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## Letter from the Editor

Over the past decade, extensive technological advancements in Earth observing systems and forecasting capabilities have lead to new opportunities in using high quality climate information in operational decision-making by many atrisk organizations in the public and private sectors. These developments have lead to a growing demand on national, regional, local and organizational levels for climate information such as detailed analysis of the impacts of climate on the natural resources in different regions in the U.S.

To address these issues, NOAA's Office of Global Programs initiated the Regional Integrated Sciences and Assessments (RISA) Program to enable the development of high quality information and other related support services to respond to climate-related risks on various levels. Specifically, this would require development of communication networks and data infrastructure as well as customizing the information to address specific needs of various decision-makers in the public and private sectors. The RISA Program involves innovative partnerships among federal, state and local governments, academia, public and private sectors to build organizational capacity within a region to ensure on-going delivery of information products and services emerging from the results of RISA funded projects.

At present, there are five RISA projects. These are focused on the Pacific Northwest, the Southwest, California, Inter-Mountain West, and the Southeast regions of the U.S. In this issue we present the latest results of the Climate Impacts Group (CIG) of the University of Washington, in the Pacific Northwest region.

In the first article, Drs. Philip Mote and Nathan Mantua provide detailed results on the key drivers of year-to-year climate variability in the Pacific Northwest region. The second article, by Amy Snover and Philip Mote, provides a summary the impacts of climate on the natural resources in this region. Lastly, in the third article, Dr. Edward Miles and his co-authors at CIG, discuss the use of climate forecast information by resource managers in this region.

Maryam Golnaraghi, Editor

## **Causes of Climate Variability in the Pacific Northwest**

### By Philip Mote and Nathan Mantua

year-to-year climate The variations of the Pacific Northwest (PNW) have two important features that improve their predictability. they are influenced First. by variations in climate over the Pacific Ocean that evolve slowly and are consequently predictable up to a year Second, the PNW in advance. climate variations tend to be coherent across the region, meaning that a cool wet winter in southern Idaho is likely to be a cool wet winter in western Washington too. The of significance this regional coherence is greater because the Columbia River Basin, which occupies much of the states of Washington, Oregon, and Idaho, exhibits the same regional coherence.

Climate variations are largely random and unpredictable, but some regularly occurring hemispheric scale patterns impose some order in the climate system. The El Niño/Southern Oscillation (ENSO) is the most important for global climate, but for much of western North America the Pacific Decadal Oscillation (PDO) is also important. Each of these major modes of has characteristic variability signatures in seasonally changing patterns of wind, air temperature, and precipitation, and they interact with the PNW's steep terrain, especially the major mountain ranges that divide wet west side from dry east side, to produce climate variations. The Cascade Mountains also bear strongly on seasonal variations in the region's climate because they present an effective barrier between the lower-atmosphere's maritime climate influences to the west and the continental climate influences (with larger daily and seasonal temperature swings) to the east.

The PNW's wet season typically begins in October, peaks in midwinter, and ends in the spring; about region's annual 75% of the precipitation falls in the period October-March. The wet season determines mountain snowpack, which in turn determines streamflow during the spring and summer in most of the region. The October-March period also has the greatest sensitivity to ENSO and PDO influences.

### ENSO and PDO phenomena

Both ENSO and PDO are patterns of Pacific climate variability that include changes in sea and air temperatures. winds. and precipitation. ENSO, a tropical phenomenon, reflects a movement of precipitation and warm ocean water, and can be characterized as having different phases: neutral, warm (El Niño) and cool (La Niña). In ENSO "neutral" conditions, persistent storm clouds lie over an enormous patch of very warm water (86-89°F) in the western tropical Pacific; easterly trade winds along the equator blow from South America towards Indonesia. During a warm phase, the winds weaken and the patch of warm water (and the rainfall that goes with it) moves eastward and equatorward from its usual locations. During the cool phase of ENSO, rather than shifting as it does in the warm phase, the tropical circulation merely intensifies.

Although ENSO takes place in the tropics, its reorganization of the atmosphere's tropical heat engine has global repercussions, affecting winds and storm tracks thousands of kilometers away. The ENSO influence on North Pacific and North American climate is especially strong in the months from October through March, when weather is dominated by large-scale flow patterns that are more susceptible to ENSO influence.

Like ENSO, PDO is a hemispheric-scale seesaw pattern in Pacific climate, but with several important differences. First, PDO appears to have its strongest signature in the North Pacific, instead of the tropical Pacific (Mantua et al. 1997). Figure 1 shows

Figure1: Spatial pattern of anomalies in sea surface temperature (shading, degrees Celsius) and sea level pressure (contours) associated with the warm phase of PDO (top) and ENSO (bottom) for the period 1900-1992 (Mantua et al. 1997). Note that the main center of action for the PDO is in the north Pacific, while the main center of action for ENSO is in the equatorial Pacific. Contour interval is 1 millibar, with additional contours drawn for +0.25 and 0.5 mb. Positive (negative) contours are dashed (solid).

(a) SST and SLP egressed on the PDO index



the sea surface temperature (SST) anomalies that are associated with the warm phases of PDO and ENSO. The spatial patterns are very similar: both favor anomalously warm sea surface temperatures near the equator and along the coast of North America, and anomalously cool sea surface temperatures in the central North Pacific. (The cool phases for PDO and ENSO, which are not shown, simply have the opposite patterns of SST anomalies: cool along the equator and the coast of North America, and warm in the central north Pacific.)

The temporal rhythms of ENSO and PDO (Figure 2) are different too: the lifetime of a typical ENSO event ranges from 6 to 18 months, and complete ENSO cycles typically have a 2 to 7 year period (Rasmussen and Carpenter 1982); by contrast, major PDO events in the twentieth century have stayed in one phase or the other for 20 to 30 years at a time, yielding a 50 to 70 year period for a complete PDO cycle (Mantua et al. 1997).

A final key difference between ENSO and PDO lies in the state of current scientific understanding of the two phenomena. Scientists are reasonably agreed that ENSO exists because of strong air-sea interactions that take place in the tropical Pacific. These interactions give rise to a deterministic set of climate events that are inherently predictable at lead times of at least one to a few seasons. While ENSO has been extensively studied and is now routinely predicted at more than a dozen centers around the world, the causes for, and the potential ability to predict, PDO variations are not currently known. Part of the difficulty in understanding PDO results from the fact that its period is so long, compared to the period of good instrumental records in the North Pacific (since about 1900), that

only two complete PDO cycles have been observed. The PDO was in its cool phase from about 1890 to 1925 and from 1945 to 1977. It was in its warm phase from 1925 to 1945 and from 1977 to at least the mid-to-late 1990's (Mantua et al. 1997). Based on empirical evidence linking PDO phases to extreme water year streamflows in the Columbia River. Hamlet and Lettenmaier (1999) posit that exceptionally high flows in water year 1995 marked a phase change back to cool PDO conditions. Other researchers speculate that а simultaneous cooling of the NE Pacific Ocean and a warming of the interior North Pacific Ocean in 1998 marked a switch to cool phase PDO conditions, coincident with the end of the extreme 1997-98 El Niño episode (Hare and Mantua 2000). Finally, Hare and Mantua (2000) caution that the lack of PDO understanding makes it impossible to determine true "PDO reversals" soon after they occur.

Impacts of ENSO and PDO on PNW climate

Because ENSO and PDO influence the atmospheric circulation over the North Pacific and North America, they are important factors for Northwest climate. Cool phases of both PDO and ENSO favor cooler and wetter weather from about October to May, and warm phases favor warmer and drier weather.

Another view of the ENSO and PDO influences on PNW climate is provided by warm and cool phase composites of PNW climate records such as those shown in Figure 3. Here, we have selected monthly averaged surface temperature and precipitation for the PNW (Oregon, Washington, and Idaho). The largest differences in El Niño versus La Niña year composites occur in the cool season months (see lower panels of Figure 3). The composite El Niño surface temperature is ~0.7 to 1.3°F higher. on average, than the composite La Niña surface temperature in December through June. From October to March, composite El Niño year precipitation is on average about 1 cm per month less than in the La Niña year composite. Overall, the El Niño October-March composite precipitation is 14% less than that in the La Niña composite.

PNW temperature and precipitation composites based on cool and warm extremes of the PDO have their largest differences in the fall, winter and spring seasons. The warm PDO composite has Octoberto-May temperatures that are on average  $\sim 0.5$  °C higher than those in the cool PDO composite, with a range of +1.3 °C in March-April to -





0.25 °C in November-December (Figure 4) **October-January** precipitation is  $\sim 1.2$  cm per month lower in the warm PDO composite than in the cool PDO composites. Overall, the water year precipitation in the warm PDO composite is  $\sim 10\%$  less than that in the cool PDO composite. As might be expected, the combined influences of cooler-wetter climate in La Niña and/or cool phase PDO years favors higher snowpack and water year streamflows than during El Niño and/or warm phase PDO years.

# Implications for climate and resource predictions

The results of our retrospective analyses suggest that an ability to monitor and predict the rhythms of ENSO and/or PDO could be exploited to predict swings between the cool-wet and warm-dry PNW pattern, purely on an *empirical basis*. On the other hand, the ability to predict aspects of PNW climate not captured by the region's dominant winter pattern may not be as promising, at least via empirically determined relationships.

At the seasonal to inter-annual time scale, skill in monitoring and predicting variations in the ENSO cycle has been demonstrated for nearly a decade (Battisti and Sarachik 1995). Once an ENSO forecast is made, relatively simple ENSO-related predictions can be generated from empirical relationships based on historic climate data, or from climate model simulations.

As a general principle, all climate forecasts are probabilistic. For example, a typical El Niño-related climate forecast for the PNW might be presented as follows:

Based on expectations for continued El Niño conditions in the tropical Pacific, we also expect increased likelihoods for above average winter and spring temperatures with below average precipitation, with small but non-zero odds for the opposite conditions (i.e., below average likelihood for below average winter and spring temperatures and above average precipitation).

The probabilistic approach is necessary because although ENSO and PDO influence the mean conditions as shown above, they do not guarantee that any one year will resemble the mean – in fact, there are many examples of winters that defied the "typical" pattern.

Some of the event-to-event differences in the PNW climate response appear to depend on the strength of the ENSO event in question. Although the sample size for extreme El Niño events is small,

Figure 3: Composite 1931-1999 monthly temperature and precipitation associated with warm (El Niño) and cool (La Niña) phases of ENSO for the PNW (Washington, Oregon, and Idaho). Warm phase values are shown with solid lines, cool phase values with dashed (top). The bottom panels show the monthly differences between the warm and cool ENSO composites (El Niño - La Niña).



there is evidence supporting the notion that PNW winter climate tends to warmer temperatures but near-normal precipitation conditions during these rare cases. El Niño events in 1982-83 and 1997-98 were the most intense observed in this century, as measured by tropical ocean temperature, wind, and rainfall anomalies (Barnston et al. 1999). Instead of simply causing intensification in the typical El Niñofavored warm-dry PNW climate pattern, these two extreme El Niño events coincided with well above average winter and spring temperatures but near or above average precipitation across the region (Table 1). The net result was that snowpack and streamflow anomalies following the winters of 1982-83 and 1997-98 were smaller than those typical of an average intensity El Niño event.

Climate forecasting with physically based models, rather than empirical relationships, offers great potential for improving forecasting skill because the models are not constrained by historical relationships. Present day forecasting centers are generally increasing their reliance on models while still making extensive use of empirical relationships (Barnston et al. 1999).

As previously noted, there is currently little demonstrated skill in predicting PDO variations. This situation is directly related to the fact that the mechanisms giving rise to the PDO are not understood. The mechanisms giving rise to PDO will determine whether skillful decadeslong PDO climate predictions are possible. If PDO arises from air-sea interactions that require ten-year ocean adjustment times, then aspects of the phenomenon will (in theory) be predictable at lead times of up to 10 years.

Even in the absence of a theoretical understanding, the state of PDO improves season-to-season and year-to-year climate forecasts for North America because of its strong tendency for multi-season and multipersistence (Hamlet vear and Lettenmaier 1999; Dettinger et al. 1999). Simply assuming persistence of observed PDO-related North Pacific SST anomalies in the fall in any given year provides some skill in predicting PDO-related winter climate anomalies in the PNW region. NOAA's Climate Prediction Center has exploited this facet of North American climate with their "Optimal Climate Normals" (OCN) statistical prediction tool. In the absence of El Niño or La Niña, assuming persistence in the observed PDO state provides much of the skill in seasonal climate forecasts for North America. Of course, this persistence-based forecast will always fail to predict the relatively infrequent switches from one PDO phase to another.

Combining ENSO and PDO information offers a promising means of maximizing climate information for use in predicting PNW climate (and North American climate more generally, see Gershunov and Barnett 1998). PNW climate departures from normal are greatest when ENSO and PDO are in the same phase. either warm/warm or cool/cool. In contrast, when ENSO and PDO are in opposing phases (one warm, the other cool), PNW climate statistics are close to average.

Tendencies for temperature and precipitation anomalies to sometimes covary in predictable ways offers a means for making skillful predictions for snowpack, streamflow, and Figure 4: As in Figure 3, but here composites are based on warm and cool phases of PDO assuming that the PDO pattern is truly regimelike, with continuous epochs switching phase in 1925, 1947, and 1977.



other resources sensitive to the water cycle. Based on expectations for La Niña to persist through the winter and spring of 2000, Dettinger et al. (1999) issued the first ever streamflow forecast for river basins across the entire U.S. Likewise, Hamlet and Lettenmaier (1999, 2000) have developed a methodology for extending the lead time of water

Table 1. Comparison between PNW temperature and precipitation anomalies during a composite of El Niño years in the 1946-99 period of record (excluding the extreme 1982-83 and 1997-98 events) and those observed during 1982-83 and 1997-98. Data comparisons made for October-March averages based on U.S. climate division data (Karl et al. 1986) for Idaho, Oregon, and Washington.

	Surface temperature anomaly	Precipitation anomaly (% of normal)
Composite El Niño year	+ 0.5 °C	93%
1982-83	+ 0.7 °C	125%
1997-98	+ 1.2 °C	101%

resources forecasts for the Columbia Basin by selectively resampling the historic climate record based on forecasts for ENSO and PDO. Thus, climate forecasts can provide a basis for making resource forecasts. The full value of climate forecasts can only be realized with the added value predictions that go beyond forecast products like probability outlooks for temperature or precipitation.

Finally, "noise" and the chaotic nature of earth's climate will always place strict limits on both the potential and realized skill in climate predictions. Perfect predictions for and PDO would have ENSO accounted for about 27% of the total variance in twentieth century October-March PNW climate data even in this best-case scenario about 70% of the region's winter climate variance remains unexplained. There are indications that both improved climate modeling and climate diagnostics will allow for predictions that reduce fraction the of unexplained climate variance (Higgins et al. 2000). The exciting message from recent successes in climate prediction is that forecasts associated with major climate events - like the El Niño of 1997-98, and the La Niña event of 1998-2000 can skillfully predict shifts in the odds for realizing distinct climate

conditions (e.g., wet vs. dry, or cool vs. warm) in select regions. As far as seasonal to interannual climate variations are concerned, the PNW is situated in one of the more predictable parts of North America, with the added bonus of having an amplified response in the region's water cycle to the most predictable swings in Pacific/North America winter climate.

# Suggested references and Web sites

Barnston, A. G., A. Leetmaa, V. E. Kousky, R. E. Livezey, E. A. O'Lenic, H. Van den Dool, A. J. Wagner, and D. A. Unger. 1999. NCEP forecasts of the El Niño of 1997-98 and its U.S. Impacts. *Bulletin* of the American Meteorological Society **80**:1829-1852.

Battisti, D. S. and E. S. Sarachik. 1995. Understanding and Predicting ENSO. *Reviews of Geophysics* **33**:1367-76.

Dettinger, M. D., D. R. Cayan, and K. T. Redmond. 1999. United States streamflow probabilities based on forecasted La Niña, winter-spring 2000. *Experimental Long-Lead Forecast Bulletin, Center for Land-Ocean-Atmosphere Studies* **8**(4): 57-61.

Gershunov, A. and T. P. Barnett. 1998. Interdecadal modulation of ENSO teleconnections. *Bulletin American Meteorological Society* **79**:2715-2725.

Hamlet, A. F. and D. P. Lettenmaier. 1999. Columbia River streamflow forecasting based on ENSO and PDO climate signals. *American Society of Chemical Engineers Journal of Water Resources Planning and Management* **125**(6):333-341.

Hamlet, A. F. and D. P. Lettenmaier. 2000. Long-range climate forecasting and its use for water management in the Pacific Northwest region of North America. *Journal of Hydroinformatics* **2**(3):163-182.

Hare, S. R. and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* **47**:103-145.

Higgins, R. W., A. Leetmaa, Y. Xue, and A. Barnston. 2000. Dominant factors influencing the

seasonal predictability of US precipitation and surface air temperature. *Journal of Climate* **13**:3994-4017.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**:1069-1079.

Rasmussen, E. M., and T. H. Carpenter. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* **110**:354-384.

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## **Climate Impacts on the Natural Resources of the Pacific Northwest**

By Amy K. Snover and Philip Mote

## Background

Natural resource-dependent such farming. activities. as hydropower production, or timber management, perpetually face the challenge of coping with uncertainty in what benefit or damage the climate will bring. Many other industries that are affected by climate variations, such as construction or energy purveyors, could also benefit from advance knowledge of future climate conditions. Recent scientific climate advances in seasonal forecasting now provide a glimpse of what the climate might bring in the next 3-12 months, especially in the Combined western U.S. with enhanced understanding of the effect climate variations have on key natural resources, these forecasts can enable natural resource managers, among others, to make better-informed decisions, often at longer lead-times than those they could make only a couple years ago. Looking to the future, there is a growing consensus among scientists that Earth's climate is changing in ways unprecedented in human history, raising the prospect that managers will perpetually be adjusting to new conditions. Recent advances in climate impacts science enable us to "translate" now projections of global warming to place-specific, regional-scale information about likely changes in climate and their impacts on natural resources.

The Climate Impacts Group (CIG) at the University of Washington performs trailblazing research in these areas, studying climate fluctuations and their effects on the natural resources of the Pacific Northwest. CIG identifies

how fluctuations in climate affect the water resources, forests, fish, and coasts of the Pacific Northwest through interdisciplinary (PNW) research combining the expertise of researchers in atmospheric sciences, hydrology, forestry, fisheries, coastal management, economics, and other social sciences. In addition to its research activities, CIG strives to enhance the resilience of regional activities to changes in climate by providing regional managers with the information and tools required to better incorporate an understanding of climate and its impacts into resource planning and management processes. To this end, CIG develops improved climate and resource forecasting methods and actively facilitates the transfer of this information from the research context to one of practical resource management applications. Users of this information become better equipped to minimize the losses and maximize the benefits associated with natural and humancaused variations in climate.

CIG has developed a detailed understanding of the pathways through which climate variations affect natural and human systems, based on a comprehensive study of the past – of how actual climate variations have affected important systems in the PNW. This knowledge provides a solid basis for projecting the consequences of future climate variations. The components of this approach include:

1) Examining past climate variations and their impacts on natural systems in order to understand the consequences of natural – and, in many cases, predictable – climate variations for important natural resources. This enables us to answer such questions as: How does El Niño affect summer Columbia River streamflow? How does PDO change the likelihood of forest fires? In summary, our results have indicated that the summertime streamflow in the Columbia River is decreased by  $\sim 10\%$  on average during El Nino years. Forest fires tend to be more frequent during warm phases of the PDO and less frequent during cool phases of the PDO.

2) Examining the impacts of these past variations on the human systems that manage and depend on these resources. *How does El Niño influence availability of irrigation water supply for wine grapes in the Yakima Basin?* We have found that the reliability of irrigation water supply in the Columbia River basin (of which the Yakima is a sub-basin) decreases during El Nino years

3) Working to increase the adaptability of natural resources management. For example, we have developed new forecasting methods and specific applications of hydrologic forecasts for PNW water resources management. How far in advance can winter snowpack be predicted? Recent advances in ENSO forecasting enable us to predict wintertime snowpack in the Columbia Basin 6-9 months in advance.

4) Using the lessons learned in steps 1-3 to evaluate the likely consequences of climate change for **PNW** natural resources and associated human systems and evaluating the vulnerability of both to projected changes in climate. What does global warming mean for reliability of *future hydropower production?* Our studies indicate that By the 2040s, the reliability of both firm and non-firm

hydropower production in the Columbia basin is projected to decrease significantly.

CIG focuses its work on the United States' Pacific Northwest, defined as the states of Washington, Oregon and Idaho and all of the Columbia River basin (Figure 1). The Pacific Northwest region has a great diversity of ecosystems, from desert to lush rain forest to alpine meadows, and has long been rich in natural resources such as timber, fresh- and saltwater fisheries, and productive agricultural lands. (Coastal waters in the PNW are among the most productive in the world.) The region is divided climatically, ecologically, economically, and culturally by the Cascade Mountains. The wetter lowlying areas west of the Cascades hold three quarters of the region's population, concentrated in the metropolitan areas of Tacoma-Seattle-Everett along the Puget Sound coast, and Portland at the confluence of the Willamette and Columbia Rivers. Manufacturing, trade and services dominate the economy west of the Cascades, while agriculture is much more important east of the Cascades thanks to irrigation, fertile soils, and abundant sunshine.

In common with much of the American West. the **PNW** experiences huge seasonal fluctuations in precipitation, with low precipitation in summer and high precipitation in winter. Storage of water in reservoirs and as snow in the mountains provides water during the dry summers, supplying the region's ecosystems, agriculture, cities, and hydropower.

### Key findings

Natural climate variations play a predictable role in influencing PNW natural resources. Understanding of this role, combined with recent advances in

#### climate forecasting capabilities, can be used to benefit those whose profits depend on natural resources or on advance knowledge of climate conditions.

The climate of the PNW is strongly influenced by atmospheric circulation patterns, especially those connected with the Pacific Ocean. There are two main patterns of Pacific climate variability: the Pacific Decadal Oscillation (PDO) and the EL Niño Southern Oscillation (ENSO). The PDO is a pattern that reverses on a 20-30 year timescale and is dominant in the North Pacific; naturally, the adjacent regions of North America see the greatest effects of this variation in climate. ENSO, which recurs on a 2-7 year timescale, is dominant in the tropical Pacific but exerts considerable influence over the North Pacific and North America too.

Recent advances enable scientists predict **ENSO** up to to approximately one year in advance. Skillful prediction of ENSO was made possible by the deployment of a system of monitoring buoys that measure environmental conditions (including winds, air and sea temperatures, and currents) in the tropical Pacific, called the Tropical Ocean Global Atmosphere-Tropical Atmosphere Ocean (TOGA-TAO) Array. Observations made by this system are sent via satellite to NOAA's Pacific Marine Environmental Laboratory where they are then made available to the public via the World Wide Web. Forecasts of U.S. climate based on ENSO conditions are available with a thirteen-month lead-time. In contrast, the mechanisms causing the PDO are not currently understood: with the result that there is little demonstrated skill in predicting PDO variations. Even in the absence of a theoretical understanding, however, PDO climate information can be Figure 1: The Pacific Northwest region defined by the CIG.



used to improve season-to-season and year-to-year climate forecasts for the PNW. The strong tendency of the PDO for multi-season and multiyear persistence means that simply assuming persistence of the current state of the PDO provides some skill in predicting winter climate anomalies in the PNW.

Like a quarterback calling one of two main types of plays, PDO and ENSO each tend to push PNW climate toward one of two main patterns: cool-wet or warm-dry. The cool-wet and warm-dry patterns of PNW climate each have a different set of impacts on the region's natural resources (see Figure 2). When winter conditions are cool and wet, the region tends to experience deeper than average snowpack, which results in higher than average spring streamflow and wetter than average soil moistures in the spring and summer. Flood risk increases and likelihood of drought decreases. As a result, there is more water for both natural uses (salmon in the freshwater stage of their life cycle, trees going through their spring



Figure 2: Primary patterns of winter and spring climates in PNW.

growth) and human uses (irrigated agriculture, hydropower, municipal water supply). Cool-wet conditions tend to result in above average salmon survival and forest growth (at lower elevations) and below average risk of forest fires. When winter conditions are warm and dry, the region experiences the opposite effect in each case (below average snowpack, summertime streamflow, and flood risk; increased likelihood of drought; below average salmon survival and forest growth; above average risk of forest fires).

these Because impacts on regional resources are linked to ENSO and PDO (via their dependence on the cool-wet/warmdry pattern of PNW climate) enhanced climate forecasting capabilities can be exploited to provide new capabilities in resource forecasts. In other words, our understanding of the impacts of climate variations on PNW natural resources can be used to translate *climate* forecasts into *resource* forecasts.

Using ENSO and PDO information to predict PNW climate provides probabilistic estimates of winter and spring temperature and precipitation anomalies at lead times of one month to a year. Tendencies for temperature and precipitation anomalies to sometimes covary in predictable ways offers a means for making skillful predictions for snowpack, streamflow, and other resources sensitive to the water cycle. Based on expectations for La Niña to persist through the winter and spring of 2000, researchers issued the first ever streamflow forecast for river basins across the entire U.S. Likewise, the Climate Impacts Group has developed a methodology for extending the lead time of water resources forecasts for the Columbia Basin by selectively resampling the historic climate record based on forecasts for ENSO and PDO.

These developing capabilities in climate and resource forecasting can free natural resources management and planning from both (1) the need to base decisions on an evaluation of past conditions (an assumption of climatology) and (2) the need to defer decisions until real-time measurements of actual conditions are available. Using ENSO and PDO to predict PNW climate (and consequences for resources) can narrow the window of expected future conditions and do so at leadtimes advantageous for planning. Users of this information become better equipped to minimize the losses - and maximize the benefits associated with natural and humancaused variations in climate when early clues about climate anomalies can improve the management of a resource. For example, CIG has estimated the economic value of using seasonal forecasts in managing the Columbia River system. Fall hydropower production could be increased, with almost no impacts on other water resource objectives, increasing average revenues by roughly 4% (\$150 million).

Human-caused climate change ("global warming") will have significant effects on PNW climate as early as the 2040s. The impacts of climate change will be similar to those observed during warm/dry years in the current climate - characterized by reductions in mountain snowpack and in spring/early summer river run-off. These changes will stress the region, exacerbating current areas of resource shortfall and conflict. In many cases, the severity of the consequences of climate change for social and industrial systems will depend on the decisions and investments of today.

The natural resources of the Pacific Northwest - the region's water, forests, fish and coasts - will be affected by natural climate variability and regional manifestations of global warming in ways we can partially foretell. Despite remaining uncertainties about the specific ways climate change will manifest itself in the Pacific Northwest, we can describe the nature of some key impacts with sufficient confidence to advise action.

What can we see in the future of the PNW? Warmth. Eight global climate models all show substantial increases in temperature over the PNW by the 2020s, increases that are well outside the natural range of climate variability observed in the twentieth century. The models suggest small changes in yearly average precipitation, but seasonal trends that are larger and more consistent: nearly all the climate models show wetter winters and drier summers in the future. The most significant consequence of these projected changes in climate, one we can be fairly sure will happen, is that snow cover will shrink in coming decades, with lower elevations losing snow first. During the winter, warmer temperatures will mean that precipitation falls less as snow and more as rain, reducing the amount of water stored naturally for later use.

Less snow means earlier and lower spring runoff, and less water available for summer use (this was the case in 1992, for example). Peak flows from spring snowmelt would happen earlier as a result of climate change; about one month earlier for the Columbia River. The increases in winter precipitation, combined with increases in the amount of precipitation that falls as rain rather than snow, will result in higher winter runoff, increased river flow, and a higher likelihood of floods, mostly in lower elevation river basins.

The future, therefore, probably holds increases in winter flooding and - paradoxically - increases in summer drought. How will the region fare? Droughts, like the 1994 drought in the Yakima Valley, cause bitter disputes and huge economic losses for those who depend on summer water and do not receive it. In a future with drier summers, such conflicts and losses will become more frequent; droughts of this magnitude are projected to be two to four times as frequent by the 2040s as a result of climate change. Furthermore, vigorous population growth in the PNW will increase the demand for water (especially west of the Cascades) at a time when climate change is squeezing the existing water supply.

There are strong indications that global warming will add to the already long list of human-caused problems that now plague PNW salmon. Both extremely low summer streamflow, which is likely to occur throughout the Northwest, and extremely high winter streamflow, which can occur on the west side, are deleterious to salmon. These two extremes are each more likely to occur as a result of all climate change scenarios. Trends toward warmer temperatures in streams, estuaries, and the coastal ocean, combined with these changes in streamflow – a likely byproduct of climate change – may push already threatened salmon stocks over the brink to extinction.

The warmer winters projected under climate change would also pose problems for PNW forests. Less snow means drier soil, making it harder for seedlings to get started and harder for bigger trees to grow (again, except at high elevation). But perhaps the biggest threat to forests is that posed by the possible increases in "disturbances", wildfire and pests in particular, which can damage or kill large sections of forest and "wipe the slate clean" for a new forest. In a changing climate, there may not be any nearby trees suitable for establishing a new forest; the slate may stay clean in some areas. This is more likely to occur east of the Cascade Mountain range because of the naturally dry conditions there.

To understand how climate change would affect the coasts of the Pacific Northwest, we must consider not only changes in temperature and precipitation, but also future changes in sea level and ocean circulation. Both the physical landscape and the ecosystems of the coasts will be affected by climate change and rising sea level. Changes in wave direction may increase coastal erosion, as often happens during El Nino events. Several areas of the coast, like southern Puget Sound (near Olympia), are already at great risk of inundation; this risk would increase as sea levels rise. Temporary coastal flooding also occurs near the mouths rivers like the Skagit of in Washington when a river flood coincides with high tide. Increased precipitation winter (which is consistently projected by climate models) will probably lead to more frequent landslides: recent wet winters have shown that thousands of homes are at risk from landslides

around Puget Sound and on the Oregon coast. These risks pose important challenges to governments and businesses in vulnerable areas along the coast and should be considered as part of planning for any new coastal commercial and residential development. Climate change is also likely to cause changes in biological systems - damaging or inundating wetlands and influencing the invasion of exotic species like Cordgrass, which was introduced in the 1890s from Chesapeake Bay, and flourished in the warm spell of the 1980s.

Organizations that use knowledge of past climate conditions to guide decisions, such as an energy company that uses historical winter conditions in their calculations of future hydropower production capacity, must no longer assume that the climate of the future will be the same as the climate of the past. Climate change projections imply that future conditions of Pacific Northwest temperature, snowpack, and streamflow are likely to be substantially different from those observed in the past, as early as twenty years from now. Likewise, the future likelihood of droughts, floods, and forest fires may be noticeably increased.

Prudent management will account for these altered risks. Where there is potential for harm to a business or industry, steps taken now to reallocate investments or rethink a strategy could increase a firm's resilience. Alternately, the advantage may be gained by those who prepare for these changes. For example, owners of ski areas at low elevations in the Pacific Northwest - which would be hurt by future loss of snowpack - could minimize losses by foregoing investments in upgrading infrastructure. Owners of higher elevation ski areas that would not see a loss in snowpack could begin investing in improvements now to take advantage of a future relative advantage.

Decisions of investment and business growth and development rely on assumptions about future demographics, market trends, and the characteristics of the future regulatory and competitive environments. To the degree, which variations in climate affect these or other key components of planning, our current ability to predict climate variations 6-9 months in advance, and to project major changes in regional climate over the next 20-40 years, can provide a useful tool.

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#### Applications of Climate Forecasts in Natural Resource Management: Implications for Industry

By Daniel Huppert, Janne Kaje, Alan F. Hamlet, Edward L. Miles\*, and Amy K. Snover

#### **Introduction**

The Climate Impacts Group enable (CIG) aims to the of development resource management and planning strategies that are resilient to climate variations. One method of accomplishing this is to provide regional resource managers and decision-makers with information useful about the connections between the regular patterns of Pacific Northwest (PNW) climate variability and their regional impacts, since an understanding of the natural rhythms of variation is essential for successful management of natural systems. Furthermore, because many of these rhythms of climate variation can currently be forecasted months in advance. understanding connections the between climate and impacts can provide managers with tools for better informed, longer term planning.

In this article, we examine the implications of what we know about the regular patterns of climate variability in the Pacific Northwest (PNW) for natural resource planning and management in the region. To what degree do PNW natural resource managers recognize and plan for predictable patterns of climate impacts? What benefit could be obtained by an improved use of seasonal climate forecasts and how could seasonal forecasts themselves be improved?

To begin our discussion, it is important to differentiate between climate and weather forecasts. Weather forecasts seek to predict the exact state of the atmosphere at a specific time and place. Climate forecasts, on the other hand, seek to predict the statistics of the atmosphere for a region over a specified period of time.

Climate forecasts also can address the expected probabilities for extreme events (floods, freezes, blizzards, hurricanes, etc.), and for the expected range of climate variability. Climate variability refers to the range of atmospheric states that a region experiences in a specified window of time and can be quantified with probability distributions for measures of interest (daily total rainfall, seasonal mean snowfall, daily high/low temperature, etc.).

Because the mechanisms causing PDO not currently the are understood. there is little demonstrated skill in predicting PDO variations. Even in the absence of a theoretical understanding, however, PDO climate information can be used to improve season-to-season and year-to-year climate forecasts for the PNW. The strong tendency of the PDO for multi-season and multiyear persistence means that simply assuming persistence of the current state of the PDO provides some skill predicting winter climate in anomalies in the PNW.

Hemispheric scale climate variations associated with the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) exert important influences on PNW climate, especially during October through March. At the seasonal to inter-annual time scale, skill in monitoring and predicting variations in the ENSO cycle has been demonstrated for nearly a decade (Battisti and Sarachik 1995).

The predictability of regional climate and the quantification of its impacts on natural resources allow the development of impacts, or resource, forecasts. In other words, our understanding of the impacts of climate variations on PNW natural resources can be used to translate *dimate* forecasts into *resource* forecasts. In contrast to climate forecasts, resource forecasts describe the expected impacts of climate on a natural resource, such as fish stocks, forest harvests, or streamflow.

Because ENSO and PDO exert important influences on PNW climate, we focus on these two climate patterns as key elements in skillful PNW making climate forecasts. Using ENSO and PDO information to predict PNW climate therefore provides probabilistic and spring estimates of winter temperature and precipitation anomalies at lead times of one month to a year. Furthermore, tendencies for temperature and precipitation anomalies to covary in predictable ways offers a means for making skillful predictions for snowpack, streamflow, and other resources sensitive to the water cycle. Figure 1 briefly diagrams the connections made in translating **ENSO** information into climate forecasts for use in the Pacific Northwest. A forecast of tropical sea surface temperatures indicates the upcoming ENŜO state (e.g., El Niño, La Niña, or ENSO neutral) of the tropical Pacific; the regional climate forecast uses this information to project winter climate conditions in the PNW: and the regional resource (or impacts) forecast translates this

information into projected impacts on regional natural resources.

Most decision-makers are concerned with climate impacts or with resource forecasts rather than with the climate forecast itself. When we contrast resource forecasts that are based on observations of antecedent conditions to those that are based on forecasts of antecedent conditions. we differences find in forecast uncertainty and lead time. As we look closer, we discover the trade-off between lead-time and uncertainty. The lead-time of a resource forecast can be increased by increased reliance forecasts of antecedent on conditions. However, each step in the forecast chain involves an additional amount of error; these errors are compounded at each step reducing the ultimate predictive utility of a climate forecast. So it is necessary to ask: Which resource forecasts would benefit from use of longer lead-time climate forecasts? Would such forecasts be sufficiently accurate for operational needs? These questions frame the topics tackled in this article.

We begin the article by mapping generation the current and distribution of climate and resource forecasts among water resource managers in the Columbia River Basin. Next, we examine the potential utility of incorporating more sophisticated ENSO/PDObased resource forecast information into management decisions, using a case study approach. We analyze the potential utility of this type of forecast for the Columbia basin hydroelectric power production sector. Finally, we discuss the key policy and institutional issues that must be addressed before improved climate forecasts will be widely used in regional resource management.

# *Production, distribution, and use of forecasts in the Columbia River Basin*

Many users and groups in the Columbia River Basin depend on specific patterns of water supply and plan their crucial activities based on expectations of certain timing in supply streamflow. water or Organizations concerned with hydropower production, fish and wildlife management, water quality and watershed management, flood control, irrigation, municipal and industrial water supply, and river navigation all have activities or responsibilities that are affected by the amount and timing of water in the Columbia River. In 1996, CIG undertook a study of water managers in the Columbia Basin, in order to determine the degree to which they utilized either climate or resource (i.e., snowpack or streamflow) forecasts in their planning and decision-making process. The results of this study indicated a complex web of interactions and communications among the various forecast and user groups that make the path between climate forecaster, resource forecaster, and forecast user both redundant and obscure. This characteristic has significant implications for those seeking to improve the use of forecasted information in regional decisionmaking and for those interested in introducing new forecast information into the system.

A wide variety of governmental units produce either climate or resource forecasts which are potentially useful to managers of the water resources of the Columbia River: the National Center for Environmental Prediction (NCEP) of NOAA, the International Institute for Research Climate Prediction. the NOAA River Forecast Center (RFC) (Portland, Figure 1: Diagram of the connections made in translating ENSO information into climate forecasts for use in the Pacific Northwest.



Oregon), the Natural Resources Conservation Service (NRCS) (Portland, Oregon), the U.S. Army Corps of Engineers, and Oregon Climate Services (Corvallis, Oregon). The basic climate forecast for the region is issued by NCEP's Climate Prediction Center (CPC). Although this forecast underlies all of the climate resource forecasts or produced by other entities, it is not the primary forecast used directly by water managers in the region.

When CIG surveyed regional water managers in 1996, we found that most water managers used the River Forecast Center's forecasts for spring and summer streamflows to guide their planning and decisionmaking; see Table 1 for the forecast use rates reported by water managers. The River Forecast Center is the primary regional source for streamflow forecasts (which it coordinates with NRCS, the Corps of Engineers, and the Bureau of Reclamation), although the forecasts may be distributed via the Army Corps of Engineers, NRCS.

Washington State Department of Ecology, or Oregon Climate Services. The NWRFC is guided by its mission to address one of the region's primary vulnerabilities, flooding. It provides river stage forecasts for the Columbia River (and other rivers in the region) that are tailored to flooding, as well as forecasts for navigation, recreation, seasonal and extended water supply concerns. It also provides flood guidance, drought bulletins, and support of flash flood warning systems. While some managers that we interviewed did not use forecasts at all, those that always used the NWRFC did product. It is the primary forecast source for Columbia River water managers.

Та	ble	1:	Rank	of Clim	iate	Produ	ct Source	s
by	Stu	dy	Partic	cipants (	(Ca	Illahan	1997).	

Source of Climate Information	Number (%) of Respondents Receiving Products ( <i>n</i> = 17)		
Northwest River Forecast Center (NWRFC)	12	(71%)	
Climate Prediction Center (NCEP/CPC)	9	(53%)	
Army Corps of Engineers (ACOE)	9	(53%)	
Natural Resources Conservation Service (NRCS)	6	(35%)	
National Weather Service (NWS)	5	(29%)	
Bureau of Reclamation (BOR)	3	(18%)	
US Geological Survey (USGS)	3	(18%)	
Washington State Department of Ecology (WDOE) (intermediary)	3	(18%)	
Oregon Climate Service (OCS) (intermediary)	2	(12%)	
Private Consultant, such as Weather Net (intermediary)	2	(12%)	

Numerous public and private services, such as Oregon Climate Services (OCS), the Washington State Department of Ecology (WDOE), and Weather Net, provide a synthesis of available forecasts. OCS provides climate information to the region in monthly reports, often including the CPC forecasts of ENSO events, and the WDOE puts out a monthly water supply newsletter for the state

These types of groups act as conduits of forecasts, but in these cases, the original source of climate forecast is unknown to the user. This is a well-understood fact of life for the forecasters, but it bears mention because of the anonymity that it imparts to their achievements. For example, Congressional a representative once stood up during a Congressional meeting and announced that he did not need the National Weather Service because all he had to do was turn on the television to get the weather. This gap also makes it difficult for users to contact the source that can provide them with interpretation or more detail on the climate forecasts.

The number and variety of sources of climate information and streamflow forecasts for the Columbia basin can be overwhelming to the unfamiliar user, yet there is also a great degree of overlap and redundancy among them. In each interview, we asked the managers to tell us where they got their forecasts. The flow of forecast distribution, with respect to formal and informal use, is diagrammed in Figure 2. The central source for the water management sector in the Columbia River Basin management system is the NWRFC. Any improvements to the forecasting system would therefore need to involve the NWRFC.

Figure 2: Diagram of the flow of forecast distribution, with respect to formal and informal use.



Forecast information is also disseminated at monthly meetings of Columbia River Basin the Management Group, which has a Forecast Committee. This committee can facilitate introduction of the climate forecasts to the system, relying on the NWRFC product. In 1996, however, the NWRFC did not fully embrace the ENSO-based longterm forecasts because it believed that ENSO did not provide a strong signal for predictable climate variability in this region (NWRFC 1996). As we know from Chapter Four, however, knowledge of ENSO can be quite useful for regional water resources planning.

Despite the high potential utility of climate forecasts for hydropower operations, flood control, freshwater fisheries, irrigated agriculture, municipal and industrial water

supply, water quality and watershed management, and river navigation, the CIG found that the actual utilization rate of climate forecasts (i.e., CPC projections of temperature and precipitation) by PNW water managers was quite lowMore than half of the water resource managers surveyed did not use climate forecasts at all in their planning or climate decision-making. When forecasts were used, they rarely role prominent in played а operational decisions. Many managers used climate forecasts informally as background material, but forecasts were rarely brought to the forefront of decision-making (Callahan 1997; Callahan et al. 1999).

CIG also examined (in 1996) the pathway of communication between the forecasters and the users of the forecasts and found very little direct communication and feedback between the two groups. For the use of climate forecasts to grow and to applications for develop these products, feedback and dialogue between these groups must occur on a regular basis. Managers expressed a interest reciprocal strong in education and dialogue between forecasters and the user community during the interviews.

Current climate forecasts contain considerable amount а of information that could potentially be put to use by natural resource managers across the PNW. The short-term forecasts are those that predict conditions up to 30 days in advance. These all relate to acute conditions that may require emergency responses from state and federal agencies. They are also of interest to insurance companies because they focus on extreme events like winds, coastal storm surges, and medium-term forest fires. The forecasts contain predictions for a 30-day to one-year time frame and therefore emphasize changes in seasonal/interannual conditions concerning tropical sea surface temperatures (with implications for ENSO events), winter precipitation (with implications for snowpack), and droughts. The long-term forecasts, i.e., those beyond one year, emphasize trends in global warming and/or changes in the PDO.

The potential utility of shortterm forecasts of acute conditions is obvious. Many actions that could be informed by short-term forecasts are linked to emergencies, except in the case of managing fisheries resources, where short-term operational targets related to the timing of fishing seasons and hatchery releases are indicated. Medium-term forecasts relate primarily to operational actions, except in the case of managing forest resources, where planning is involved. In the longterm category, the major emphasis is on long-term planning. As we move from the application of short-term, to medium- and long-term climate forecast information, we shift from tactical to strategic decision-making.

# Measuring the economic value of climate forecasts

When improved climate information forecasts or appropriately support management decisions, i.e., decisions about how to manage a resource, the benefits associated with these decision processes can potentially be increased better managing the by risks associated with climate uncertainty. When these decision processes guide activities with financial implications, the economic value of those activities may also be enhanced. Generally, the value of a forecast is identified as this increased value stemming from more informed decision-making. The value of a specific forecast depends upon the specific decision context and degree to which it matches decisionrelevant time and space scales.

Further, the economic value of the forecast will depend crucially upon the accuracy and specificity<sup>1</sup> of the information contained in the forecast.

Two distinct approaches to evaluating use of climate the forecasts descriptive and prescriptive studies - have been developed (see Stewart 1997). The "descriptive study" attempts to discover how decisions are being made, to determine the role of forecasts in those decisions, and to evaluate how the decision-makers might use better forecasts. The emphasis of the descriptive study is to reflect accurately the context of decisions and the institutional limits of the decision systems. A new forecast is assessed by constructing realistic scenarios that mimic, for example, the bureaucratic behavior or inertia of decision processes that respond to multiple objectives. The outcome of the descriptive study will include a realistic-looking description of who would do what, when, and how in response to a climate forecast. A "prescriptive study" of forecast value will sacrifice detail and richness in the description of the decision process in order to develop a tractable quantitative model of

<sup>&</sup>lt;sup>1</sup> In fact both are important characteristics of forecasts. Use of a forecast that is very specific (i.e., indicates a small range of values) but is inaccurate (i.e., the actual outcome is frequently outside the forecast range of values) will frequently result in erroneous decisions. On the other hand, a forecast that is not specific enough to eliminate some of the potential outcomes with some degree of certainty is not very helpful in guiding management decisions. The accuracy and specificity of a particular forecast are directly linked and can be adjusted to a certain extent to meet specific risk assessment needs (see Hamlet and Lettenmaier 1999a).

decisions. The prescriptive study emphasizes simplified models of decision systems that enable the analyst to develop optimal decision rules using forecast information. The decision problem can be divided into four basic parts:

- The climate events that affect outcomes relevant to decision objectives (e.g., excessive rainfall causes flooding which threatens lives and property);
- Specific known consequences for each action-event pair (e.g., damage due to flood);
- The actions available to the decision maker (e.g., evacuate residents, build levees); and
- The frequencies of specific climate events, and the likelihood that such events are accurately forecasted.

Given each of these, the prescriptive model seeks an optimum decision rule (a set of forecast-action pairs) that maximizes the expected economic value, given the constraints and available actions.

Whether assessed by the descriptive or prescriptive approach, the value of a forecast is reckoned as the increase in economic value<sup>2</sup> of the decision outcomes that can be expected when the decision-makers incorporate the new information in their decision process. The outcomes are quantified in terms of products or hydroelectric consequences, like power or agricultural crop production, flood damage, etc. The increased value is the value of outcomes achieved after incorporating the new forecast information in the decision process minus the value of outcomes with the old climate information. The "old

information" could be a naïve prior probability distribution (e.g., uniform probabilities across future events), an historical frequency distribution (e.g., equals future likelihood past frequency), or a less accurate forecast having a larger variance or error rate. By comparing outcomes across various forecasts, the economic assessment provides а useful indicator of value for improved forecasts. Finally, the value of the forecast can be compared to the cost of developing climate forecasts in a benefit-cost decision framework.

Descriptive studies will tend to find that organizations do not know how to use new information, and that organizations adapt slowly and haltingly. Furthermore, by focusing on existing decision rules and the limited understanding of a small number of key individuals involved in the current management structure, descriptive study the may inappropriately discount the potential for new information to transform the organization and its decision rules. Hence, the descriptive study is likely to underestimate the value of forecasting. improved CIG's of the assessment ability of institutions in the Columbia Basin to use existing climate information is an example of a descriptive study that showed an ENSO forecast to provide almost no utility to those institutions. As we shall show below. however, these forecasts could be applied quite profitably towards hydropower production.

On the other hand. the prescriptive study tends to ignore the importance of organizational behavior and dynamics in the use of information. The prescriptive study prescribes the optimal decisions considering without how the organizational context limits quick adaptation. Hence, the prescriptive study is likely to overstate the social value of improved forecasts, as it ignores behavioral limitations to decisions that may reflect social conventions or cognitive limitations of decision-makers. In making economic assessments, it can also be very difficult to estimate the true costs of making institutional changes associated with a prescriptive methodology.

Studies of forecast value can incorporate elements of both descriptive and prescriptive approaches. In prescriptive studies, the specification set of actions available, information sets, and relevant outcomes and values rely on essentially descriptive information about the decision context. And even in descriptive studies, the analyst must consider reasonable responses to new information that depart in some way from observed, standard behavior of the decision-makers and organizations. In the case studies that follow, we pursue a middle course that uses heuristic optimization within decision models having explicit but simplified decision rules. We limit the decisions and climate forecast use to comply with known objectives and institutional limitations of the decision-makers. The descriptive elements are based upon extensive reading, discussions and conversations with people involved in the natural resource management decisions modeled. particularly hydroelectric power planners and fishery managers. By taking this approach, we hope to come closer to a realistic assessment of climate forecast values than would either a purely descriptive or prescriptive approach.

<sup>&</sup>lt;sup>2</sup> The economic value of the forecast must be measured over time, i.e. over a range of forecast-action pairs.

#### CASE STUDY: The value of long-lead streamflow forecasts for non-firm hydropower production in the Columbia River Basin

The operational streamflow forecasts for the Columbia River basin described in Section 0 are all based on statistical relationships between observations of descriptive snowpack) variables (e.g., and runoff volumes. The summer primary limitation of this method is that the forecast for water year (October-September) planning is not available until January (Lettenmaier and Garen 1979). Recent advances in experimental streamflow forecasting techniques, based on long lead climate forecasts, provide opportunities to extend the lead-time of streamflow forecasts by roughly six months, providing useful forecast skill before any winter snowpack measurements are available (i.e., in June preceding the water year). In this case study (condensed from Hamlet et al. 2001), we describe the new forecast technique and examine the potential utility and economic value of this type of long-lead streamflow forecast for production of non-firm hydropower in the Columbia River basin.

# Overview of power generation and marketing practices in the PNW

The delivery of electrical energy to consumers is achieved through a three-stage process of generation, transmission to market areas, and distribution to end users such as industrial and residential consumers. The two most common methods of electrical energy generation are thermal generation (typically steam plants that burn coal or other fossil fuels, nuclear steam plants, or natural turbine gas-fueled combustion plants) and hydroelectric generation, which uses the stored potential energy of water in reservoirs to produce electricity via water turbines and generators installed in the dams. Hydroelectric plants have very low maintenance and operating costs relative to thermal plants, primarily because there are no fuel costs. As a result, there is a strong incentive to use the hydroelectric portions of the generation system as much as possible to reduce operating costs.

Because electrical energy cannot be stored economically in appreciable quantities. electrical distribution systems are designed to balance demand and supply in real-time, employing a variety of techniques to monitor the demand for electricity. The instantaneous demand for electricity is termed the load. If the power generation system is to avoid failures such as brownouts or generation blackouts. the total capacity must exceed the instantaneous peak load with some margin of safety.

Unlike thermal generation plants, hydroelectric systems are directly limited by natural variations in water availability. which affect the instantaneous, seasonal, and annual average generation capabilities. These limitations have led to special terms hydropower associated with generation and marketing. Firm energy is the largest amount of energy that could be produced by the hydro system during the lowest streamflow sequence on record. Historically, firm energy has been sold on long-term contracts and at relatively high prices. Non-firm energy, on the other hand, has traditionally been sold on shorterterm contracts, or as interruptible power, at lower prices, during times of the year when surplus water is frequently available (typically spring and early summer in the PNW). When water is available, non-firm power is supplied, and when the hydrologic conditions are unsuitable,

the power is not supplied. Industries with high energy needs in the PNW, for example aluminum smelting, have traditionally been eager consumers of non-firm power. Deregulation of the wholesale electricity market has significantly altered the traditional framework for marketing non-firm hydroelectric power. Instead of the traditional framework of interruptible industrial sales focused in spring, energy is sold in the deregulated market in short term contracts in the relatively volatile spot market -Before deregulation, non-firm power was typically sold at about \$15 per MW-hr. After deregulation, spot market prices have been as high as \$1300 per MW-hr during periods of high demand (Karier 2000). These new marketing decision processes are designed to sell non-firm energy when prices are highest. This is opposite to the traditional marketing structure for non-firm hydropower in the Columbia basin, which focused non-firm energy production at the time of year when demand and prices were lowest.

About 77% of the electricity used in the Pacific Northwest Region region defined as Oregon, Washington, Idaho, the parts of Montana that are west of the Continental Divide and the parts of the states of Nevada, Utah and Wyoming that are within the Columbia River basin - is supplied by hydropower plants (BPA 1991), most of them within the Columbia River Basin. This accounts for the low cost of power in the PNW, which is on the order of five cents per kilowatt-hr for retail residential consumers. Note that average costs of electricity in Idaho, Washington, Oregon are ranked first (cheapest), second, and sixth in the nation, respectively in 1998 (EIA 2000). The Pacific Northwest Region has a total of 40,500 megawatts (MW) of installed

generating capacity, distributed over 450 individual plants. Some of these plants are less than a megawatt in size, and others like Grand Coulee Dam's hydroelectric plant are gigantic, with a rated capacity of 6500 MW. The PNW power plants are linked with the facilities in British Columbia, California, and the Southwest<sup>3</sup> through tie-lines that allow the transfer of power. With the broader Western regional perspective, hydropower in the Columbia basin accounts for a significant portion of the total generating capacity.

The strong seasonal differences in river flow in the snowmelt dominated Columbia River present challenges to the hydropower industry. Most of the precipitation falls in the winter months, much of it as snow in the Cascade and Rocky ranges, and winter Mountain streamflow is low. Snowmelt occurs predominantly between April and July, resulting in high streamflows in the spring and summer. This timing unfortunate for hydroelectric is generation, because the spring period experiences the lowest seasonal power demand in the PNW. Storage reservoirs help to alleviate this difficulty by shifting some flow from spring to fall and winter, but storage on the Columbia accounts for only 28% of average annual flow, which is relatively low in comparison with other large rivers in the U.S.<sup>4</sup>

addition producing In to hydropower, the Columbia water system also provides flood control, water supply for irrigation, lake and river recreation opportunities, navigation, and flow enhancement for the protection of riverine Addressing ecosystems. these objectives multiple prevents operation of the power system to maximize hydroelectric potential. Flow enhancement for the protection of salmon, for example, requires significant releases from storage to maintain more natural instream flows during the late summer and early fall, times when hydroelectric producers might otherwise retain reservoir storage for winter energy production.

#### The Energy Content Rule Curve and current use of streamflow forecasts in Columbia Basin operations

The reservoir operating system for the Columbia River Basin has evolved to make use of streamflow forecasts that are based on observed snowpack and its statistical relationship to spring and summer streamflow. These forecasts become available starting January 1 and guide water management decisions from January-July. In the period from August-December, however, reservoir operations are managed without any forecast information. Our discussion will focus here on the Energy Content Curve (ECC), the primary reservoir rule curve<sup>5</sup> guiding hydropower production. In simple terms, the ECC restricts the use of reservoir storage for hydropower production according to the following rules: (1) The reservoir operators are not permitted to draft below the ECC for firm energy production unless all reservoirs do so in a balanced manner; and (2) operators are not permitted to draw reservoirs down below the ECC to generate non-firm energy (BPA 1991). То provide background needed for subsequent the discussion, we now describe in more detail how the ECC is constructed.

The Energy Content Curve is a composite rule curve constructed using three reservoir rule curves: the flood evacuation curve, the "assured refill" curve, and the "critical" curve, each of which is a set of guidelines for reservoir operations designed to ensure that certain objectives are met. The flood evacuation curve is designed to ensure that sufficient reservoir storage space is available for catching and retaining the high flows of April through August to prevent (or protect against) flooding. Flood evacuation requirements are fixed from August to December, and are based on streamflow forecasts in January-July. The assured refill curve tends to guide operations in August-December and is designed to ensure about 97% reliability of reservoir refill in the following summer. For August-December, it is constructed using the third lowest streamflow sequence on record; for January-July, it is constructed using forecasted streamflow (based on snowpack measurements that become available in January). The critical curve is designed to protect the system from fall and early winter overdraft of reservoirs during droughts, i.e., to ensure that the hydrosystem meets its wintertime firm energy targets. The critical curve is constructed by simulating the amount of reservoir drawdown that would occur if firm energy requirements were satisfied during the most adverse streamflow

<sup>&</sup>lt;sup>3</sup> The Western Systems Coordinating Council divides the U.S. region into 4 sub regions: the PNW, California and Mexico, Mountain states, and Arizona and New Mexico.

<sup>&</sup>lt;sup>4</sup> Compared with other rivers, the Columbia has a low ratio of storage to average run-off. On the Missouri River, dams hold up to two or three times the annual average runoff, thus allowing for greater control. See BPA et al. (1991) and (1993).

<sup>&</sup>lt;sup>5</sup> A reservoir rule curve is a series of time varying reservoir storage levels that is used to guide dam operators. A flood rule curve, for example, will specify for each month the maximum reservoir storage permitted by the dam operating plan.

sequence in the historic record (currently a portion of 1936-37).

From August to December, and during reservoir refill in May and June. the ECC is generally determined by the higher (i.e., more restrictive of use of storage) of the assured refill curve and the critical curve. In the period from Januarythe ECC generally April, is determined by the flood evacuation requirements.

The way the ECC is determined in the fall is very cautious, because an assumption of drought conditions for the following summer is built into the construction of the assured refill and critical curves. It is this aspect of the Columbia's operating plan that will be altered, in the modeling study described below, to provide an input pathway for long-lead streamflow forecasts.

#### Improvements in Streamflow Forecasting

PNW winter climate and the subsequent summer streamflow from snowmelt are linked to the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation (ENSO). Forecasts of these recurrent patterns of climate variability can be exploited to provide summer streamflow forecasts for the Columbia River basin with lead times of about 12 months (Hamlet and Lettenmaier 1999a).

The forecasting procedure begins by assigning the upcoming water year to one of six climate categories, forecasted **ENSO** based on conditions (El Niño, La Niña, or ENSO neutral) and assumed PDO conditions (cool or warm PDO, generally based on assumed PDO persistence). An ensemble of streamflow forecasts is developed using the VIC hydrology model. The hydrology model is initialized using

meteorological data associated with estimated June-September streamflows.<sup>6</sup> To create each forecast ensemble member, the model is run for the subsequent months (October-September) using historic meteorological data from a year that was in the same climate category as that forecasted for the coming water year (Hamlet and Lettenmaier 1999a; Hamlet et al. 2001). An ENSO forecast is available each month (e.g. from the National Centers for Environmental Prediction) and by June the ENSO forecast for the coming winter has demonstrable skill<sup>7</sup> and can be used to create useful streamflow forecasts for the coming water year, therefore enabling spring peak flows to be forecasted with about one-year lead time (Hamlet et al. 2001).

These ensemble streamflow forecasts, which are based on observed patterns of regional climate variability, provide information about future streamflows within the context of climate variability observed over the past 45 years or so. The Columbia River streamflow forecast for water year 2001, for example, shows a high likelihood of average flows, with a low likelihood of either strongly above or below average flows. This ensemble forecast was created using meteorological data selected from cool PDO/ENSO neutral years in the historic record

<sup>7</sup> Retrospective studies of the accuracy of current ENSO forecasting techniques are not currently available, but June forecasts of winter ENSO conditions (warm, neutral, cool) have been correct in 3 out of 4 years since 1997-1998.

based on the 2001 ENSO forecast for neutral ENSO conditions and an assumption of cool phase PDO, based on heuristic methods of identifying PDO transitions (Hamlet and Lettenmaier 1999a). The forecast made available was on an experimental basis June 9 2000. Hamlet and Lettenmaier (1999a) discuss a number of potential uses of this kind of forecasts, among them potential improvements to fall nonfirm hydropower production, which we will quantify in the following discussion.

# Use of long-lead climate/streamflow forecasts for hydropower operations in the Columbia Basin

The increases in lead time achieved by the forecasting techniques described above provide opportunities to improve the decision processes associated with the marketing of non-firm energy from the Columbia River hydro system in the fall and early winter. The long-lead streamflow (resource) forecasts are used here as a new input to a complex decision-making process, which in this case is the reservoir-operating plan for the Columbia basin.

As described above, the ECC currently restricts fall hydropower production as though the reservoir system were experiencing a critical drought. With improved long-lead streamflow forecasts, however, these restrictions can sometimes be relaxed, permitting increased nonfirm generation in years that are likely to be wet. This energy could be generated during the fall (August-December), a time when prices are typically higher than during the spring and early summer period when non-firm energy has traditionally been marketed. As will be shown, it is possible to relax these constraints on production of non-firm energy

<sup>&</sup>lt;sup>6</sup> Estimated June-September streamflow is taken from the National Weather Service Northwest River Forecast Center's streamflow forecasts. The June-September meteorological data is obtained from a year in the historical record (1948-1995) that had summer streamflow similar to that predicted.

without affecting other uses of the system, while simultaneously increasing long-term revenue from energy sales. These revenue increases are, therefore, directly derived from use of the new forecast information, rather than from altered tradeoffs between different system uses.

To relax these fall and early winter constraints in a consistent and systematic manner, a new method of constructing the Energy Content Curve can be defined, using the longlead ensemble streamflow forecasts discussed above. A flood evacuation requirement based on the lowest simulated streamflow in the forecast may be taken as an estimate of the *least* flood evacuation expected for that forecast. A new rule curve that ensures the reservoir will refill to this least flood evacuation requirement given the lowest ensemble streamflow sequence then is constructed. This new rule curve, called the *Refill to Least Flood Curve* (RLFC) then replaces the status quo ECC for August-December. The goal here is to provide more water for energy production when streamflow is likely to be high in the subsequent summer, and less when conditions are dry. while simultaneously ensuring a high likelihood of refill to actual flood evacuation targets in spring. This is achieved by the changes in the ECC for a wet year (1972 cool PDO/La Niña) and a dry vear (1987 warm PDO/El Niño) at Libby Dam. More water is made available for energy production in the wet year compared with the status quo, and less storage is made available in the dry year than in the status quo.

To simulate the economic effects of these changes, retrospective streamflow forecasts for water years 1931-1987 were used to construct a new ECC for each water year, and the monthly time step ColSim reservoir model was used to estimate energy production and revenue for the new versus status quo ECCs over this time period. (The ColSim model simulates energy production from the major storage and run of river dams in the Columbia basin, which accounts for about 55% of the total basin energy production.) Several alternative energy targets for fall and early winter were used in these simulations: alternative 1 is associated with the least aggressive marketing in fall, and alternative 5 with the most aggressive marketing targets. These alternative marketing strategies represent different amounts of energy production transferred from the traditional spring and early summer period (status quo) to late summer and fall (alternatives).

In addition, the monthly nonfirm energy targets for August-January were scaled based on the forecasted climate categories. The scaling factors were constructed so that the overall likelihood of meeting non-firm energy targets was between 90% and 95% for each climate category. The rationale here is that greater or lesser available water in August-December associated with changes in the ECC should be accompanied by a corresponding increase or decrease in energy marketing targets.

The energy targets for February-July were always fixed as in the status quo. since energy production capability in this time period is not determined by the new forecasts. All other settings in the model were unchanged from the status quo, thus focusing the analysis on the value of forecasts for fall and early winter non-firm energy revenue. In particular, firm energy production targets, which are important because of capacity considerations, remain unchanged, and are met with 100% reliability in both the status quo and all alternative formulations.

#### **Evaluation of Economic Benefits**

In each water year of the ColSim simulation model (driven by observed streamflow data), the ECC and energy scaling factors change (based on the climate and streamflow forecasts), and the model attempts to meet the resultant non-firm energy targets without drafting the storage reservoirs below the ECC, while simultaneously attempting to meet all system objectives.<sup>8</sup> The other revenue generated is based on estimated monthly average market prices (BPA, forecasts of monthly average prices for 2002-2006 in 1998 dollars), which are assumed to equal forecasted marginal costs of power generation and to remain constant for the entire simulation period. These prices are also assumed to be unaffected by changing non-firm marketing practices in the Columbia, a reasonable assumption since the simulated changes are on the order of 0.5 percent of the total load for the western power grid upon which prices depend. Hydroelectric energy production is assumed to have associated costs of \$4.0 per MW-hr (J. Fazio, Northwest Power Planning Council, personal communication, 2000).

Using long-lead streamflow forecasts to guide the construction of the ECC would result in long-term average increases in revenue on the order of \$40 million per year for the least aggressive fall marketing strategy (alternative 1) and

<sup>&</sup>lt;sup>8</sup> Note that the retrospective streamflow sequences are used here as representations of natural streamflow variability superimposed on the current reservoir system and management objectives. Thus the simulations represent the current level of development for the entire period of record examined.

approximately \$150 million per year for the most aggressive fall marketing strategy (alternative 5). These simulated increases are achieved by moving non-firm generation from the spring to the months when energy fall generation is more valuable, and also by reducing non-power producing spill from reservoirs during the spring in wet years. The reliability of the major Columbia River water resources system objectives under these different modeled alternatives is shown in Table 2. For alternative 1, the performance of other system objectives is almost identical to the status quo, while under alternative 5, some reductions in system storage have minor negative impacts on Lake Roosevelt recreation conditions and the reliability of the McNary fish flow target (for salmon protection). The reliability of energy production non-firm declines as the energy is more aggressively marketed in fall (compare alternative 1 to 5), because the status quo spring non-firm energy targets (applied uniformly to all years in the simulation as described above) cannot be met under all conditions in the simulation when more energy production occurs in the fall. These results demonstrate that the increases in revenues reported are almost completely associated with the systematic use of new information and the revised reservoir operating plan, as opposed to resulting from tradeoffs between different system objectives.<sup>9</sup> The results probably

 Table 2: Levels of Climate Forecast Use Among PNW

 Water Resource Managers (Callahan 1997).

Survey Questions	Number (%) of Respon- dents	Number (%) of Respondents with Technical Capacity to Use Climate Fore- casts				
Actual Use of Fored	casts:					
Don't use climate forecasts at all	15 (68%)	8 (57%)				
Informally or casually use climate forecasts	4 (18%)	4 (29%)				
Formally use climate forecasts	3 (14%)	2 (14%)				
Path of forecast in a	Path of forecast in agency after receipt					
Nothing is done with it	4 (20%)	1 (8%)				
Forecast used informally	3 (15%)	3 (25%)				
Forecast processed and distributed to others in agency	13 (65%)	8 (67%)				
Use of forecast in decision making						
Forecast not used at all	10 (50%)	5 (36%)				
Forecast used in- formally	8 (40%)	7 (50%)				
Forecast used for- mally	2 (10%)	2 (14%)				

significantly underestimate the actual potential economic benefits associated with shorter time scale marketing strategies, since monthly average prices were used in this analysis, and actual marketing decision processes function on much shorter time scales.

#### **Summary**

Columbia River reservoir management does not currently use climate or streamflow forecast information to guide operations in fall and early winter. As a result, the current reservoir operating policies are very restrictive of non-firm energy production during this period, essentially assuming drought conditions until forecasts become available in January. Long lead climate/streamflow forecasts provide opportunities to relax constraints on use of available water during the fall and early winter in such a manner that other uses of the system are not significantly impacted, while nonfirm hydropower benefits from a subset of the Columbia's projects are increased on the order of \$150 million per year on average for the most aggressive marketing strategy we examined.

# Suggested references and web sites

Bonneville Power Administration, U.S. Army Corps of Engineers (North Pacific Division), and Bureau of **Reclamation** (Pacific Northwest Region) (BPA et al.). 1991. The Columbia River System: The Inside Story. Report DOE/BP-1689. published for Report the Columbia River System Review by the U.S. Army Corps of Engineers and the Bureau of Reclamation, Portland, Oregon.

Bonneville Power Administration, U.S. Army Corps of Engineers, and Bureau of Reclamation (BPA et al.). 1993. *Power System Coordination: A Guide to the Pacific Northwest Coordination Agreement.* Report published for the Columbia River System Operation Review.

Callahan, B. M. 1997. The potential of climate forecasts for water resource management in the Columbia Basin. M.M.A Thesis, School of Marine Affairs, University of Washington, Seattle.

Callahan, B., E. Miles, and D. Fluharty. 1999. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sciences* **32**:269-293.

<sup>&</sup>lt;sup>9</sup> Further, the modeled changes in Columbia River operations to generate more hydropower in the fall do not significantly affect the hydrosystem's potential to produce hydropower during the following spring (Hamlet et al. 2000).

Energy Information Administration (EIA). 2000. State Electricity Profiles. DOE/EIA-0629. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy, Washington, DC.

Hamlet, A. F. and D. P. Lettenmaier. 1999a. Columbia River Basin streamflow forecasting based on ENSO and PDO climate signals using a macro scale hydrology model and resampled meteorological data. *Journal of Water Resources Planning and Management* November/December: 333-341.

Hamlet, A. F. and D. P. Lettenmaier. 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. *Journal of the American Water Resources Association* **35**(6): 1597-1623.

Hamlet, A. F., D. Huppert, and D. P. Lettenmaier. 2001. Economic value of long-lead streamflow forecasts for Columbia River hydropower, ASCE Journal of Water Resources Planning and Management (in press).

Karier, T. 2000. "Electricity Markets Blow a Fuse." Seattle Post-Intelligencer 16 August.

Lettenmaier, D. P. and D. C. Garen. 1979. Evaluation of streamflow forecasting methods,

Proceedings of the Western Snow Conference, pp. 48-55, Sparks, Nevada: April.

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## **Upcoming Events**

**21st Conference on Severe Local Storms** 12 – 16 July 2002 San Antonio, TX

**83<sup>rd</sup> Annual conference of the American Meteorological Society** Long Beach, CA

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