COLUMBIA RIVER STREAMFLOW FORECASTING BASED ON ENSO AND PDO CLIMATE SIGNALS

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ABSTRACT: A simple method has been devised to incorporate the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) climate signals into the well-known extended streamflow prediction forecasting approach. Forecasts of ENSO are currently available up to a year or more in advance, which facilitates forecasting of the streamflow response to this climate signal at interannual forecast lead times. The biomodal phase of the PDO can be identified in real time using a combination of assumed persistence of the existing phase and the tracking of extreme events to identify transitions. The technique makes use of a gridded meteorological data set to drive a macroscale hydrology model at 1° spatial resolution over the Columbia River Basin above The Dalles. A streamflow forecast ensemble is created by resampling from the historical meteorological data according to six predefined PDO/ENSO categories. Given a forecast of the ENSO climate signal for the coming water year and the existing phase of the PDO, these meteorological ensembles are then used to drive the hydrology model based on the initial soil and snow conditions as of the forecast date. To evaluate the technique, a retrospective forecast of the historic record was prepared (1989–1998), using October–September as the forecast period, as well as an ensemble forecast for water years 1999 and 2000 that were prepared on June 1, 1998 and May 10, 1999, respectively. The results demonstrate the increase in lead time and forecast specificity over climatology that can be achieved by using PDO and ENSO climate information to condition the forecast ensembles.

INTRODUCTION AND BACKGROUND

The significance of the El Niño Southern Oscillation (ENSO) for forecasting streamflow, particularly in the western United States, is now well recognized. To cite two recent examples, Piechota and Dracup (1996) and Piechota et al. (1997) used the Southern Oscillation Index to identify patterns in atmospheric circulation and streamflow variability in the United States and Garen (1998) evaluated the use of the Southern Oscillation Index as a primary variable in streamflow forecasting using statistical methods.

The reservoir operating system for the Columbia River Basin (Fig. 1) has evolved to make extensive use of streamflow forecasts available each year in the period from about January 1 to July 31 [for a description of the forecasting techniques used see Garen (1992), or Koch and Buller (1993)]. In the period from August 1 to December 31, the current operating system uses a set of reservoir rule curves derived from analysis of the historic streamflow record. Recent advances in the understanding of global teleconnections of weather and climate make it feasible to extend the lead time of streamflow forecasts for the Columbia River by about 6 months, based on long-lead climate forecasts prepared by such groups as the National Oceanic and Atmosphere Administration (NOAA) Climate Prediction Center. Potential uses of these long-lead streamflow forecasts for improving Columbia River Basin reservoir operations are also explored.

The climate phenomenon known as ENSO, of which El Niño is the warm-phase, and La Niña the cold phase, is a complex ocean/atmosphere interaction that causes cyclical patterns of warming and cooling of the sea surface in the tropical Pacific with pronounced global climactic teleconnections. ENSO events affect the Pacific Northwest (PNW) on interannual time scales with a characteristic return frequency of 4–6 years, and typically persist for 1–2 years. The physical dynamics of ENSO are now reasonably well understood. Statistical and numerical models exist that can be used for forecasting ENSO, and the tropical atmosphere ocean buoy system maintained by NOAA for measuring ocean conditions in the tropics permits winter ENSO events to be forecast with relatively high skill at lead times of about 6–9 months (Barnston et al. 1994; Latif et al. 1994; Battisti and Sarachik, 1995). These ENSO forecasts facilitate forecasts of winter climate conditions in the PNW for the coming water year by about June 1.

The effects of ENSO outside the tropics are regionally specific. Warm-phase ENSO (El Niño) in the PNW is associated with above average temperatures and below average precipitation in winter months, with an increased likelihood of below average streamflow in spring and summer, whereas cold-phase ENSO (La Niña) in the PNW is associated with below average temperatures and above average precipitation in winter that increase the likelihood of above average streamflow in spring and summer [Fig. 2(a)]. The next section provides a description of methods used to define retrospective climate categories.

The winter climate in the PNW has also been shown to be affected by the Pacific Decadal Oscillation (PDO) (Mantua 1997), a climate phenomenon associated with persistent, bimodal climate patterns in the North Pacific Ocean that oscillate with a characteristic period on the order of 50 years (a particular phase of the PDO will typically persist for about 25 years). The PDO also refers to a numerical climate index based on sea surface temperatures in a particular region of the North Pacific (Mantua 1997), which has an interannual signature. The warm-phase of the PDO (positive numerical index value) has similar effects in the PNW to those experienced in warm-phase ENSO years, and the effects associated with the cold-phase of the PDO resemble those associated with cold-phase ENSO [Fig. 2(b)]. See the next section for retrospective definitions of the PDO phase.

In comparison with ENSO, the physical dynamics associated with the PDO are not well understood, and the phase of the PDO is generally not predictable on an interannual basis. The PDO, as an interannual climate index, also tends to be an integrator of overall winter climate conditions in the north Pacific, which raises questions regarding the PDO's independence from the interannual ENSO signal. Despite these prob-

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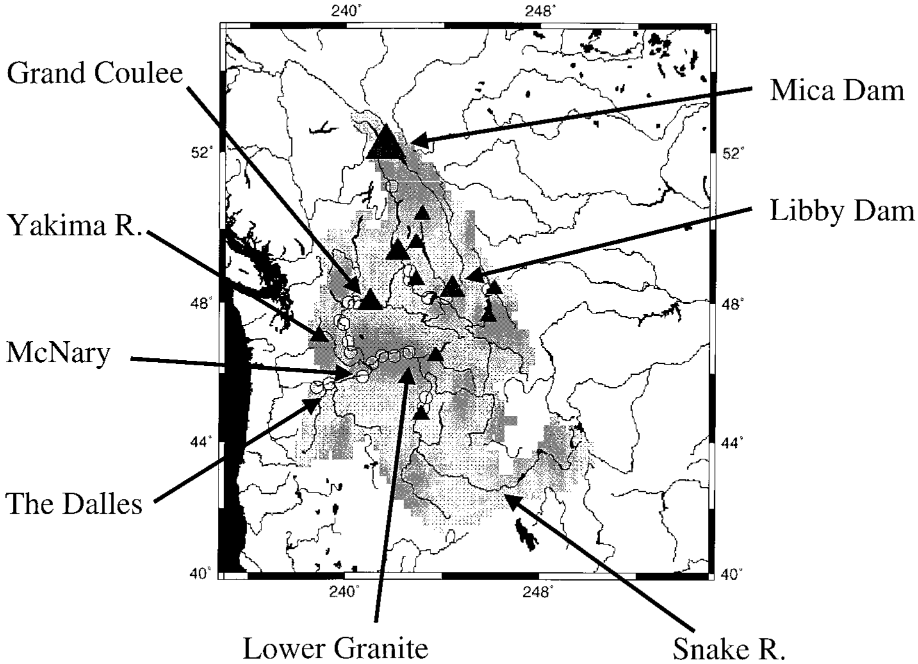

FIG. 1. Map of Columbia River Basin and Major Water Resources Projects (Triangles Are Storage Projects, Size of Icon Represents Relative Storage Capacity, Circles Are Major Run of River Projects)

lems with interannual predictability, the observed bimodal nature of the PDO on decadal time scales and the typical persistence of a dominant phase of the PDO for several decades allows the PDO to be included in real-time forecasting schemes in a useful manner. The primary challenge in the context of streamflow forecasting is to identify decadal-scale PDO transitions in real time. The technique described in the section entitled ''Predicting Regime Shifts in PDO,'' for identifying decadal-scale regime shifts from the hydrologic response of the Columbia River, while heuristic, shows some apparent skill within the context of the historic record, and provides a means of incorporating short-term variability of the PDO into the forecasting scheme. Presumably, techniques of this kind will become unnecessary as the climate dynamics associated with the PDO are more fully understood.

The naturalized or virgin streamflow record for the Columbia River at The Dalles, Oregon was analyzed [modified flows were provided courtesy of Bonneville Power Administration (BPA) (1991) and were adjusted by the writers for typical values of evaporation and withdrawals estimated by the A. J. Crook Company (1993)] (see Fig. 1 for location) for the period 1900–1997. The analysis showed that to a certain extent the climate patterns associated with PDO and ENSO tend to function independently in their effect on PNW hydrology. There is a strong tendency in the response of the hydrologic system toward high or low streamflow when the two climate indicators are in phase, and when the indicators are out of phase observed flows tend to be grouped in the normal range (Hamlet and Lettenmaier 1998) [Fig. 2(c), Fig. 3]. This apparently independent interaction between PDO and ENSO is the basis for the climate categories used in the forecasting scheme presented here. In effect, the decadal-scale variability associated with the PDO forms a low-frequency climate oscillation between wet, cold conditions (PDO cold) and warm, dry conditions (PDO warm) that conditions the interannual effects associated with ENSO.

QUANTITATIVE DEFINITIONS OF CLIMATE STATES

For retrospective tests of the forecasting method, objective definitions for the phase of each climate indicator must be specified. For this study, interannual variation in the PDO index is not considered because it cannot 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 1947–1976, and in warm phase from 1925–1946 and 1977–1996 (Mantua et al. 1997). There is considerable debate at the time of this writing as to whether the climate regime associated with the PDO shifted from a warm-phase to a cold-phase in about 1996 or 1997. We will argue, based on the observed flow record of the Columbia River, that such a transition probably occurred before 1997 (see the section entitled ''Predicting Regime Shifts in PDO'').

The ENSO phase is defined by the NIÑO3.4 index (Trenberth 1997), averaged from December–February. A water year associated with winter index value (December–February) more than 0.5 standard deviations above the long-term mean value (for the period from 1900–1996) is defined as warm-phase (El Niño). A year associated with a winter index value (December–February 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.

DEFINITION OF CLIMATE CATEGORIES FOR FORECASTING

Six climate categories (CC) are defined for the purpose of forecasting. These are the six combinations of PDO (warm or cold) and ENSO (warm, neutral, cold). The scatter plots (Fig. 3) show the April–September average streamflow at The Dalles on the Columbia River associated with each of these categories compared with the remainder of the data. Years shown as solid triangles are within the climate category, while years outside the climate category are shown as open circles. The dark line shows the average of the data within the climate category, whereas the light gray line shows the average of the data outside the climate category. A wide separation of the two horizontal lines demonstrates a strong signal, on average, associated with the climate indicator, whereas a small separation demonstrates a weak signal. Note that the strongest signal is present for the climate categories for which the PDO and ENSO are in phase (CC 1 and CC 6), and that other categories show relatively little average signal.

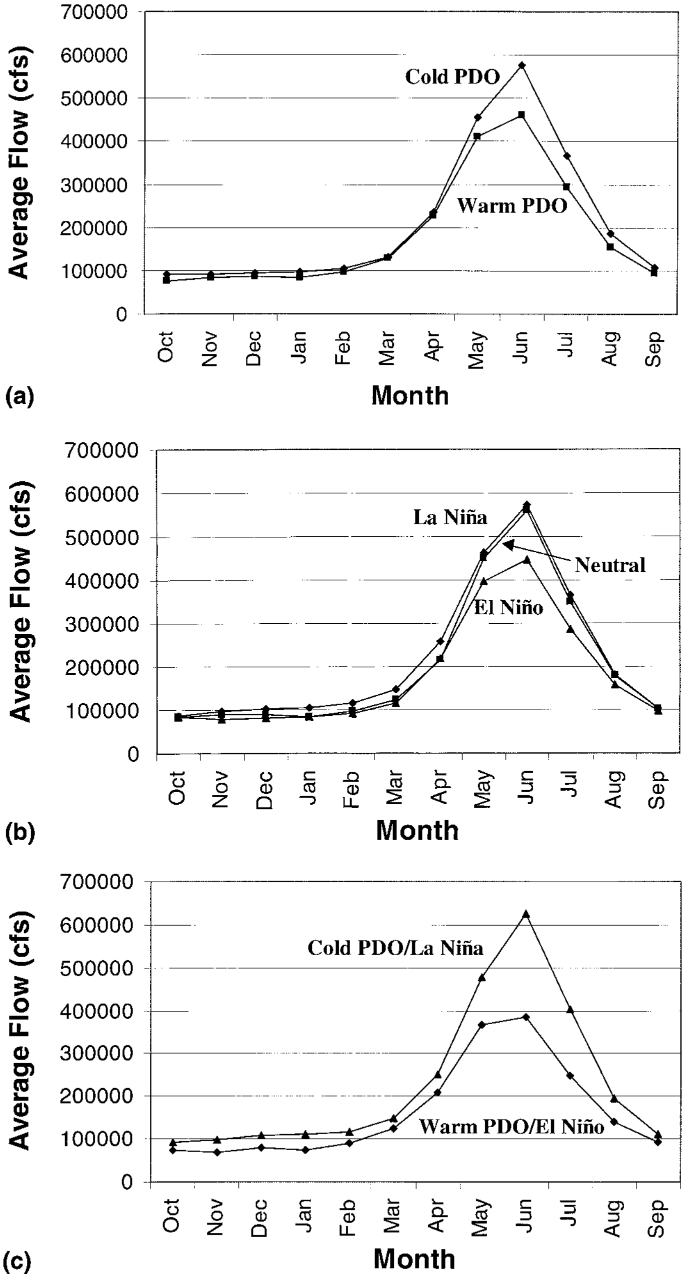

FIG. 2. Composite Monthly Virgin Hydrographs for Columbia River at The Dalles (Water Years 1900–1996): (a) PDO Phases Based on Historical Epochs; (b) ENSO Phases Based on December–February Averaged Nino 3.4 Index; (c) PDO and ENSO in Phase

PREDICTING REGIME SHIFTS IN PDO

Historically (1900–1996), April–September average virgin streamflow (effects of storage, evaporation, and withdrawals removed from observed data) at The Dalles has never been more than 1.5 standard deviations (σ) above the long-term mean during the warm-phase PDO epochs defined above. April–September average streamflow 1.5σ below the long-term mean during cold-phase PDO epochs occurred twice in the historic record from 1900–1996 in water years 1924 and 1973 (Fig. 4). Thus, the observed probability of a streamflow anomaly (departure from the mean) in excess of 1.5σ in opposition to the dominant bimodal phase of the PDO is 0.0% for warm-phase PDO epochs, and 3.5% for cold-phase PDO epochs. 1997 was an extremely wet year ($\sim$2.2σ for April–September), which suggests that, based on the patterns of historic streamflow, it is likely that we are currently in a cold-phase PDO epoch (Fig. 4).

FORECASTING COLUMBIA BASIN STREAMFLOW

The forecasting scheme makes use of a daily timestep, macroscale hydrology model of the Columbia River Basin at 1° resolution driven by observed meteorological data from 1948–1988. The model, based on the variable infiltration capacity algorithm (Liang et al. 1994), is well described elsewhere, as is its implementation for the Columbia River Basin (Nijssen et al. 1997), and will not be further discussed here.

Fig. 5 shows a schematic of the forecasting method, which is an extension of the familiar extended streamflow prediction technique (Twedt et al. 1977). The hydrology model is initialized using meteorological data from the previous water year, if available, or from a water year with similar hydrologic characteristics. One of the six climate categories is then selected based on real-time climate forecasts for the coming water year (usually available in May or June of the preceding year). Meteorological data from the historic record associated with the forecast climate category are then assembled as members of a forecast ensemble. The term ensemble refers to a group of individual streamflow traces, called ensemble ''members,'' each having some probability of occurrence. The initialized hydrology model is then driven by each member of the meteorological ensemble to produce an ensemble streamflow forecast (Fig. 6). The ensemble members (gray lines) are bounded in each case by the observed high and low streamflow for each month in the period from 1948–1988 (black dashed lines).

EFFECTS OF INITIAL CONDITIONS

Unusually wet or dry late-summer soil moisture has a pronounced effect on simulated streamflow in the following summer. Compare, for example, the CC 2 forecast for 1991 [dry soil conditions, Fig. 6(c)] and the CC 2 forecast for 1997 [wet soil conditions, Fig. 6(i)]. The CC 1 forecasts for 1992 [wet soil conditions, Fig. 6(d)] and 1995 [dry soil conditions, Fig. 6(g)] show the same relative effects on summer streamflow volumes. Note that the forecast meteorological sequences associated with a particular climate category are the same in each case, and any differences between particular forecasts in the same climate category are entirely due to initial conditions.

Given the sensitivity of the hydrologic model to late summer soil moistures, some uncertainty exists regarding which water year from the historic record to use for model initialization. The initialization years for the tests were chosen by selecting water years in the period from 1948–1988 that had similar summer streamflow volumes and timing to the actual water years preceding the forecast year (Table 1), which tends to produce about the right soil conditions in September. While these characteristics of the preceding water year are not perfectly known in June, good volume estimates are available based on, for example, May streamflow forecasts using existing statistical methods. In an operational setting, soil moistures would presumably be revised throughout the summer, and the streamflow forecasts updated to reflect current knowledge, which would improve the forecasts if unusual conditions were encountered in the late summer.

MODEL TESTING

To test the forecasting technique, retrospective forecasts for water years 1989–1998 were prepared [Fig. 6(a–j)]. Data from each climate category were selected from the observed time series from 1948–1988, and initial conditions were selected as described in the section entitled ''Forecasting Colum-

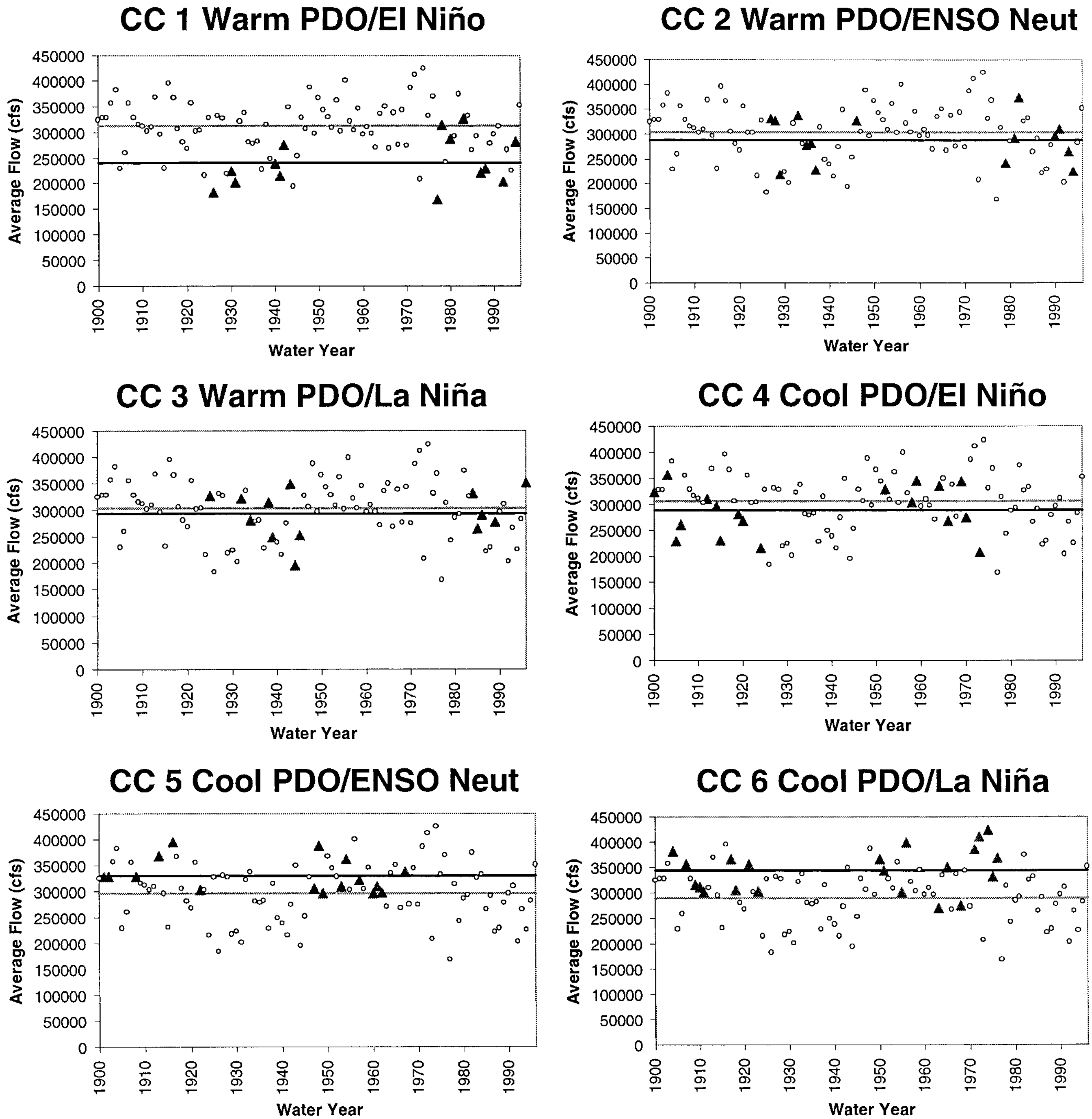

FIG. 3. Scatter Plots of April–September Average Virgin Streamflow at The Dalles for Six Climate Categories (CC 1–CC 6). (Dark Triangles Are Years within Climate Category, Open Circles Are Years Outside Category. Dark Line Is Average of Years within Climate Category, Light Gray Line Is Average of Those Years Outside Category)

bia Basin Streamflow'' (Table 2). Water years 1989–1997 were assumed to be warm-phase PDO, and 1998–2000 were assumed to be cold-phase PDO based on the 1997 high-flow event and the methods used to predict regime shifts described in the section entitled ''Predicting Regime Shifts in PDO.'' Perfect foreknowledge of the historic ENSO state is assumed for the tests. Actual ENSO forecasts may be in error under certain circumstances, and may introduce errors in the streamflow forecasts that are not accounted for in the tests.

DISCUSSION OF TEST RUNS

For the purpose of discussion, the terms ''skill'' and ''specificity'' will be used to describe the ensemble forecasts. An ensemble forecast will be said to have skill if the observed streamflow falls within the upper and lower bound of the ensemble for the period of interest. Specificity describes the relative size of the area between the upper and lower bound of the ensemble. An ensemble forecast will be said to have greater (or lesser) specificity if the area between the upper and lower bounds of the ensemble is smaller (or larger) than another forecast.

The experimental streamflow forecasts show a significant improvement in forecast specificity when compared with climatological upper and lower bounds. In the period from April–September, 95% of the observed monthly streamflow events are bounded by the experimental forecasts. For the remainder of the months in the test period, ensemble forecasts using climatology (all data from 1948–1988) demonstrate more skill in terms of the observed flows falling within the upper and lower bounds. Performance in forecasting winter

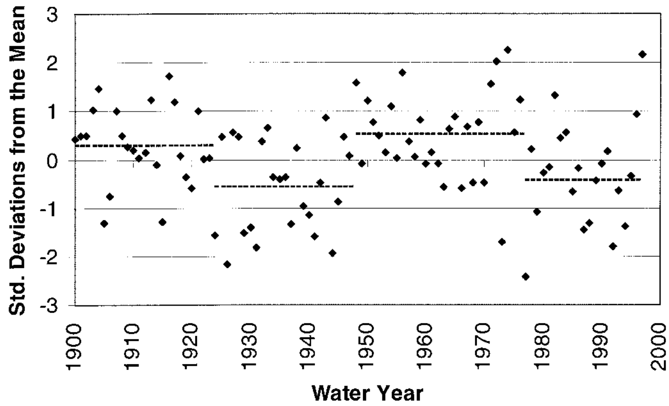

FIG. 4. April–September Average Virgin Streamflow Anomalies for Columbia River at The Dalles (Diamonds Indicate April–September Average for Each Water Year, Dashed Lines Are Epoch Averages

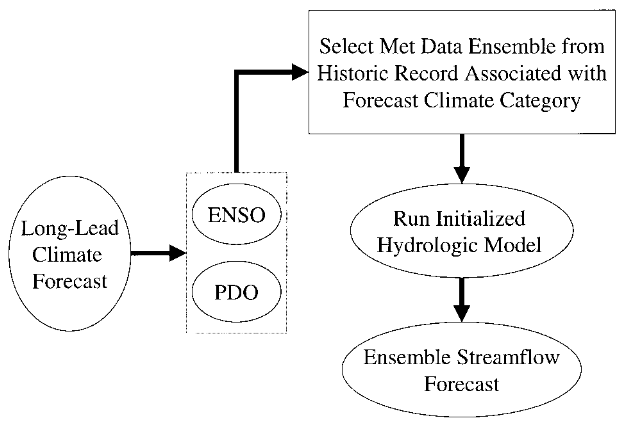

FIG. 5. Schematic of Forecasting Method

streamflow variability is not as good because the climate categories were chosen based on the April–September streamflow signal.

1997 shows the greatest discrepancy between the forecast and observed streamflow. Although 1997 was an unusually wet ENSO neutral year, the forecast is also in error partly because the transition in the decadal-scale variability had not yet been identified according to the forecasting method. This assignment of climate category is correct, however, because this is the information that would have been available in June of 1996.

Forecasts for climate categories that have relatively few observed ensemble members are generally less statistically reliable than are those forecasts for climate categories for which more data exist. Due to limitations in the meteorological forcing data for the warm-phase PDO epoch (data are available from 1977–1989, about half the warm-phase PDO epoch from 1977–1996), CC 2 and CC 3 have only three ensemble members, and CC 1 has six ensemble members. Thus, the skill of the forecasts depends, to a certain extent, on the forecast climate category. The true range of variability associated with those climate categories that occur relatively infrequently in the historic record are most likely not fully represented by the experimental forecast ensembles.

EXPERIMENTAL FORECASTS FOR 1999 AND 2000

In June, 1998 ENSO forecasts and ocean temperature measurements from the tropical atmosphere ocean buoy system predicted La Niña developing for the winter of 1998–1999 (for an example of the type of real-time ENSO forecasts available on the worldwide web see http://www.pmel.noaa.gov/toga-tao/el-nino/forecasts.html). The climate category for 1999 is therefore CC 6 (PDO cold/La Niña). Note the difference between the PDO cold/El Niño forecast for 1998 [Fig. 6(j)] and the PDO cold La Niña for 1999 [Fig. 7(a)]. The forecast shows a high likelihood of high spring and summer flows, with peak flows occurring in June or July, and a low probability of summer low-flow conditions.

As of May 10, 1999, early ENSO forecasts have predicted that La Niña conditions may persist through the winter of 2000 (i.e., CC 6). Because summer streamflow in 1999 is likely to be unusually high due to record precipitation and snowpack in the winter of 1999, 1974 was used as the model initialization year for the forecast. The forecast shows an ensemble biased heavily toward the high-flow range of the spectrum, with one ensemble member exceeding the previous climatological upper bound [Fig. 7(b)]. It should be noted that this forecast is being delivered 1 month earlier than usual and the ENSO forecast could change in the early summer to more neutral conditions, which might make the forecast CC 5 at that time [Fig. 7(c)]. CC 5 conditions would give a forecast with a high likelihood of median spring and summer flows.

SPECIFICITY VERSUS SKILL IN ENSEMBLE FORECASTS

The specificity of a given ensemble forecast can be increased by eliminating some of the ensemble members from consideration. There is a relationship, however, between forecasting skill and the forecast specificity. Consider, for example, the forecast ensemble for water year 1999 [Fig. 7(a)]. The forecast contains 12 ensemble members. If any two adjacent flow outcomes are selected to define a new expected range of streamflow outcome, we might expect approximately 9% (1/11) of the actual streamflow outcomes to fall within this narrow region of flow response (assuming uniform distribution of ensemble members). Or one could eliminate the two lowest ensemble members and expect about 82% (9/11) of the actual flow outcomes to fall within the band of moderate to high flow represented. Depending on the use of the forecast, different portions of the ensemble can be selected and the probability of the actual flow falling within this region can be estimated. Those interested in irrigated agriculture or hydropower production, for example, might consider spring and summer volume forecasts falling below a certain predetermined threshold, such as 100,000,000 acre-ft (~340,000 cfs average) for April–August. For 1999, the probability of such an event is estimated to be about 30% (Table 2).

Conversely, a probability of occurrence can be selected and an appropriate region of the ensemble forecast can be associated with this likelihood. Flood control operators might want to know the approximate upper bound on streamflow for the coming water year associated with a 90% likelihood of occurrence. This upper bound would be estimated for the 1999 forecast as approximately the 90th percentile of the streamflow ensemble for April–August: An average flow of 439,000 cfs, or a total volume of 133,000,000 acre-ft (Table 2). Many other formulations for interpreting the ensemble forecasts are possible using these concepts as a basis.

USING FORECASTS IN COLUMBIA RIVER BASIN OPERATORS

Current streamflow forecasting techniques begin to provide forecasts about January 1, based on observed snowpack and statistical relationships to spring and summer streamflow. As the snow accumulation season progresses, the forecasts of spring runoff become increasingly accurate until about April or May, as estimates of the total snow water equivalent that will contribute to runoff during the spring melt become in-

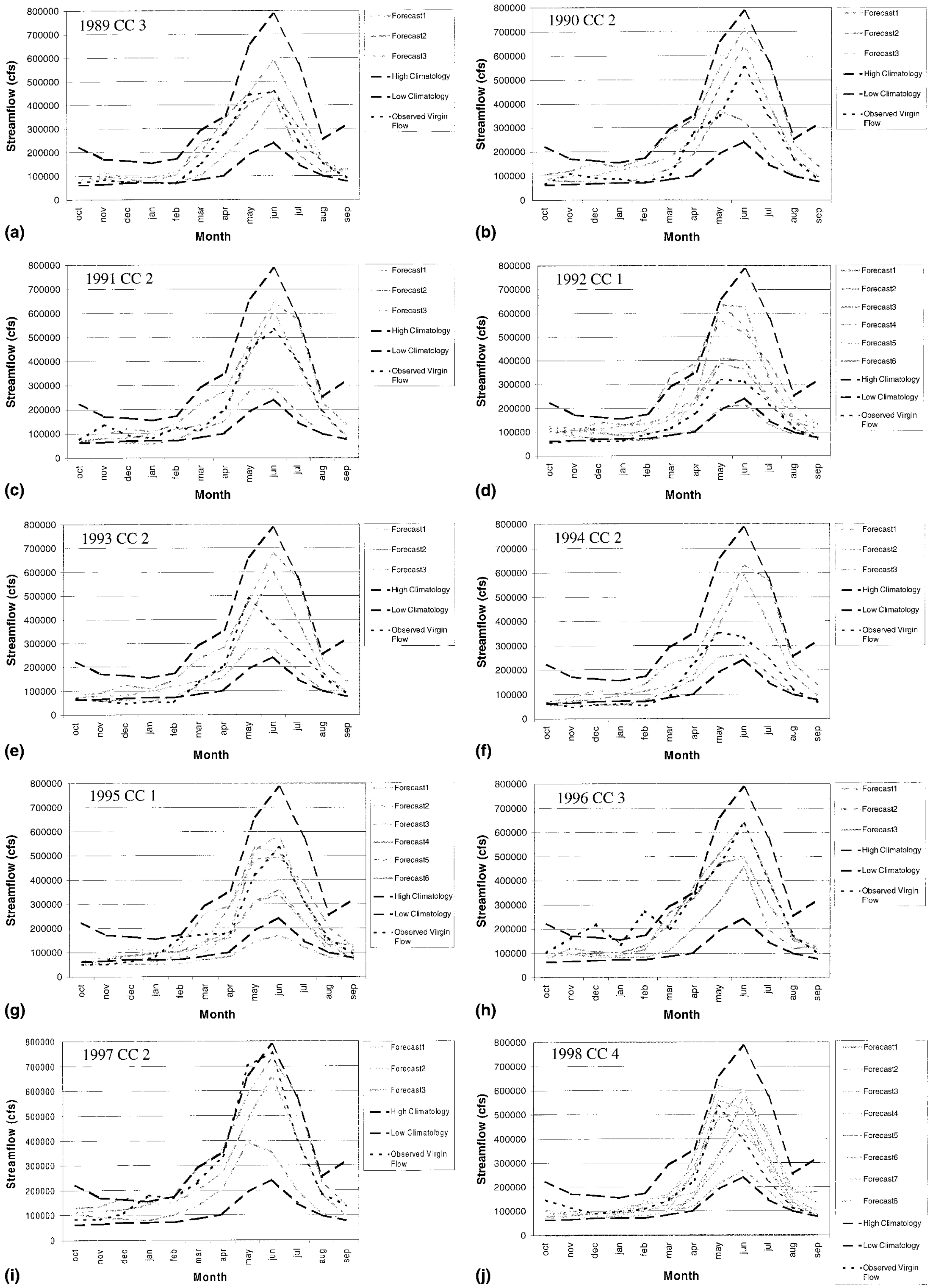

FIG. 6. Retrospective Forecasts for 1989–1998

TABLE 1. Water Years Used for Model Initialization for Different Forecast Water Years

Forecast year (1)	CC (2)	Runup year (3)	Surrogate runup year (1948–1988) (4)
1989	3	1988	1988
1990	2	1989	1985
1991	2	1990	1960
1992	1	1991	1954
1993	2	1992	1973
1994	2	1993	1979
1995	1	1994	1987
1996	3	1995	1970
1997	2	1996	1965
1998	4	1997	1974
1999	6	1998	1952
2000	6	1999	1974

TABLE 2. Percentile Flows and Runoff Volumes for 1999 Water Year Ensemble Forecast

Percentile (1)	Forecast 1999 average streamflow at The Dalles, April–August (cfs) (2)	Forecast 1999 volume runoff at The Dalles, April–August (million acre-ft) (3)
90th	439,000	133.2
80th	430,000	130.4
70th	406,000	123.2
60th	393,000	119.3
50th	380,000	115.4
40th	379,000	114.9
30th	341,000	103.4
20th	318,000	96.5
10th	299,000	90.6

creasingly precise (Koch and Buller 1993). As the snow melts through the summer, the actual streamflow becomes progressively less dependent on the accumulated snow from the previous winter season, and the forecast accuracy declines, until by August there is relatively little prediction skill. The forecasting method described here essentially extends the lead time for forecasting spring and summer streamflow by approximately 6 months.

Columbia River Basin streamflow forecasts are used to determine flood evacuation requirements and reservoir refill curves that affect the amount of hydropower production allowed under the current operating plan. Fig. 8 shows the flood storage evacuation diagram for Libby Dam (see Fig. 1 for location in the basin). This diagram is typical in structure for the major federal storage projects in the basin, although the details are different at each project. Until January, the evacuation targets are fixed values that are independent of forecast information. Starting in January, forecasts of spring runoff volumes determine greater or lesser evacuation requirements, based on estimates of total spring runoff either at The Dalles or at the individual project. If the average Dalles runoff volume is used, the averaging period is typically April–August. Similarly, ''assured refill'' curves for each reservoir that are used to determine limits on hydropower production are based, from August–December, on conservative assumptions of reservoir inflow designed to enforce a high likelihood of reservoir refill in summer. Similarly, the so-called ''critical'' rule curves are based on the critical period used for planning (essentially the most severe low-flow streamflow sequence in the historic record) to prevent overdrafting of the system early in the water year that could threaten firm energy production later in the year. Starting in January, the assured refill rule curves are based on forecast inflows (BPA et al. 1991). In the last several

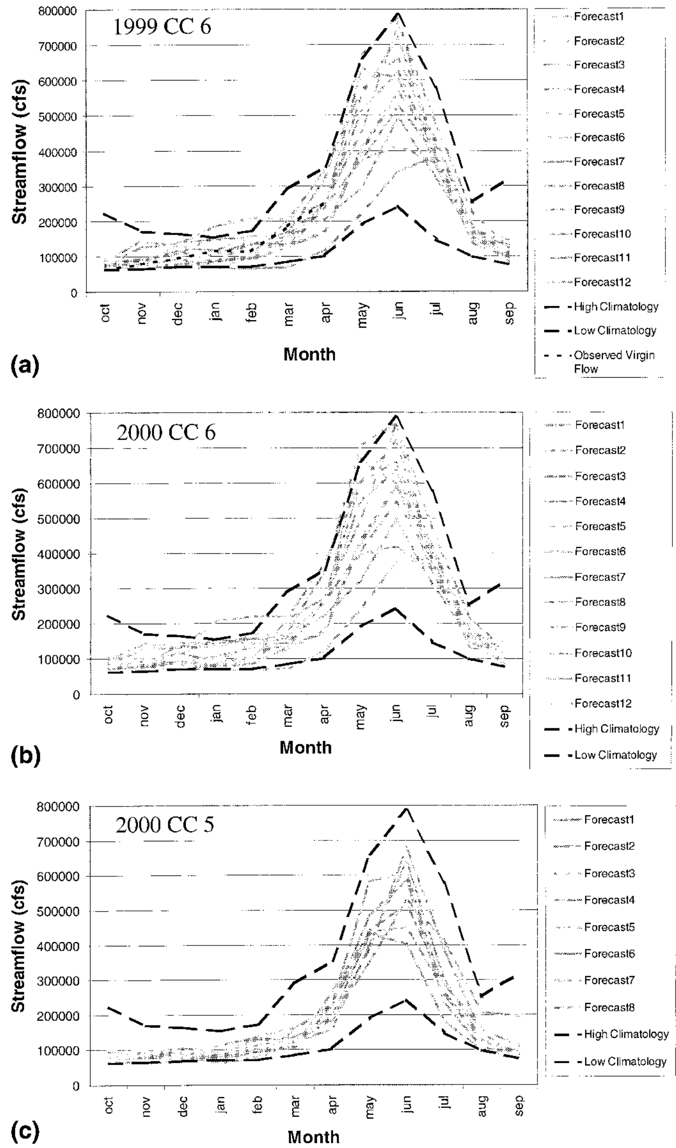

FIG. 7. Experimental Forecasts for Water Year 1999–2000

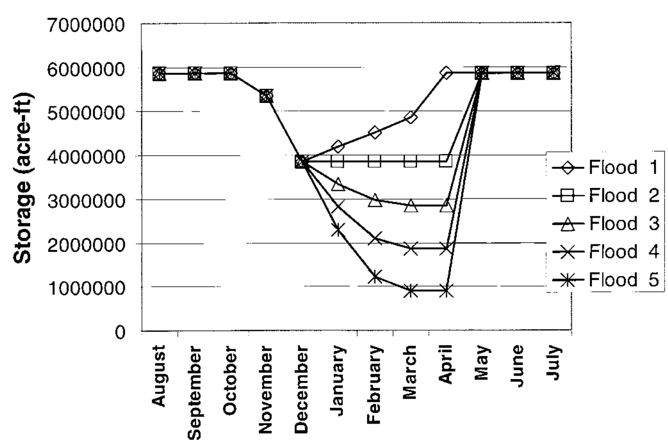

FIG. 8. Flood Evacuation Diagram for Libby Dam

years, additional constraints on winter reservoir drafting have been added at some projects with the intent of ensuring a high likelihood of being at, but not below, flood pool levels on April 15 of each water year. This is intended to limit hydropower releases in winter during dry years and to provide more summer storage for meeting flow targets in the lower river at McNary and on the Snake River at Lower Granite (see Fig. 1

for locations in the basin). A primary advantage to having forecasts with longer lead times is that the fixed flood control and refill estimates in early winter could become more dynamic, with overall benefits to hydropower and fisheries flow targets. Hydropower would benefit in wet years because increased use of storage in fall and winter would be permitted when the value of energy is high, without impacting reservoir refill. Fisheries would benefit in dry years because flood control evacuation targets and winter hydropower releases would be reduced appropriately to refill the reservoirs with greater reliability, thus ensuring maximum storage for enhancement of spring and summer flows.

In the Yakima and Snake subbasins of the Columbia River (see Fig. 1 for locations in the basin), streamflow forecasting is important to planning for irrigated agriculture and other uses in the system. Forecasts with long-lead times facilitate coordination between different system users and uses that may be important in these multiple-use water resources systems. This is particularly true with respect to the protection of fisheries, which has become a high priority in recent years, and frequently conflicts with other uses of the system in spring and summer.

There are essentially two categories of water users in the Columbia River Basin: (1) Those who can take calculated short-term risks to maximize long-term benefits (e.g., hydropower marketing, irrigated agriculture); and (2) those who are partially or wholly constrained to adopt relatively conservative policies to minimize risk (e.g., flood control). These essentially distinct types of system users would presumably make different use of the forecasts. The timing of the decision processes in each case may also determine the usefulness of the forecasts.

Medium-term planning for irrigated agriculture and the marketing of hydropower could rely on hedging rules (e.g., to determine crop type, planting schedule, expected available water for junior water rights holders, marketing targets for the sale of hydropower, etc.) formulated to optimize decision processes for expected long-term benefits. As its determining condition, the hedging rule might use the forecast for the 30th percentile streamflow in the ensemble forecast as described above, for example.

Flood control is somewhat different in that there is apparently less ability on the part of the U.S. Army Corps of Engineers to trade short-term flood risk for long-term gain. Technical opportunities would appear to exist to improve the efficiency of flood control operations in November and December without increasing flood risk. This could be accomplished by using longer lead-time forecasts to make November and December evacuation targets a function of streamflow forecasts, as opposed to the fixed values currently used. Although the legal, political, and institutional obstacles to changing these operating rules in the short term appear to be large, other potential uses for longer lead-time forecasts present themselves for flood control, even within the context of the existing operating system. If flood risk were forecast to be very low, for example, planning for maintenance or other activities not associated with active flood control in the current year would provide a better use of resources. Similarly, a forecast of high flood risk would provide advance warning for physical and institutional preparations such as the reinforcement of levees and dredging of channels, coordination with Canada for the extended use of Canadian projects for flood control, or the hiring of additional personnel.

Consider the retrospective forecasts for water years 1992 and 1995, both El Niño years associated with a warm-phase PDO epoch [Figs. 6(d) and 5(g)]. The ensemble shows approximately a 50% likelihood of flows in the ''normal'' range, and approximately a 50% likelihood of low-flow conditions. 1995 is also dryer overall than 1992 due to the initial conditions selected. The lowest ensemble member in each case is less than the lowest observed flow from 1948–1988 (1977) for both years. Summer flows below those experienced in 1977 will be considered extremely low flows. The forecast suggests a low probability of high spring flows, particularly for 1995, and there is a high likelihood that the peak monthly flows will occur in May for 1992, and in May–June for 1995. Given a significant probability of low flow in the summer months (about 50% chance), agricultural irrigators could use the forecast to select crop type, planting schedules, price of water in water markets, etc. Those marketing energy from hydropower could use hedging rules, described above, formulated to optimize long-term benefits. Flood control planners could interpret the forecast as a strong likelihood of no extreme monthly high-flow events after May. High runoff volumes for April–August are unlikely to occur, and November and December flood control evacuation targets could potentially be altered to reflect the reduced high-flow risks forecast, with benefits to other aspects of the system. Fisheries managers could expect approximately a 50% likelihood of a low-flow event, and about a 17% chance of an extreme low-flow event lower than any experienced in the historic record. Coordination with other water users could provide contingency plans for dealing with such an event to protect instream flow and habitat. Water year 1992 occurred as a moderately severe low-flow event. Water year 1995 occurred as a relatively normal year with fairly average spring and summer flows. Both events occurred in the expected range of the ensemble forecasts, however, and an appropriate interpretation of the forecasts would have resulted in correct decisions for the actual conditions encountered.

APPLICATION AND EXTENSION OF FORECASTING METHOD

The forecasting method is relatively flexible and portable, and may be applied to large- or small-scale river basins for which a hydrology model and meteorological forcing data exist. An understanding of the linkages between global climate patterns and interannual streamflow events is essential for the creation of meaningful climate categories; however, this process is not technically challenging if appropriate streamflow data exist. In some basins for which limited historical streamflow data exist, this process of defining useful climate categories may involve the use of simulated streamflow from a hydrology model driven by observed meteorological data or simulated meteorological data from weather models.

In general, forcing data for the hydrology model used to forecast streamflow may come from historical observations, weather models, or may be simulated explicitly by global or regional circulation models in areas of the world where these tools provide sufficient accuracy to allow meaningful hydrologic simulations. Using models to simulate meteorological variables has advantages because the number of ensemble members can be made uniform for all climate categories, and presumably more of the variability will be captured in the simulations.

Another advantage of the forecasting method is that increased understanding of the climate system and/or improvements to climate simulation tools automatically increases the skill and specificity of the forecasts without any modifications to the hydrologic forecasting tool. Only the climate categories or simulated meteorological ensembles change.

CONCLUSIONS

The use of ENSO and PDO climate indicators to condition streamflow forecasts extends the lead time by about 6 months over current streamflow forecasting practices. For the test period, the forecasts produced are significantly more specific than forecasts based on climatological upper and lower bounds for 95% of the months falling in the period from April–September. Appropriate use of these ensemble forecasts within the general framework of the existing operating system would appear to provide potential benefits to system hydropower production in the fall and early winter during high-flow years, seasonal planning for irrigated agriculture, maintenance of systemwide flow targets in low-flow years, seasonal planning for fisheries management in conjunction with other system uses, and the efficiency of flood control operations in November and December in low-flow years.

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