MRF model, which has a global domain, uses a spectral representation with triangular truncation at wave number 40 (T40) to yield a spatial resolution of approximately 2.8° latitude by longitude. A sigma coordinate system having 18 unequally spaced levels in the vertical is used. Atmospheric processes such as deep convection, vertical mixing, cloud, and radiation are described by the parameterizations documented by Ji et al. (1994). This AGCM is an integral part of the coupled ocean–atmospheric seasonal forecasting system at NCEP, which is used to produce an SST forecast. The latter is used to drive the AGCM for an ensemble seasonal climate forecast. The average simulation and forecast skill of this model over North America has been reported by Livezey et al. (1996).

The Pacific Northwest National Laboratory (PNNL) Regional Climate Model (RCM) is used to downscale the AGCM climate simulations over the United States. The RCM is based on the hydrostatic version of the Penn State–NCAR mesoscale model (MM5) (Anthes et al. 1987; Grell et al. 1993). Several physical parameterizations important at climatic timescales have been applied to the model for climate applications. The most noteworthy feature of RCM is the implementation of a parameterization of subgrid-scale orographic precipitation processes and land surface cover (Leung and Ghan 1995, 1999). The subgrid parameterization accounts for airflow and thermodynamic effects of subgrid topographic variations and calculates many physical processes for each subgrid elevation/vegetation class defined for each model grid cell. At the completion of the simulation, variables predicted for each subgrid class can be mapped to different geographical locations according to a high-resolution distribution of surface elevation. This mapping yields high-resolution two-dimensional spatial distributions of surface temperature, precipita-
tion, soil moisture, snow water equivalent, and runoff. This model, with or without the subgrid orographic precipitation parameterization, has been applied over the Pacific Northwest when driven by analyzed (Leung and Ghan 1995; Leung and Ghan 1998) and GCM-simulated (Leung and Ghan 1999) large-scale conditions. It has also been applied to East Asia (Leung et al. 1999) without the subgrid orographic precipitation parameterization. Simulations are found to compare well with observed climate at different spatial and temporal scales.

The climate simulations are used to drive the Two-Layer Variable Infiltration Capacity (VIC-2L) model (Liang et al. 1994) to simulate the streamflow of the Columbia River basin. VIC is a macroscale hydrology model for water and energy balance. It includes a representation of subgrid-scale spatial variability of infiltration to simulate runoff, soil moisture, and surface fluxes, and an explicit representation of multiple land-cover types. It uses two different timescales of runoff to capture the dynamics of runoff generation. The fast component of runoff is represented by direct runoff, and the slow component is represented by nonlinear subsurface runoff. The upper soil layer of the model is designed to represent the dynamic response of soil to rainfall events, while the lower layer is used to characterize seasonal soil moisture behavior. Runoff from individual grid cells is combined using a simple routing scheme based on assumed travel time and distance. VIC-2L and a more recent version, VIC-3L, have been tested and applied to various river basins and intercompared with other land-surface schemes in the Project for Intercomparison of Land-Surface Parameterization Schemes where the simulations compared well with observations (e.g., Wood et al. 1998). Nijssen et al. (1997) described the application of VIC to the Columbia River basin where the model-simulated seasonal hydrographs compared very well with observations.

b. Numerical simulations

Two ensembles of climate simulations have been performed with the MRF and RCM models. Each ensemble contains 24 perpetual January simulations. In the first set, referred to as the "normal" simulation, the MRF was driven by observed climatological mean SST. In the second set, referred to as the "warm" simulation, the MRF was driven by the mean observed SST for the warm ENSO years between 1950 and 1994. The difference between the sets of simulations is defined as the warm ENSO signal. In the GCM simulations, the MRF was initialized using a random 1 January initial condition from the NCEP archives. The RCM simulations were initialized using atmospheric conditions from the MRF. Initialization of soil moisture follows the approach of Giorgi and Bates (1989). The snow simulation in the RCM is initialized every two months using a December snow-cover condition previously simulated by the RCM for the Pacific Northwest to avoid continuous accumulation of snow that could affect the simulations because the use of subgrid elevation classification does capture realistic snow cover at the higher elevations.

The 12-hourly MRF-simulated wind, temperature, water vapor mixing ratio, and surface pressure were interpolated to the lateral boundaries of the RCM using the standard preprocessing procedures of MM5. A relaxation procedure was used to blend the lateral boundary conditions with the RCM model predictions within a 10-layer buffer zone on the sides. Following Giorgi et al. (1993), the nudging coefficients decrease exponentially from the outermost layer toward the interior domain. Although the RCM simulations have been performed using the subgrid orographic precipitation parameterization, results have been aggregated from simulations at the subgrid elevation/vegetation bands to form grid cell means at 90-km resolution for comparison with observations, and to drive the hydrology model. Figure 1 shows the RCM model domain with surface topography and the location of the Columbia River basin.

VIC was applied to the Columbia River basin at 1° latitude by longitude resolution. There is a total of 71 grid cells in the domain. The model implementation and parameters are as described by Nijssen et al. (1997). Figure 2 shows the model domain and the river channel network within the basin. In our numerical experiments, climate simulations are only available for perpetual Januarys. To estimate the impacts of ENSO variability on seasonal runoff, we performed three sets of simulations starting 1 October through the annual cycle. In all the simulations, the 1960 observed meteorological conditions, which resemble the climatological mean condition, are used to force the hydrology model throughout the annual cycle except January. The only difference among the three sets of simulations is the January surface temperature (daily maximum and minimum) and daily precipitation inputs to the hydrology model. Simulations performed using the repeating observed 1966 meteorology for a warm ENSO condition instead of the 1960 conditions showed that the results are not sensitive to the base
meteorological conditions used to form the seasonal cycle.

In the first set of simulations, two ensembles of observed January meteorological conditions were inserted as inputs to replace the 1960 January. The first ensemble used the daily January observations for each normal year (23 years in all) between 1948 and 1987, and the second ensemble used only the observations for the warm ENSO years (nine years in all) within the same period. These are called “normal control” and “warm control” simulations. Hydrologic warm ENSO signals can be derived from the difference between these two ensembles. In the second and third sets of simulations, the perpetual January simulations from the MRF and RCM driven by the climatological and warm SSTs were used to replace the 1960 January condition.

c. Data

Several datasets were used as inputs to the models and for evaluation of the model results. The mean SSTs used to drive the MRF were obtained from the global monthly SST analysis for the period 1950–94 (Reynolds and Smith 1994). The observed atmospheric conditions used to drive the hydrology model were based on the Summary of the Day from the National Climate Data Center and meteorological data from Environment Canada within the Columbia River basin for 1948–87. The station data were objectively analyzed onto the 1° VIC grid cells, and grid cell means were then adjusted to reproduce the means over the same (1°) spatial grid cells generated by the statistical–topographic model of Daly et al. (1994) based on observations. This dataset was also used to evaluate the surface temperature and precipitation simulated by the MRF and RCM over the Columbia River basin. Table 1 lists the warm and cold ENSO years between 1948 and 1987 selected based on absolute values of the November–March averaged Southern Oscillation Index (SOI) exceeding 0.8. We also used the Legates and Wilmott (1990a,b) 0.5° resolution surface climatology to evaluate the MRF and RCM simulations over the RCM model domain. Finally, monthly mean unimpaired streamflow data at The Dalles, which includes all of the Columbia River

FIG. 1. The 90-km resolution regional climate model domain with surface elevation (m) and location of the Columbia River basin. Contours are plotted in 100-m intervals.

FIG. 2. The Columbia River basin hydrology model domain with the river channels. The model grid cells have been numbered from the upper basin, moving from west to east down the lower basin. The numbers have been marked for the grid cells on the west end. The arrow shows the location of The Dalles at the mouth of the river.
drainage east of the Cascades mountains, were taken from a dataset produced by the Bonneville Power Administration. The unimpaired flows can be used to estimate the observed warm ENSO streamflow signal over the entire Columbia River basin.

3. Climate simulation results

a. Regional patterns

To determine how well the nested MRF–RCM models simulate the observed climate, Fig. 3 compares the ensemble means of the MRF and RCM normal simulations with the 0.5° resolution observed climatology compiled by Legates and Wilmott (1990a,b). The large-scale features simulated by the RCM are similar to those of the MRF model. These include not only temperature and precipitation as shown in Fig. 3, but also atmospheric circulation features (not shown) such as wind, temperature, and geopotential height at the upper levels, as discussed previously by Liu et al. (1994), Leung and Ghan (1999), and others. However, the RCM simulations also show mesoscale features that are influenced by the lower boundary conditions such as surface topography and mesoscale circulation. For surface temperature, the model simulation is generally within 2°C of the observations over most of the model domain. However, there are stronger warm biases in the northeast corner of the domain where the model is 4°–8°C too warm. This bias is found to be mainly inherited from the MRF model. For precipitation, the model simulated the precipitation gradients along the West Coast that compare well with observations. However, there is a general wet bias over the Pacific Northwest. Both the MRF and RCM simulations show a larger north–south gradient along the coast than the observations.

From the model simulations, we calculated the anomaly fields (or warm ENSO signals) by taking the difference between the simulations driven by the warm and climatological mean SST conditions. In the 500-mb geopotential height anomaly simulated by the MRF (not shown), there is a strengthening of the Aleutian low pressure center over the North Pacific and the high pressure center over the continental United States.

This Pacific–North American–like (PNA) pattern has been linked to SST forcings during ENSO years (e.g., Horel and Wallace 1981). The anomalous pattern derived from the perpetual simulations is similar to that obtained from the MRF multiyear seasonal simulations (e.g., Kumar et al. 1995). Previous studies (e.g., Cayan and Peterson 1989) have shown high correlations between the PNA pattern and the positions of the North American jetstream that affect the spatial distribution of precipitation in the western United States.

Figure 4 shows the surface temperature and precipitation signals simulated by the MRF and RCM. These anomalies can be compared with the observed anomalies analyzed by Livezey et al. (1996) based on monthly mean temperature and precipitation data for the U.S. climate divisions between 1950 and 1994. The model correctly simulates the warming over the Pacific Northwest, except the warming is stronger and more widespread compared to observations. The temperature signal simulated by RCM compares better with the observed signal; it is about 1°C less than the MRF simulation and is positioned farther to the north.

For precipitation, the observed warm ENSO anomaly shows enhanced precipitation over the California coast of up to 1 mm per day and reduced precipitation over the Pacific Northwest of up to 0.7 mm per day. Both models correctly simulated this dipole pattern. However, over the Pacific Northwest, the

### Table 1. Warm and cold ENSO episodes selected between 1948 and 1987 based on winter SOI below −0.8 and above 0.8.

<table>
<thead>
<tr>
<th>Year</th>
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<tr>
<td>1957–58</td>
<td>1949–50</td>
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<tr>
<td>1958–59</td>
<td>1950–51</td>
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<td>1972–73</td>
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<td>1977–78</td>
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<td>1982–83</td>
<td>1975–76</td>
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<td>1986–87</td>
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Fig. 3. The observed, RCM- and MRF-simulated January climatology for (a)–(c) surface temperature (°C) and (d)–(f) precipitation (mm per day). Contour intervals are °C and 1 mm per day, respectively.

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MRF only simulated a very weak negative signal. The RCM signal is more refined in spatial structure and has a larger magnitude of up to 1 mm per day over the lower Columbia River basin.

b. Analysis over the Columbia River basin

To analyze the climate conditions over the Columbia River basin, Fig. 5a compares the observed and model-simulated mean surface temperature for normal years over the 71 grid cells defined by VIC within the basin. The numbering of grid cells starts from the upper basin and progresses from west to east down to the lower basin (see Fig. 2). In the observations, temperature is colder in the upper basin than the lower basin, and there are strong temperature gradients from west to east that follow the surface topography distribution (Fig. 5c) with the Cascade Mountains to the west and the Rockies to the east, and the Columbia basin in the middle. Both models capture the spatial distribution of surface temperature well, except for a warm bias.
over the upper basin. Furthermore, the RCM simulation does better in simulating the east–west variations in temperature because of its use of higher spatial resolution.

Figure 5b compares the observed and model-simulated precipitation. For the observation, there is more precipitation over the upper basin than the lower basin. Again, strong east–west gradients are apparent that show more precipitation over the mountains (on the east and west ends of the basin) and less precipitation over the basin (in the middle). The simulations are generally too dry over the upper basin and too wet over the Columbia basin when compared with observations. Furthermore, the models do not capture the spatial variations in precipitation as well as surface temperature.

The observed and simulated warm ENSO surface temperature signals are shown in Fig. 6a. The MRF-simulated signal has a strong overall north–south gradient, which is not present in the observations. Both simulated signals are much weaker than those observed in the upper basin and the spatial distributions are not simulated very well by the models. Figure 6b shows the observed and simulated ENSO precipitation signals. Although the basin-averaged observed precipitation signal is clearly negative, there are large variations in its spatial distribution. Over some areas (mainly the western part of the basin) there is actually more precipitation during the warm ENSO years than normal years. In contrast to the observations, the MRF signal has very little spatial variation. The RCM simulated pre-

Fig. 5. The ensemble mean observed and model-simulated (a) surface temperature (°C) and (b) precipitation (mm per day) over the Columbia River basin during normal years. Surface topography (m) used by the hydrology model is shown in (c).
Table 2 summarizes the basin-averaged statistics based on observations and model simulations. The RCM simulations consistently show better agreement with the observations than the MRF simulations. For example, similar to the observations, the RCM ensemble simulations have significantly higher spatial variability than the MRF simulations, and they correlate spatially better with observations than the MRF simulations. This indicates the important control of surface topography on the spatial distribution of regional climate over the basin. The correlations between the simulated and observed signals are not particularly high because there are very strong mesoscale variations within the basin. A low correlation could be produced even if the signs of the simulated and observed signals show general agreement. We have calculated the similarity coefficient between the simulated and observed warm anomalies. The calculation is similar to that of the correlation coefficient, except the anomalies are calculated not based on spatial means, but with respect to the historical means (averaged observed conditions over the normal years) of each grid cell. The similarity coefficient is estimated to be 0.51 and 0.81 for the RCM-simulated warm precipitation and temperature anomalies, and 0.46 and 0.63 for the GCM-simulated anomalies, respectively.

To determine the statistical significance of the warm ENSO signals, the one-sided Student t-statistic was calculated using basin-averaged observed and simulated data. The observed precipitation and temperature signals are tested separately to be statistically significant at the 0.02 and 0.04 confidence level, and the simulated signals from both models are all significant at the 0.01 confidence level or higher. Therefore, both observations and model simulations show that there is a statistically significant regional climate signal over the Columbia River basin comparing the winters of warm ENSO to normal years.
4. Hydrological simulation results

a. Streamflow signals

The warming and drying tendencies over the Columbia River basin during warm ENSO years can have significant impacts on streamflow. Figure 7 shows the observed monthly basin mean surface temperature and precipitation, and streamflow averaged over all the normal and warm ENSO years between 1948 and 1987 at The Dalles. During the warm ENSO years, higher temperatures are found between December and April and precipitation is reduced between January and February, and during April, when compared to normal years. Annual streamflow is greatly reduced as a result of the combined warmer temperature (which causes more precipitation to fall as rain rather than snow) and reduced wintertime precipitation. Furthermore, because of earlier snowmelt caused by the warming, the streamflow in May is comparatively higher in the annual cycle during warm ENSO years than normal years, indicating changes in the timing also.

Figure 8 shows three ensembles of hydrological simulations for the normal years as VIC was driven by the observed, RCM-simulated, and MRF-simulated meteorological conditions. In the control simulations, the different observed January conditions create a large interannual variability mainly in the April–July streamflow. The simulations driven by the RCM and MRF inputs are different from the control simulations in two aspects. First, because of the warm and wet bias in the RCM and MRF simulations, much more runoff is generated between January and March when these model simulations were used to drive the hydrology model. Upstream flows that are affected by the January conditions can alter the February and March streamflow at The Dalles because of time delay. Second, as a result of the warm bias causing earlier snowmelt, the VIC simulations driven by climate models have less runoff during summer.

Figure 9 summarizes the ensemble mean streamflow signals derived from the three sets of VIC simulations. The simulated streamflow signals are relatively small compared to the observed signal (Fig. 7c) because only the January climate conditions have been perturbed with the warm ENSO conditions. Although Figs. 7a,b show that the January climate conditions are representative of the normal and warm ENSO cold season climate conditions that drive changes in streamflow, the extended warming between February and April is an important contribution to the total streamflow signal. It remains to be tested whether the nested models can reproduce the seasonal pattern of the climate conditions correctly for useful streamflow forecasts. Here we will focus on intercomparing the three sets of VIC simulations as a means of evaluating the methodology described.

In the control simulations, the impacts of the warm ENSO Januaries are mainly seen in the streamflow between April and July. The reduction is caused by the warmer and dryer conditions during warm ENSO years. There is also a small positive signal during January that results from the excess warming effect over the drying effect. Note that the control signal should not be compared with the observed streamflow signal (Fig. 7) because only the meteorological conditions for January have been varied in the simulations, but the impacts of SST on the Pacific Northwest weather during the ENSO events usually last through winter and spring.

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**Table 2.** Statistics summarizing the basin averaged monthly precipitation (mm) and daily averaged surface temperature (°C) for January from observations and simulations. Rmse is the root-mean-square error, and CORR is the correlation coefficient.

<table>
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<tr>
<th></th>
<th>Normal</th>
<th>Warm</th>
<th>Signal</th>
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<tr>
<td>Mean</td>
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<tr>
<td>OBS</td>
<td>84.5</td>
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<tr>
<td>MRF</td>
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<tr>
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<tr>
<td><strong>Rmse</strong></td>
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The streamflow signal from the VIC simulations driven by the MRF simulations has a much stronger peak during winter than observed. This is caused by the larger warming and less drying simulated by MRF as compared to the observed climate signals. The larger warming has two effects. The warmer temperatures tend to melt the existing snow accumulated through December to increase streamflow in January and reduce snowpack contributing to spring flow. Furthermore, warmer temperatures increase the fraction of precipitation falling as rain rather than snow, which again tends to increase winter streamflow and reduce snowpack available for spring flow. On top of the larger warming, the reduced drying effectively increases precipitation that also contributes to increased runoff. Because of the increased snowmelt during
winter, less snow is available for melting in spring and summer in the MRF-driven VIC simulations. Therefore, the summer peak is shifted two months earlier to April.

The RCM-driven VIC simulations do not show a noticeable streamflow signal during winter when compared with the signal in the control simulations. This can be explained by the warmer and dryer climate signal simulated by RCM as compared to the observed. As explained above, the larger warming can cause more snowmelt and increase the chances of precipitation falling as rain to increase winter streamflow. However, the stronger drying simulated by RCM reduces both winter and spring streamflow because both rain and snow accumulation are reduced, although the effect is partly determined by the spatial character of the precipitation signal. For example, changes in precipitation at the higher elevation during warm ENSO years may not induce any streamflow signal at all until spring when the snow begins to melt. Furthermore, if the most pronounced precipitation signal occurs in the upper basin, changes in the streamflow may not be detected at The Dalles until spring because of travel time. While it is difficult to ascertain the exact nature of the differences between the control and RCM simulations due to the complex dependency of streamflow on the spatial distributions of temperature and precipitation, the effects of the warming and drying signal simulated by RCM on streamflow balanced out in winter. Last, the stronger warming and drying causes more snowmelt as well as less snow accumulation during winter. Therefore, there is a reduction in streamflow during summer, and again the runoff peak in the VIC simulations driven by the RCM simulations is earlier than the control simulations. Table 3 summarizes the statistics comparing the three sets of hydrological simulations. The VIC simulations driven by the RCM simulations generally have less root-mean-square error (rmse) and higher correlation coefficients (CORR) than those driven by the MRF simulations when comparing with the control simulations.

b. Application of a bias correction scheme

Because of limitations in the physical representation and spatial resolution, global and regional climate simulations are often biased in terms of both regional means as well as spatial distributions. These biases can greatly reduce the usefulness of seasonal climate forecasts for water resource management because, as shown above, direct applications of climate model results that contain biases in surface temperature and precipitation can distort snow accumulation and melt patterns.

Despite these problems, our analyses also showed that climate simulations do contain climate signal in-

**Table 3. Statistics summarizing the streamflow (kcf/s) simulated by the hydrology model when driven by observations and the MRF- and RCM-simulated meteorology. The bias, RMSE, and CORR are calculated with respect to the control simulations.**

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Data</th>
<th>Normal</th>
<th>Warm</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Control</td>
<td>188</td>
<td>184</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>MRF driven</td>
<td>192</td>
<td>189</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>RCM driven</td>
<td>193</td>
<td>188</td>
<td>4.7</td>
</tr>
<tr>
<td>Bias</td>
<td>MRF driven</td>
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<td>5.7</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>RCM driven</td>
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<td>4.8</td>
<td>0.2</td>
</tr>
<tr>
<td>RMSE</td>
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<td>23</td>
<td>25</td>
<td>4.4</td>
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<tr>
<td></td>
<td>RCM driven</td>
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<td>20</td>
<td>2.6</td>
</tr>
<tr>
<td>CORR</td>
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<td>0.98</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>RCM driven</td>
<td>0.99</td>
<td>0.99</td>
<td>0.92</td>
</tr>
</tbody>
</table>
formation that may be useful to streamflow forecasting with long lead times. In this section, we describe a simple bias correction scheme that retains the daily temporal structures and the shape of the probability distribution of the ensemble RCM simulations, but constrains the simulated surface temperature and precipitation to lie within the observed bounds for each grid cell in the hydrological simulations.

To apply the bias correction scheme, ensemble means and standard deviations (std dev) are calculated from the historical and RCM-simulated monthly mean precipitation and surface temperature for each VIC model grid cell for the normal years. The RCM normal simulations are then reprocessed as follows: 1) Monthly mean anomalies are calculated for each grid cell by subtracting the ensemble mean of the monthly averages from the monthly average of each simulation. 2) A new monthly mean is calculated for each grid cell of each simulation by multiplying the monthly mean anomaly by the ratio of the std dev of the observations to the std dev of the simulations, and adding this to the observed ensemble mean. The new monthly mean is therefore bounded by the range of the climate records. 3) A new daily time series is then created for each RCM normal simulation by scaling the daily simulated values by the ratio of the new monthly mean to the uncorrected monthly mean.

After applying the above procedures, the new RCM normal simulations have the same ensemble mean and std dev as the observations for each grid cell. To apply bias correction to the warm RCM simulations, the above procedure is repeated, except the ensemble mean and std dev from the RCM normal simulations are still used instead of those from the RCM warm simulations. For example, if one particular warm simulation has a monthly mean that is 1 std dev above the ensemble mean of the normal simulation, then the transformed simulation will be 1 std dev above the ensemble mean of the observations for the normal years. This way the statistical distribution of the signal is preserved.

Figure 10a shows the ensemble hydrological simulations simulated by VIC as driven by the bias-corrected RCM normal simulations. Compared to Fig. 8c, the bias-corrected normal hydrological simulations have a much smaller spread between January and March after the removal of the warm bias. Overall, the simulations are much closer to the control simulations after bias correction has been applied to the RCM simulations.

To determine if bias correction has similar effects on the MRF simulations, the same bias-correction scheme discussed above was also applied to the MRF simulations based on the MRF simulation statistics. Figure 10b compares the streamflow signal simulated by VIC as driven by the observed, bias-corrected RCM, and bias-corrected MRF simulated climate conditions. The streamflow signal agrees much better with that of the control simulations after bias correction has been applied to the RCM climate simulations. Bias correction also improves the MRF simulations but the effects are less pronounced. The simulated signal driven by the bias-corrected MRF simulations is still too high (wet) during spring, and the reduction during summer is too large. This demonstrates that dynamical downscaling does provide improved climate simulations that possess some useful statistical information about the ENSO signal. Without the bias-correction scheme, differences between the streamflow signals simulated by using the GCM and RCM climate conditions would be obscured by biases in the simulated climatology. In combination with some statistical methods for bias correction and uncertainty analysis, dynamical seasonal climate forecasts could be made very useful for reservoir management.

5. Conclusions

Because of the complex terrain, both regional climate and ENSO climate signals vary spatially within the Columbia River basin. In this study, we have shown that a regional modeling system consisting of a regional climate model and a macroscale hydrology model is a useful tool for downscaling global climate simulations. These nested models correctly captured many spatial features of the warm ENSO hydroclimate signals such as the warming and drying over the Pacific Northwest, increased precipitation over California during winter, and the impacts of the atmospheric signals on streamflow in the Columbia River basin. By using higher spatial resolution, the regional climate model consistently performed better than the global model in simulating the spatial distribution of regional climate and climate signals.

This study also shows that by applying a simple bias-correction scheme to the RCM simulations, streamflow simulations can be further improved to be of value to water resources planning. The results from this early attempt to determine the extent to which ENSO hydroclimate signals can be reproduced by climate and hydrology models have demonstrated the potential for using such model structures to provide seasonal climate.
and streamflow forecasts. Our study also provides justification for more detailed studies to further refine the strategies and estimate the values of using seasonal climate forecasts for water resources management.

Some of the shortcomings in the approach we used can be avoided in the future by using more detailed studies to improve the assessment of the prediction skill of the nested models. First, because of the nonlinear nature of the atmospheric response to SST forcings, studies such as this one that only discern the difference between the mean ENSO and climatological conditions represent only early attempts. More detailed numerical experiments can be performed in the future to generate ensemble simulations that cover a longer period using time series of observed SST to drive the models. In this way, the individual atmospheric response to different SST forcings can be represented to assess the hydroclimate prediction skill, and problems associated with perpetual simulations such as winter snow accumulation in the GCMs can be avoided. These simulations also permit the study of the ENSO climatic impacts on streamflow throughout the seasons.

Second, our study was crude in terms of water applications because we only analyzed streamflow simulations for the entire Columbia River basin. As such, our streamflow simulations integrate the simulated climate signals spatially over a large area and can obscure errors that are associated with misrepresentation of the spatial distribution of the climate signals. Future studies should compare the simulated and observed streamflows over a variety of locations drained by different subbasins within the watershed so that implications for local water resources planning can also be assessed more fully using reservoir models. Furthermore, this allows a more comprehensive evaluation of the differences between the regional and global climate simulations and their impacts on streamflow.

Last, although we used the subgrid parameterization of orographic precipitation and land surface cover in our regional climate simulations, simulations performed for each subgrid elevation/vegetation class were aggregated back to form grid cell means for driving the macroscale hydrology model to match the spatial resolution currently adopted in the Columbia River basin applications. Since this study suggests that by resolving mesoscale topographic and circulation features, improved simulations of the ENSO signal can be obtained, in future studies both the regional climate and macroscale hydrology models can be applied at higher spatial resolution. Alternatively, subgrid regional climate information can be applied to a spatially distributed hydrology model to study the impacts of ENSO-related climate variability on streamflow at the catchment and watershed scales. Leung et al. (1996) used a Pacific Northwest regional climate simulation to drive a distributed hydrology model in the Middle Fork Flathead watershed in Montana. The simulated snow and streamflow compared very well with observations. The spatial resolutions of the hydrology model should be dictated by the accuracy at which the spatial distribution of climate and climate signals can be simulated by the climate models.

The dynamical ensemble forecast methods tested here for predicting seasonal climate and streamflow are computationally much more intensive than statis-
tically based methods. However, the economic implications can be enormous if these methods can be improved to the extent that the seasonal forecasts can be put into practical use for managing natural resources. To improve the production and application of seasonal forecasts, demonstration projects that implement the modeling strategies in an operational environment should be carried out to evaluate the economic consequences of utilizing seasonal climate forecasts. One such strategy, as suggested by this study, is the combined use of dynamical and statistical methods that bias correct dynamical forecasts. Furthermore, forecast uncertainties that can be derived from the variance of the ensemble forecasts can be incorporated in a statistical framework to estimate the uncertainty in the streamflow forecasts.

At this stage, it is not clear how the dynamical approach compares with the much more efficient statistical approach in producing seasonal climate forecasts that are useful for water resources management. Both approaches should be further explored to answer this question. By working with water managers on suitable basins that show hydroclimatic responses to ENSO SST forcings, operational procedures can be developed that make the best use of seasonal climate forecasts on a “forecast of opportunity” basis.

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References


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Containing expanded versions of the invited papers presented at the International Symposium on the Life Cycles of Extratropical Cyclones, held in Bergen, Norway, 27 June–1 July 1994, this monograph will be of interest to historians of meteorology, researchers, and forecasters. The symposium coincided with the 75th anniversary of the introduction of Jack Bjerknes’s frontal-cyclone model presented in his seminal article, “On the Structure of Moving Cyclones.” The monograph’s content ranges from a historical overview of extratropical cyclone research and forecasting from the early eighteenth century into the mid-twentieth century, to presentations and reviews of contemporary research on the theory, observations, analysis, diagnosis, and prediction of extratropical cyclones. The material is appropriate for teaching courses in advanced undergraduate and graduate meteorology.

The Life Cycles of Extratropical Cyclones is available for $65 list/$45 members. Prices include shipping and handling. Please send prepaid orders to Order Department, American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693 or call (617) 227-2425. Visa, MasterCard, or American Express accepted.