

## Three Recent Flavors of Drought in the Pacific Northwest

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### ABSTRACT

In common with much of the western United States, the Pacific Northwest (defined in this paper as Washington and Oregon) has experienced an unusual number of droughts in the past decade. This paper describes three of these droughts in terms of the precipitation, temperature, and soil moisture anomalies, and discusses different drought impacts experienced in the Pacific Northwest (PNW). For the first drought, in 2001, low winter precipitation in the PNW produced very low streamflow that primarily affected farmers and hydropower generation. For the second, in 2003, low summer precipitation in Washington (WA), and low summer precipitation and a warm winter in Oregon (OR) primarily affected streamflow and forests. For the last, in 2005, a lack of snowpack due to warm temperatures during significant winter precipitation events in WA, and low winter precipitation in OR, had a variety of different agricultural and hydrologic impacts. Although the proximal causes of droughts are easily quantified, the ultimate causes are not as clear. Better precipitation observations in the PNW are required to provide timely monitoring of conditions leading to droughts to improve prediction in the future.

### 1. Introduction

Drought, as Redmond (2002) aptly put it, is “insufficient water to meet needs,” not necessarily a deficit of precipitation, and must be described in terms of its impacts. Drought is difficult to define, but the importance of impacts in defining drought has long been recognized. Wilhite and Glantz (1985) categorized drought definitions as meteorological, hydrologic, agricultural, and socioeconomic, each with impacts taken into consideration. That list has since expanded, and these types of drought can occur together or separately. A hydrologic drought—not enough water in streams and/or reservoirs—need not coincide with an agricultural drought (not enough water to grow crops, whether with or without irrigation) or a forest drought (moisture-stressed trees). Unlike other weather-related natural hazards, drought unfolds slowly and is often difficult to identify or quantify as it is

occurring. Nonetheless, because most U.S. states have drought policies that allow the governor to permit certain kinds of mitigative activities by declaring a drought, it is important that droughts be understood, quantified, and predicted.

With its low summer precipitation, the western United States (including even the notoriously damp Northwest) experiences dry conditions and some mild signs of drought most summers, with periods of weeks with little or no rain. The recent droughts in the west, however, exceeded these typical dry conditions. Beginning in 1999, much of the western United States has been more or less continuously experiencing some type of drought (MacDonald 2007). Total precipitation during the past 10 water years (1999–2008) has been at least 10% below average in parts of Washington (WA), Oregon (OR), Idaho (ID), Montana, Wyoming, Utah, Nevada, California, and Arizona, according to U.S. climate division data. Additional perspectives on drought come from paleoclimate studies. For the Northwest, perhaps the most relevant is the reconstruction of Columbia River flow by Gedalof et al. (2004) using tree rings. They showed that the drought of the 1930s was probably the second worst in the past 250 years, but also that the worst drought (in the

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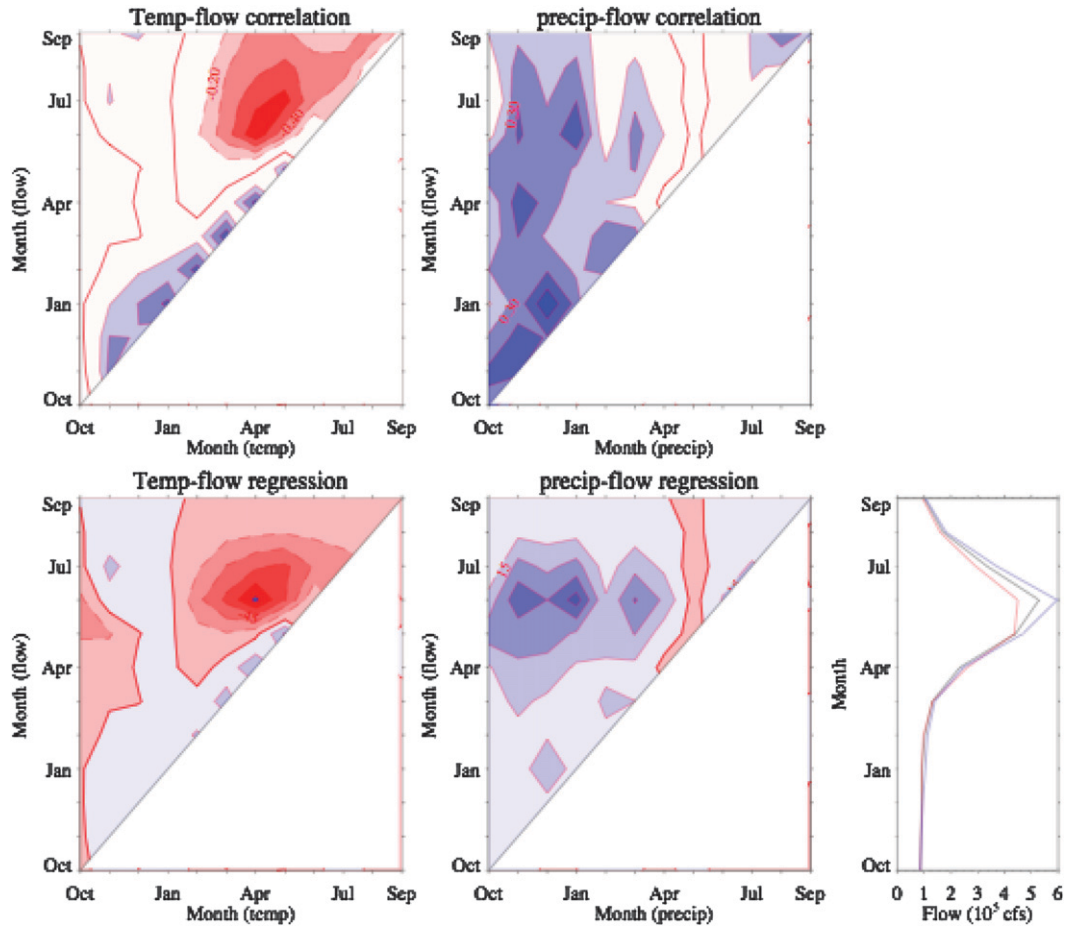


FIG. 1. (top) Correlation and (bottom) regression of monthly naturalized Columbia River flow at The Dalles Dam with monthly mean WA, OR, and ID (left) temperature and (right) precipitation. In each panel, the climate anomaly in a given month is plotted on the *x* axis and the flow response in a given month on the *y* axis; negative anomalies are red and positive are blue. For example, December precipitation anomalies are positively correlated with December streamflow at The Dalles Dam (top-right panel). In the top row, the correlations are shaded beyond  $\pm 0.2$  and the contour interval is 0.1. In the bottom row, the contour interval is  $15\,000\text{ ft}^3\text{ s}^{-1}$ . The additional panel at bottom right shows the long-term mean hydrograph and the results from the regression for a positive 1 std dev anomaly in January precipitation (blue) and a positive 1 std dev anomaly in April temperature (red).

1840s–50s) lasted much longer, an event that would severely strain water resources in the region were it to occur today.

Understanding drought in the Pacific Northwest is particularly critical because of the importance of snowpack in seasonal hydrology and the role that climate anomalies can play at different times of the year in altering snowpack and streamflow. Figure 1 illustrates the importance that precipitation and temperature anomalies have on Columbia River flow. In this calculation, monthly temperature and precipitation for WA, OR, and ID from the U.S. Climate Division dataset were combined into a Columbia basin average (period of record was 1900–98), and were then lag correlated with monthly, naturalized streamflow at The Dalles Dam

(located on the border of Dallesport, WA, and The Dalles, OR). Warm temperature anomalies from November to May have a small positive correlation with flow in that month, by enhancing snowmelt (Fig. 1, left panel). Late winter and spring temperature anomalies are even more important for flow, however, as summer flow is negatively correlated with the temperature anomalies, especially in June. Spring precipitation, on the other hand, is surprisingly not correlated with flow (Fig. 1, right panel). Precipitation during the winter is the most important for current and summer streamflow, as anomalies in October through March are positively correlated with Columbia River flow from that month forward to midsummer. The hydrograph in Fig. 1 further illustrates these points as higher April temperatures

result in less summer flow and higher January precipitation results in higher spring and summer and flow. Droughts can be caused by high temperatures as well as by low precipitation.

In this paper, we describe the meteorological and hydrological conditions in WA and OR (defined in this paper as the Pacific Northwest) during three recent droughts (2001, 2003, and 2005) and discuss them in terms of their impacts. These three distinctive flavors of drought are certainly not the only mechanisms for drought in the Pacific Northwest (PNW), but they illustrate multiple onsets in a small span of 4 years. We emphasize the differences between winter-genesis and summer-genesis drought, and note that some droughts originate partly because of unusual temperatures independent of anomalies in precipitation. In addition to precipitation and temperature as drivers of drought, soil moisture, evaporation, and evapotranspiration can also be indicative of a developing drought. Keyantash and Dracup (2002) scored commonly used drought indicators for meteorological, hydrological, and agricultural droughts on the basis of 6 criteria, and the top-rated indices for meteorological (standard precipitation index) and agricultural (soil moisture) droughts are included in this analysis.

The first flavor of drought, in 2001, occurred simply because of exceptionally low winter precipitation and primarily affected farmers, especially in the Klamath basin of OR and the Yakima region in WA. This flavor, caused by a lack of precipitation during the snow accumulation season, also occurred in OR during 2005. The 2003 drought had slightly different causes in the two states—in WA, exceptionally low summer precipitation, and in OR, a combination of a warm winter and low summer precipitation. The 2003 drought primarily affected forests in OR, leading to forest fires, and also affected rivers and river uses in western WA and OR. A similarly dry summer developed again in 2004 but unseasonably heavy rains in mid-August ended the incipient drought. The third flavor of drought, in 2005, occurred because of a series of short-lived warm temperature anomalies during precipitation events in the winter snow accumulation season in WA. This last example bears special emphasis because the Pacific Northwest is, with California, the region that has the greatest sensitivity to changes in temperature (Bales et al. 2006), and it also relies greatly on spring snowpack for streamflow and water uses in the summer.

## 2. Data sources

Precipitation, temperature, streamflow, and soil moisture data were used to quantify the droughts explored in this paper. The precipitation and temperature data

primarily come from the “Climate-at-a-Glance” utility provided by the National Climatic Data Center (NCDC), a convenient way to aggregate climate data by state, region, or season (NCDC 2009). We used this utility, which relies on monthly climate division temperature and precipitation data, to calculate the mean seasonal cycle of monthly precipitation over the 1895–2005 period of record, the mean monthly precipitation amounts for each of the drought water years, and the yearly December–February (DJF) and June–August (JJA) total precipitation and average temperature for WA and OR. An area-weighted average of the total precipitation and average temperature data using the area of WA and the area of OR was used to produce values that represented the PNW, to which we refer in this paper. Other precipitation and temperature records referred to in the text are from official cooperative observer (COOP) stations or automated surface observing system (ASOS) stations and are archived at NCDC. The standard precipitation index (SPI) for PNW climate divisions was also used, and was retrieved from the archived maps from the National Drought Mitigation Center (NDMC) (NDMC 2010).

Monthly average streamflow data at 204 gauges the PNW were downloaded from the U.S. Geological Survey (USGS) (USGS 2009). We restricted the analysis to gauges that were recording data for at least 55 years and included 2001 and 2003. The peak average monthly flow for each of the gauges was used to determine whether the stream was snowmelt dominated. Peak flows that occurred in March through July were designated as snowmelt-dominated gauges. In addition, modeled monthly soil moisture data from 1932 to 2009 for 9 climate divisions in OR and 10 climate divisions in WA were obtained from the Climate Prediction Center (CPC) (CPC 2010). Each state’s climate divisions were combined using an area-weighted average to get monthly soil moisture data for WA and OR. Soil moisture anomalies, compared to the entire period of record normal, were then plotted for each of the drought years.

## 3. Meteorological and hydrological description of the three droughts

The PNW area-averaged seasonal cycle of precipitation is shown in Fig. 2, which illustrates the dry conditions often experienced in the Northwest during summer, with typically less than 2 cm per month. From December to July, the mean monthly precipitation declines, except that May precipitation is somewhat higher than April precipitation in the mountains of northeastern WA. In the descriptions of the droughts, we focus primarily on precipitation and temperature in DJF and JJA. Figure 3

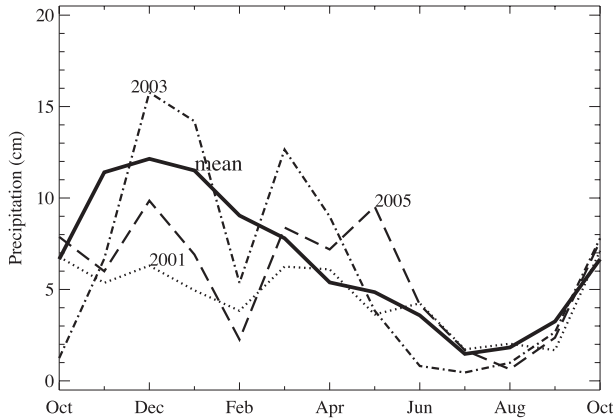


FIG. 2. Mean seasonal cycle of monthly precipitation in the PNW over the 1895–2005 period of record (thick solid line), along with precipitation observed in the water years 2001 (dotted line), 2003 (dot-dashed line), and 2005 (dashed line).

ranks 111 years of DJF and JJA precipitation and average temperature from lowest to highest for WA and OR. Details of this figure are discussed in the following sections.

*a. 2001 and 2005 (OR): Low winter precipitation*

The first flavor of drought, experienced in 2001, is by most measures the most potent in the Northwest and results from low winter snowpack caused by low winter precipitation. The most significant impacts from this type of drought are experienced in the spring and summer. For this example, each month from November 2000 to March 2001 had below-average precipitation (Fig. 2) and the December–February period was the second driest on record after 1977 (Fig. 3a), with only 46% of the long-term average precipitation (compared with 38% for 1977). The archived SPI from the NDMC indicates that the 6-month SPI ending in March 2001 was classified as  $-1.50$  or less, indicating “severely dry” or “extremely dry” conditions for a majority of the climate divisions in the PNW (NDMC 2010).

The water year as a whole was also very dry. The 2001 water year precipitation in many locations in OR (e.g., Astoria, Corvallis, Eugene, and Portland) and WA (e.g., Spokane and Vancouver) ranked as the driest water year on record, breaking records that were previously set in 1977. The record length for these stations ranged

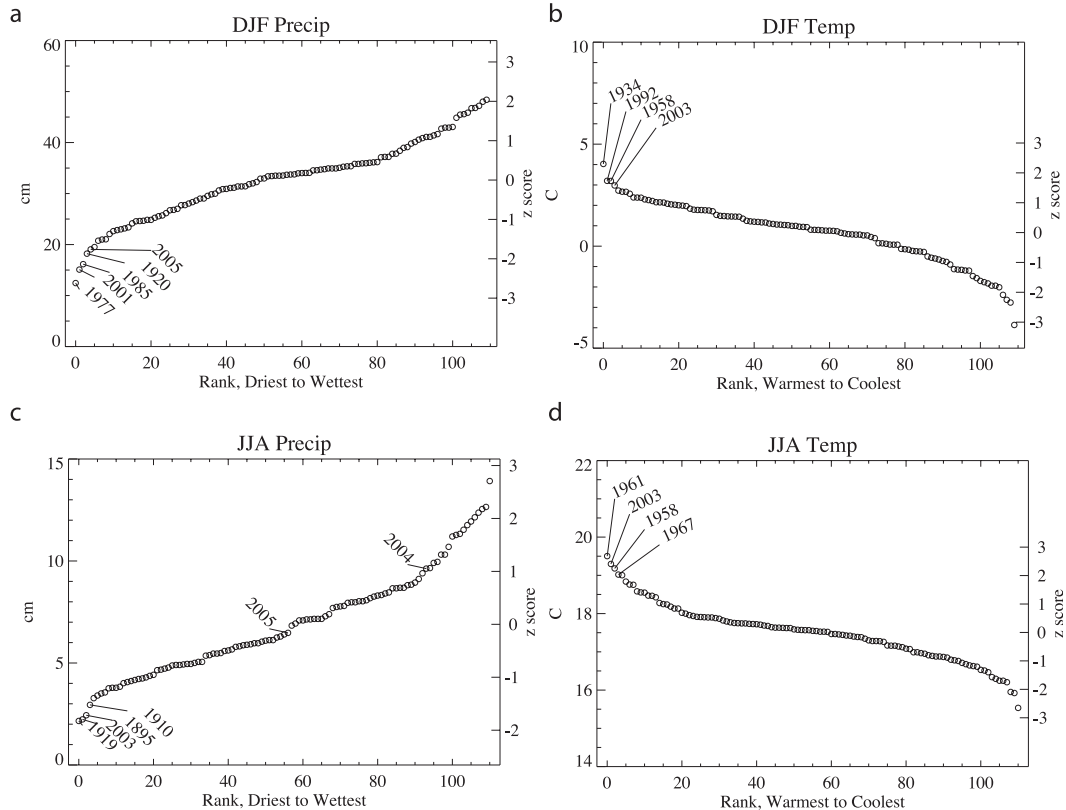


FIG. 3. Plots of 1895–2005 ranked (a) precipitation (cm) for DJF, (b) average temperature ( $^{\circ}\text{C}$ ) for DJF, (c) precipitation for JJA, and (d) average temperature for JJA for the PNW with the value and  $z$  score on individual axes. Selected years are indicated.

from 55 to 92 years, and the 2001 water year precipitation totals ranged from 42% to 67% of normal. Soil moisture anomalies also indicated extremely dry conditions in 2001 (Fig. 4). A weighted area average of climate division soil moisture anomalies indicate that the anomalies in WA and OR were between 80 and 100 mm below the 1932–2009 normal in January through March. Steady improvement was shown after February, but the anomalies were still negative through October 2001 for WA and through the end of the year for OR.

The below-average precipitation, along with a sunny and mild winter, led to low streamflow in DJF in the western portions of the PNW. Figure 5 ranks the 2001 DJF streamflow compared to 55 years of DJF streamflow. As shown in the figure, western parts of the PNW experienced extraordinarily low streamflow in the 2001 winter, ranking second throughout much of the Northwest. Both the gauges dominated by snowmelt and the gauges that are not dominated by snowmelt were impacted by the dry winter conditions, as expected. Even more important for human impacts, however, was the effect that the low winter precipitation had on the snowpack. Critically low snowpack led to a serious agricultural drought in the spring and summer, made clear by the June–September (JJAS) streamflow. The 2001 JJAS streamflow was ranked in a similar manner (not shown) and revealed record low streamflows east of the Cascades in the PNW resulting from the lack of snowpack. Snowmelt-dominated streams scattered in western OR and western WA (near the Olympic Mountains) also ranked among the top 5 lowest JJAS streamflows in 55 years.

Farmers in the Yakima basin in WA felt the effects of the 2001 drought where the rationing of water rights proportionally (i.e., prorationing) took place. Prorationing refers to the practice of classifying users based on the seniority of their water rights to determine who feels the consequences in a water shortage. In other words, “nonproratable” senior water districts always get their water and “proratable” junior water districts get a percentage of their allotment when the supply is low (Ottem 2008). The 2001 supply was so low that proratable water users only received 37% of their proratable entitlement following the decision of the U.S. Bureau of Reclamation (USBR) on 1 April. According to the Yakima Basin Storage Alliance (2008), approximately \$130 million in agriculture revenues were lost that year.

The Klamath basin in OR was the site of a modern showdown over water, fueled both by the drought and by ever-increasing water demands. Concerned about meeting the minimum streamflow requirements for the endangered sucker fish and for the runs of the threatened coho salmon, the USBR announced in the spring that farmers in a certain area would not be provided with

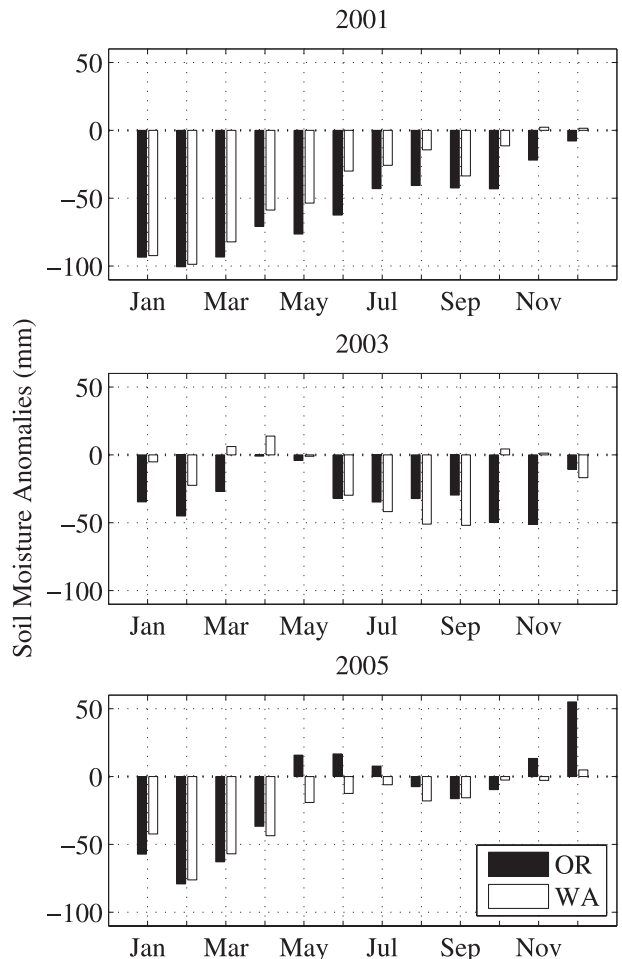


FIG. 4. Modeled monthly soil moisture anomalies (CPC 2010) for the (top to bottom) 2001, 2003, and 2005 calendar years in WA (white) and OR (black).

any water for irrigation. The backlash was intense, and the USBR eventually released water 4 months later, but it was too late; farmers lost an estimated \$157 million in gross agricultural sales (Meiners and Kosnik 2002; National Research Council 2002).

Though primarily classified as an agricultural drought, this drought had other impacts as well. The low river flows in 2001 resulted in a 5300 MW loss in hydropower equating to approximately \$3.5 billion in WA. The loss in hydropower adds up to \$5.8 billion when considering the entire Northwest region (Fontaine and Steinemann 2007). The lack of hydropower also caused electricity rates to increase by 10%–58% in WA by May (Kriz 2001). While the closure of aluminum plants throughout the Northwest is a complex story with many different factors, this hydropower deficit facilitated the permanent closure of plants, which are heavy users of electricity, across the state (Kriz 2001; Yudken and Baugh 2004).

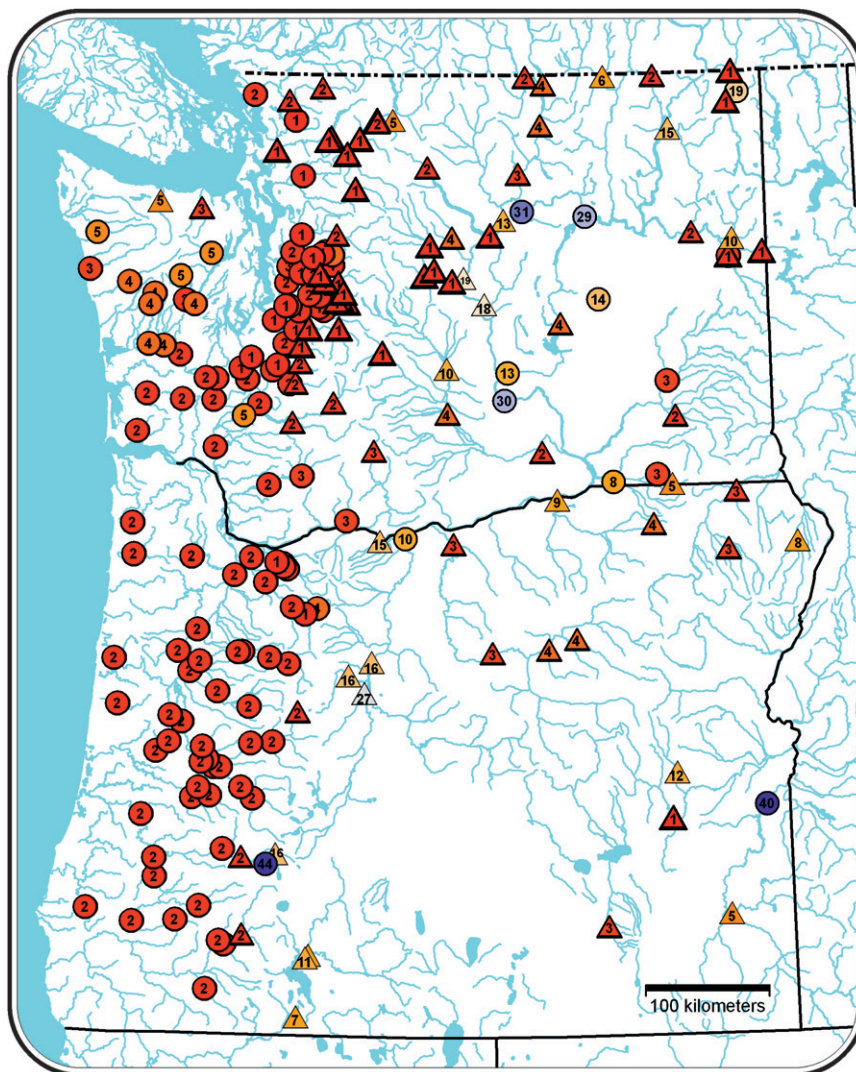


FIG. 5. The rank of 2001 DJF streamflow in a sample of 55 years of streamflow data. Colors indicate rank as well, with red being near the lowest. The triangle symbol denotes the gauges that are snowmelt dominated. Note that most of the rivers in the western PNW were at or near their record low flows for DJF.

Conditions in OR during the 2005 water year were also consistent with the low winter precipitation flavor of drought. The DJF statewide averaged rainfall in OR was only 53% of normal, and the SPI in western OR was classified as “severely dry” (from  $-1.50$  to  $-1.99$ ). The low snowpack initially posed a threat to parts of OR: for example, in the Klamath basin, the USBR implemented its “Drought Plan” in March that gave second and third priority for water to smaller irrigation, smaller drainage districts, city parks, cemeteries, and athletic fields. The USBR also warned that water for higher priority irrigation could be curtailed (Darling 2005), but rains in March and April eased the drought in OR and eliminated the need for curtailments (see soil

moisture rebound in Fig. 4). Spring rains prevented a statewide drought emergency declaration in March, but this rainfall was insufficient to offset drought in some locations, and drought was declared in individual counties throughout the summer (Oregon Governor’s Office 2009).

*b. 2003: Low summer precipitation*

The second flavor of drought, experienced in 2003, is the dry-summer drought, in which summer precipitation is exceptionally low. Because summers are typically dry, the ecosystems and human systems are already somewhat prepared for dry conditions every year, but this flavor of drought can have significant consequences as well. Some of the elements leading up to the drought in the

two states were different, but for both states the result was dry forests and a hydrologic drought of limited scope. Precipitation was near average in the October–April period for both states, but the period June–August was very dry (Fig. 2).

December through February was warm, ranking as the fourth warmest DJF in the PNW (Fig. 3b), 2.3°C warmer than the 1896–2005 mean. Despite this warmth, the 2003 snowpack in WA was near normal, while the OR snowpack was below normal. Precipitation was normal in both states for DJF (~2.7 cm more than 1895–2005 mean), so the warmer temperatures in OR may have been responsible for limiting the snowpack there. The more negative soil moisture anomalies for January through March (Fig. 4) in OR reflect the warmer and drier winter conditions compared to WA. Washington, on the other hand, had soil moisture anomalies that were much closer to normal, or even above normal, during the winter and spring. The summer, however, was the significant season leading to the drought.

The summer was exceptionally warm and dry, ranking as both the second warmest (Fig. 3d) and the second driest (Fig. 3c) JJA for the PNW, 1.8°C warmer and 4.66 cm drier than the 1895–2005 mean. Every month from May through September had below-average precipitation (Fig. 2) and July was remarkably dry. The 6-month SPI ending in October 2003 from NDMC (2010) indicates extremely dry conditions (–2.0 and less) in southeastern WA climate divisions and severely dry conditions (–1.50 to –1.99) for the remainder of the eastern WA climate divisions and for most of OR. Western WA in this index was near normal. Yakima, in eastern WA, had a total of 68 consecutive days without precipitation (June 1–August 7) and a total for May–November of only 2.41 cm. The summer soil moisture anomalies (Fig. 4) were negative in both states, with 50 mm the largest anomaly in WA (September) and OR (November).

The warmer-than-normal temperatures caused the available snowpack to melt a bit earlier than the long-term average, helping to mitigate the warm, dry conditions in many areas. Ultimately, however, the conditions described in the PNW led to record or near-record low flows during the June–September period in the rivers with low snowmelt contributions. Figure 6 illustrates where the June–September 2003 streamflows rank against 55 other years. This hydrologic drought most affected western WA, where the 2003 streamflow was the record low flow at many gauges. OR was not affected as much, although some basins in western OR reached record low flows as well. Note that a majority of the rivers that have low flows for this case are not dominated by snowpack, and the rivers that have closer to normal flows are reflecting the greater influence of snowpack on that basin.

The unusually warm and dry summer impacted forests throughout the Northwest. In OR, 4956 fires occurred between June and September, compared with the 10-year average of 4342. One of the most serious fires in OR in 2003 was the Booth and Bear Butte fire that began on 19 August and spanned 370 ha ( $3.7 \times 10^6 \text{ m}^2$ ), closing a 21-mi stretch of Highway 20 and causing Governor Kulongoski to declare a state of emergency (Oregon Department of Forestry 2008). Conditions in WA were favorable for fires as well, but fortunately, WA escaped the season without significant fires. British Columbia, however, was not as lucky, with 2003 ranking as the worst year on record for forest fires (Filmon 2004). The province saw 2500 wildfire starts, over 260 000 ha ( $2.6 \times 10^9 \text{ m}^2$ ) of forest burned, and 334 homes and businesses destroyed. A total of 45 000 persons were evacuated over the course of the season—the largest evacuation ever to take place in British Columbia. Kelowna had the driest JJA since records began in 1899 and one of the major fires took place there on 16 August, burning a total of 25 600 ha ( $256 \times 10^6 \text{ m}^2$ ). The total cost was \$700 million in firefighting and property damage, and a state of emergency was declared on 1 August (Filmon 2004).

### c. 2005 (WA): High winter temperature

The third flavor of drought is one in which warm winter temperatures reduce snowpack, leading both to winter impacts (e.g., poor ski season) and to summer drought. During the 2005 water year in the PNW, low snowpack produced a summer drought but occurred from slightly different mechanisms in the two states. In OR, low snowpack originated from low precipitation (described above), whereas in WA high temperatures played a more important role.

This drought unfolded in an unusual way in WA. Averaged statewide precipitation was below normal (63%) for December–February, but precipitation in the Cascades was between 70%–80% of normal for the same period. The 3-month SPI ending in January (NDMC 2010) was only “moderately dry” (from –1.00 to –1.49) in parts of western (including the Cascades) and southeastern WA. Snowpack, however, in most basins in the Cascade Mountains was at 20% of normal for much of the winter. Temperature played an important role in transforming this from a modest precipitation deficit into a bona fide drought. Figure 7 illustrates the role of temperature in the development of the 2005 snowpack, showing precipitation and snow water equivalent compared to the period-of-record means for an automated Snowpack Telemetry (SNOTEL) [National Resource Conservation Service (NRCS) 2009] site at 985 m in the WA Cascades. Despite an exceptionally dry February, at most points in the water year the precipitation was

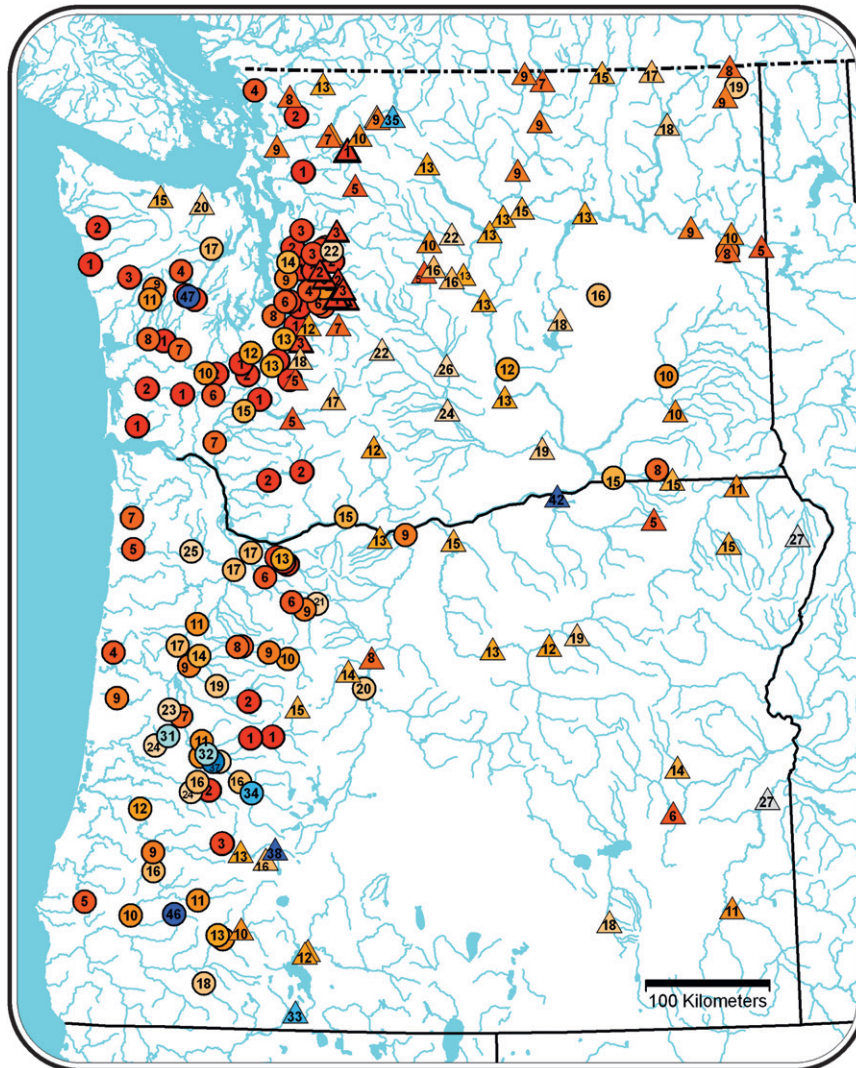


FIG. 6. As in Fig. 5, but for JJAS 2003. Most of the rivers in western WA and parts of OR were at or near their record low flows for JJAS.

above 70% of average, but snowpack at this site was not close to 70% of normal at any point in the season. The ovals emphasize why: during the first two major storm periods of the season, in early December and mid-January, temperatures quickly rose to well above freezing, and the high temperatures combined with heavy rainfall washed away the snow. The mid-January event was rare in its impact on the region’s snowpack: even at the highest locations monitored (Miners Ridge: 6110 ft, 1862 m) the temperatures stayed above freezing for several days *and* nights and the snow water content actually decreased. Midseason (mid-December through mid-March) decreases in SWE only occurred one other time at Miners Ridge, WA—the 1997 water year—in the past 20 years. Typically with a mature snowpack, if the higher elevations experience melting, the water is trapped and

refrozen in the snowpack, preventing a decline in snow water content: this was not the case in 2005.

Finally in late March 2005 another wet week arrived and this time temperatures were low enough to build snowpack. The early spring rains also helped refill reservoirs and replenish soil moisture, ameliorating the incipient drought somewhat (see Fig. 4). Furthermore, the low-snowpack drought was not compounded by a dry-summer drought: Fig. 3c shows that precipitation during JJA 2005 ranked in the middle of the pack. Flows, however, were substantially below normal in summer in most of the snowmelt-dominated streams in WA; in fact, in most of the months between May and September it was the lowest month’s flow ever (e.g., Wenatchee River at Peshastin and Dungeness River at Sequim, 55-year record), and peak flow occurred early, in April or May.



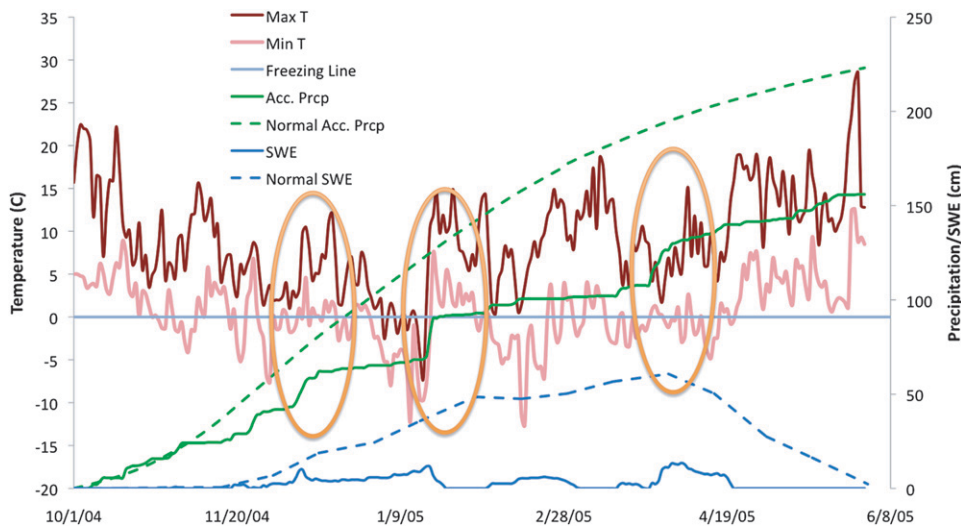


FIG. 7. Daily meteorological conditions at the Meadows Pass (WA) SNOTEL site (elev 3230 ft, 985 m) for October 2004 through May 2005 (NRCS 2009). Dashed lines show period-of-record averages for cumulative precipitation (green) and snow water content (blue), while the solid lines of the same colors show the values for each of these variables for 2005. The maximum (dark red) and minimum (pink) daily temperatures are also shown, as well as the freezing line (gray). The orange ovals highlight three significant stormy periods, each of which delivered 12–20 cm of precipitation.

The impacts of the 2005 drought in WA were widespread. Governor Gregoire formally declared a drought on 10 March 2005 that allowed affected farmers in eastern WA more options but severely hurt the horticulture industry in western WA. With the declaration of the drought, the industry (plant nurseries, landscaping, garden supplies, etc.) lost 8%–20% of revenue in western WA because of the cancellation, postponement, or scaling back of projects that hurt residential landscapers, wholesalers, and retail nurseries (Fontaine and Steinemann 2007). Declaring a drought allowed proratable water users more options like buying from nonproratable water users, using backup groundwater wells, or drilling for new backup groundwater wells. A grower in the Yakima region, however, reported losing an entire 2005 cherry crop, estimated at 50 000 lbs. (about 23 000 kg), because backup groundwater was not available. Recreation was also affected, as ski areas in WA lost 1 million visitors, 69% of their 10-year average in visitation, which equates to approximately \$43 million in revenue. The loss is only based on admission fees and does not take into account the loss in other sources of revenue like restaurants or rentals (Fontaine and Steinemann 2007).

#### 4. Discussion and conclusions

The Northwest droughts highlighted here represent three recent flavors of drought, each of which has different causes and consequences. The distinct flavors specifically discussed here were illustrated more clearly in

WA than in OR, and there are many other conditions not discussed here that would be favorable for drought development. Some droughts have their genesis in the winter, when either very low precipitation (2001) or a combination of low precipitation and high temperatures (2005) produce low snowpack. In these situations, summer water shortages can be anticipated and mitigated. These types of droughts do, however, have wintertime impacts (e.g., winter recreation—2005) so it is important that conditions are monitored and predicted as early and accurately as possible. Other droughts (2003) result from exceptionally dry summer conditions; these come on more suddenly and unexpectedly, and the impacts are different. From a purely hydrologic perspective, record low streamflows in western WA and OR are more likely to result from the dry-summer-type drought, whereas record low summer streamflows in eastern WA and OR are more likely to result from the low-snowpack type of droughts. This is a general statement, and it is important to remember that each basin must be considered independently, and any basin with snow-dominated hydrology in the west is more prone to the latter. An example of a location like this in western WA would be the Dungeness River near Sequim, where low flows were observed in 2001 and 2005, but there was less of an impact in 2003.

Projections of future climate change for the region strongly indicate future warming, but future changes in precipitation are much less clear (e.g., Mote and Salathé 2009). Global climate model simulations do suggest that mean precipitation may increase in winter and will likely

decrease in summer in the PNW (Mote and Salathé 2009). Hydrologic simulations with a range of temperature and precipitation changes indicate that even with moderately large increases in precipitation, the rising temperatures will substantially decrease snowpack and summer streamflow, leading to summertime hydrologic droughts in certain river basins regardless of how summer precipitation changes (Elsner et al. 2009). On the other hand, reductions in summertime precipitation would have relatively more hydrologic effects in western WA and OR than in eastern WA and OR. Thus, the first flavor of drought (low snowpack due to below-normal precipitation) will probably become less common, and the second (summer-genesis drought) and third (low snowpack due to increased temperatures) will become more common, according to the majority of climate models. We stress that none of these recent droughts can yet be attributed to rising greenhouse gases.

The region has autonomously adapted to drought during the past several decades, but these recent droughts confronted the region with some new challenges. In some cases, institutions handled these droughts well. For example, after learning from the difficult 1992 drought, the City of Seattle implemented a 4-stage drought plan, which was put to use in 2001 and 2005 when the city reached stage 2 (requesting voluntary reductions by consumers, which was adequate to reduce demand by about 10%). Without the exceptionally wet spring in 2005, however, the city might have had to issue mandatory reductions in water use (stage 3).

Better drought information requires better, more timely, observations and better numerical forecasting of streamflow. Both of these goals were identified as centerpieces of the National Integrated Drought Information System (NIDIS), which was signed into law by President Bush in 2006. Our analysis underscores that summer-type droughts do affect the Northwest and provide justification for overhauling the observation system to provide timely reporting of precipitation at all long-term weather stations in the region and further research to determine the causes, consequences, and predictability of Northwest droughts. Further work needs to be done to link PNW droughts to large-scale events. The known influences of the El Niño–Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO) do not entirely explain the causes of drought, especially in the summer when ENSO and PDO lose their predictive skill. In addition, more research could be conducted to further examine societal impacts of the different types of drought using more than one example of each type to quantify impacts from year to year.

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#### REFERENCES

- Bales, R. C., N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier, 2006: Mountain hydrology of the western United States. *Water Resour. Res.*, **42**, W08432, doi:10.1029/2005WR004387.
- CPC, cited 2010: Soil moisture monitoring and prediction over U.S.A. [Available online at [http://www.cpc.ncep.noaa.gov/soilmst/index\\_jh.html](http://www.cpc.ncep.noaa.gov/soilmst/index_jh.html).]
- Darling, D., 2005: Drought plan: Parks may go brown. *Herald and News*, 10 March. [Available online at [http://www.heraldandnews.com/news/top\\_stories/article\\_2c6a89c1-ec52-52b2-9f9f-fa63c64020f7.html](http://www.heraldandnews.com/news/top_stories/article_2c6a89c1-ec52-52b2-9f9f-fa63c64020f7.html).]
- Elsner, M. M., and Coauthors, 2009: Hydrology and water resources: Implications of 21st century climate change for the hydrology of Washington State. *Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 69–106. [Available online at <http://www.cses.washington.edu/db/pdf/wacciareport681.pdf>.]
- Filmion, G., 2004: Firestorm 2003 provincial review. Government of British Columbia, Canada, 100 pp. [Available online at <http://www.2003firestorm.gov.bc.ca/firestormreport/FirestormReport.pdf>.]
- Fontaine, M. M., and A. C. Steinemann, 2007: University of Washington drought project final report. Washington Department of Community, Trade, and Economic Development, 126 pp. [Available online at <http://water.washington.edu/Theses/fontaine.html>.]
- Gedalof, Z. M., D. L. Peterson, and N. J. Mantua, 2004: Columbia River flow and drought since 1750. *J. Amer. Water Resour. Assoc.*, **40**, 1579–1592.
- Keyantash, J., and J. A. Dracup, 2002: The quantification of drought: An evaluation of drought indices. *Bull. Amer. Meteor. Soc.*, **83**, 1167–1180.
- Kriz, M., 2001: Future shock. *Natl. J. (Wash.)*, **33**, 1556–1560.
- MacDonald, G. M., 2007: Severe and sustained drought in southern California and the West: Present conditions and insights from the past on causes and impacts. *Quat. Int.*, **173–174**, 87–100.
- Meiners, R. E., and L. R. Kosnik, 2002: Restoring harmony in the Klamath basin. PERC Policy Series, PS-27, Property Environment and Research Center, 32 pp. [Available online at <http://www.perc.org/pdf/ps27.pdf>.]
- Mote, P. W., and E. P. Salathé Jr., 2009: Scenarios: Future climate in the Pacific Northwest. *Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 21–43. [Available online at <http://www.cses.washington.edu/db/pdf/wacciareport681.pdf>.]

- National Research Council, 2002: *Scientific Evaluation of Biological Opinions on Endangered and Threatened Fishes in the Klamath River Basin: Interim Report*. National Academy Press, 33 pp.
- NCDC, cited 2009: U.S. climate at a glance. [Available online at <http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html>.]
- NDMC, cited 2010: Monitoring drought. [Available online at <http://drought.unl.edu/monitor/archivedspi.htm>.]
- NRCS, cited 2009: SNOTEL data & products. [Available online at <http://www.wcc.nrcs.usda.gov/snow/>.]
- Oregon Department of Forestry, cited 2008: Fire in the forest. [Available online at [http://www.oregon.gov/ODF/FIRE/fire.shtml#Fire\\_Stats\\_Info\\_Updates\\_](http://www.oregon.gov/ODF/FIRE/fire.shtml#Fire_Stats_Info_Updates_).]
- Oregon Governor's Office, cited 2009: 2005 Oregon Drought and Fire Conditions. [Available online at [http://governor.oregon.gov/Gov/fd/main\\_drought\\_fire.shtml](http://governor.oregon.gov/Gov/fd/main_drought_fire.shtml).]
- Ottem, S. P., 2008: The general adjudication of the Yakima River: Tributaries for the twenty-first century and a changing climate. *J. Environ. Law Litigation*, **23**, 275–355.
- Redmond, K. T., 2002: The depiction of drought: A commentary. *Bull. Amer. Meteor. Soc.*, **83**, 1143–1147.
- USGS, cited 2009: Site inventory for the nation. [Available online at <http://waterdata.usgs.gov/nwis/inventory/>.]
- Wilhite, D. A., and M. H. Glantz, 1985: Understanding the drought phenomenon: The role of definitions. *Water Int.*, **10**, 111–120.
- Yakima Basin Storage Alliance, cited 2008: Agriculture. [Available online at <http://www.ybsa.org/agriculture.php>.]
- Yudken, J., and B. Baugh, 2004: Washington State job exports: An analysis of the role trade plays in manufacturing job loss. Job Export Database Project, 19 pp.