Seasonal Cycle Shifts in Hydroclimatology over the Western US

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Abstract

Analyses of streamflow, snowfall temperature, and precipitation in snow-melt dominated river basins in the western US indicates an advance in the timing of peak spring flows over the past fifty years. Warm temperature spells in spring have occurred much earlier in recent years, which partly explains the trend in the timing of the spring peak flow. In addition, a decrease in snow water equivalent and a general increase in winter precipitation is evident for many weather stations in the western U.S. It appears that in recent decades more of the precipitation is coming as rain rather than snow. The trends are strongest at lower elevations and in the Pacific Northwest region, where winter temperatures are closer to the freezing-point; it appears that in this region in particular, modest shifts in temperature are capable of forcing large shifts in basin hydrologic response. We speculate that these trends could be potentially a manifestation of the general global warming trend in recent decades and also due to enhanced ENSO activity. The observed trends in hydroclimatology over the western US can have significant impacts on water resources planning and management.

1. Introduction:

a. Background

There is strong evidence for persistent natural climate variation on interdecadal and century time scales (Mann et al. 1995). However, recent trends in climate, both global and regional (IPCC 2001), have gained much attention because of both their potential links to anthropogenic causes (i.e. increased human-induced CO2 concentrations), and their potentially significant economic and environmental impacts.

Signatures of the recent climate trends are seen in several regional and global variables, including (1) increased land and ocean temperatures, particularly, over midlatitude regions; (2) increased frequency of extreme weather events (severe precipitation, floods, droughts etc.); (3) shifts in seasonal cycles – e.g., early occurrence of spring (evident through early blossom of the plants and early spring flows); and (4) increased vegetation cover and extended growing period (Myneni et al. 1997)

The instrumental record of climate indicates that increases in land surface temperatures are widespread (Karl et al. 1991; Karl et al. 1993a; Karl et al. 1995; Weber et al. 1994; Quintana-Gomez 1999; and Brunetti et al. 2000). In North America and Europe, mean surface temperatures have increased by about 0.5^{o}C over the last 50 years (~0.1^{o}C per decade), consistent with global trends (IPCC 2001). These regional trends in surface temperatures modify the hydrologic cycle through changes in the volume, intensity or type of precipitation (rain versus snow), and through shifts in the seasonal timing of runoff. Increases in annual precipitation totals in Canada and in the United States (Zhang. et al. 2000; Groisman and Easterling 1994; Bradley et al. 1987; Groisman et al. 2001) and a concurrent decrease in lower-latitude precipitation (Bradley et al. 1987) are observed during 20th century. Corresponding shifts in storm tracks from the mid-latitudes to the high-latitudes have also been observed (Serreze et al. 1997; Clark et al. 1999; McCabe et al. 2001). Decreases in winter precipitation over Southern Europe (Brunetti et al. 2001) and the Mediterranean, and wet anomalies from Iceland eastward through Scandinavia are related to the persistent positive phase of the North Atlantic Oscillation (NAO) (Hurrell 1995). Global climate model simulations of enhanced greenhouse conditions show an increase in global average precipitation of about 10%, with fewer but more intense convective events at lower and middle latitudes, and more frequent moderate to high intensity nonconvective events at higher latitudes (Hennessey et al. 1997). Precipitation over the contiguous United States, in line with simulation results, appears to have increased during the 20th century as a result of an increase in the frequency of heavy precipitation events (Karl and Knight 1998; Groisman et al. 2001).

At higher latitudes, increases in surface temperature have resulted in systematic decreases in snow cover extent, and transitions in the amount of precipitation falling as rain versus snow (Karl et al. 1993b). Groisman and Easterling (1994) observed that there has been a 20% increase in annual snowfall and rainfall in Canada during the last four decades. Groisman et al. (1994) analyzed records of snow cover in the Northern Hemisphere over the period of 1972-92 and found that there was approximately a 10% reduction in the area of snow cover. They linked this decrease in snow cover extent to increase in spring temperatures and suggested the lower albedo from an increased fraction of snow-free land instigated a positive feedback that intensified the decline in snow extent.

b. Global Trends and Western US Hydroclimatology

One of the key impacts of global temperature change is the shift in the seasonal cycle of hydroclimate variables, especially precipitation and streamflow. Changes in regional hydroclimatology can have substantial economic and environmental impacts. Increasing winter temperatures could reduce the amount of snow in a basin (e.g., more precipitation falling as rain than snow); also higher spring temperatures could initiate earlier runoff and peak streamflows in snowmelt-dominated basins. These can have significant impacts on water resources management– e.g., negative impacts on irrigation, non-firm energy, recreation, flood control, and instream flow for fish (Hamlet and Lettenmaier 1999). Knowing these shifts in advance can help water managers to optimize reservoir operations to meet competing demands such as irrigation, environmental needs, and power generation.

Observations suggesting the earlier occurrence of spring are evident in shifts in several climate variables, including the phase of the annual cycle of temperature, which Thomson (1995) attributed to increased atmospheric CO2 concentrations. Shifts in the seasonality of western US precipitation and streamflows have also been observed (Bradley 1976; Rajagopalan and Lall 1995; Lins and Michaels 1994; Dettinger and Cayan 1995). Mote (2003) computed trends in snow water equivalent (SWE) in the Pacific Northwest and observed strong declines in SWE, in spite of increases in precipitation, which seems consistent with an increase in spring temperatures. In an analysis of hydrologic impacts of climate change over west-central Canada, Burn (1994) found a strong shift towards the early occurrence of the spring runoff events, especially, in the last 30 years. Dettinger and Cayan (1995) observed early flows in association with warmer winters in California. Cayan et al. (2001) documented the early onset of spring in the western US by examining changes in the blooming of plants and the timing of snowmelt-runoff pulses. McCabe and Wolock (2002) observed a step increase in streamflow in the conterminous United States over the period 1941-99, with pronounced increases in the eastern United States after 1970.

Simulations under CO_2 doubling show a strong seasonal shift in the snow accumulation and ablation seasons, leading to increased winter runoff and decreased spring runoff (Lettenmaier and Gan 1990). Nash and Gleick (1991) used conceptual hydrological models to simulate streamflow response to changes in temperature and precipitation in the Colorado basin. Increases in temperature of 2-4^{o}C decreased mean annual runoff by 4 to 20%, whereas changes in annual precipitation of +/-10-20% result in corresponding changes in mean annual runoff of 10 to 20%. Seasonal shifts in flow were observed and attributed to an increase in the ratio of rain to snow. The potential effects of climate change are quite pronounced in the Pacific Northwest region, where significant increases in winter flow, and corresponding decreases in summer flow, are shown under a range of different climate models (Hamlet and Lettenmaier 1999). The transitions in winter and summer flow volumes occur because of increased winter precipitation and winter temperature with resulting reductions in snow pack (see also Mote 2003).

From the research efforts discussed above it is clear that there is strong evidence for climate change, as seen through trends/changes in regional hydrometeorological variables. Of course, the reported trends have to be tempered in light of short observational records. Nonetheless, given the potential socio-economic impacts of changes in regional hydroclimatology more research in this area is needed. The main questions that we address for the western US are (i) What are the spatial signatures and trends in the timing of spring peak flows?; and (ii) Are these trends consistent with the observed records of precipitation, temperature and snowfall? With this as motivation, we systematically analyzed trends in precipitation, snowpack, streamflows and timing of peakflow occurrence in snowmelt-dominated river basins throughout the western US. Our analysis focuses on hydroclimatic trends over the last half of the 20th century; a relatively dense network of measurement stations and consistency in data sets for this time period allows us to examine potentially complex interactions between temperature, precipitation and runoff over a broad geographic area characterized by diverse climatology and terrain.

2. Data and Methodology

The main objective of this paper is to examine cause and effect relations between the timing of snowmelt in mountain basins of the western US and trends in associated hydroclimatic variables. Measurements of streamflow, snow water equivalent (SWE), precipitation and temperature are used to assess shifts in the seasonal cycle of snowmelt runoff over the period 1950 – 1999.

a. Streamflow

Daily streamflow data were obtained for selected unregulated basins in the western U.S. that are part of the U.S. Geological Survey (USGS) Hydro-Climate Data Network (HCDN) database (Slack and Landwehr 1992). This database was developed by the USGS to study climatically induced variations in US surface water conditions (Slack and Landwehr 1992). The full database consists of 1,659 stream gages throughout the conterminous USA. The streams and rivers in the HCDN database are relatively free from anthropogenic influences such as watercourse regulation, diversion, ground-water pumping, or land use change. We selected stations across the western USA that have dominant spring snowmelt runoff, meaning at least 50% of the annual runoff occurs from April – July. In addition, the stations selected have continuous records over the desired period (1950-1999), and have acceptable values for the daily flow analysis; 89 stations satisfied the above criteria.

Several different methods have been used previously to identify changes in the timing of spring snowmelt. Burn (1994) examined trends in peak flows by selecting the Julian day on which the maximum spring flow occurred. Cayan et al. (2001) developed an algorithm identifying the day when the cumulative departure from that year's mean flow reached a minimum value, which is equivalent to finding the day after which most flows were greater than average. We found that both of these approaches performed poorly when there are rainfall or rain-on-snow events during winter or spring. In the Sierra Nevada range, for example, high intensity rainfall events can generate floods in December or January, long before the main pulse of snowmelt. Consequently, the Julian day of peak flow may not reflect the timing of seasonal snowmelt.

Given the drawbacks of existing methods we developed an alternative procedure that, for each year, finds the date (Julian day) on which 50% of the water-year flow is equaled or exceeded. An example of the procedure is illustrated in Figure 1, which shows daily flows of the American River near Nile, WA (USGS gauge 12488500), for a portion of the 1974 water year. In this example, the annual peak flow in mid-January has a very sharp rising limb, suggesting it is the result of a rain event. Several subsequent peaks in May and June are characterized by slower rising limbs reflecting separate periods of snowmelt runoff. Our procedure identifies June 4 as the cutoff date corresponding to 50% of the annual flow. This date precedes the main snowmelt peak by about 10 days. In other years it is just as likely that the main snowmelt peak will precede the date selected by our method. In most cases the date corresponding to 50% of the annual flow lies near the centroid of the snowmelt hydrograph; this date is, therefore, reflective of the annual hydrograph as a whole rather than an individual day or event. This metric also provides information on the fraction of winter precipitation that falls as rain versus snow.

The second panel in Figure 1 shows trends in the timing of peak snowmelt runoff on the American River near Nile, WA for the period 1950-1999. The two time series represent dates corresponding to the annual maximum flow (red circles), and dates corresponding to 50% of the annual flow (blue circles). Both time series have negative trends, suggesting that peak flows are occurring earlier. However, the time series formed from annual peak flows is clearly influenced by the inclusion of a number of rainfall events, and the overall trend is not statistically significant. The time series formed with the procedure described above appears to be more robust in selecting the peak period of snowmelt; this trend is statistically significant at the 0.10 level.

In addition to trends in the timing of snowmelt, we examined changes in monthly and seasonal (Apr – Jul) volumes of runoff. The runoff analyses are used to corroborate analyses of precipitation and SWE, which may affect the timing of snowmelt independent of any change in temperature.

b. Snow

Trends in SWE were investigated using data from snow-course surveys conducted by the Natural Resources Conservation Service (NRCS) The snow-course surveys are conducted during the months of January through June, and SWE measurements are generally taken on or about the beginning of each month. Snow-course measurements are most frequently taken at the beginning of April, which is representative of peak SWE in many regions. Applications of SWE measurements across the western US, and limitations of the data are discussed by Clark et al. (2001). In our analysis we considered SWE data from March, April and May, as most of the snow is melted by June. We restricted the analysis to snow course sites that have been visited on at least 80% of the years during 1950-99. We used 469, 501 and 239 stations with SWE data for March, April and May, respectively.

c. Precipitation and Temperature

Precipitation and temperature data were obtained from the National Weather Service cooperative network (COOP). Most COOP stations have records beginning from the mid-1900s. Stations with continuous daily records from 1950-99 over the Western US were selected. Approximately seventy five percent of the stations are situated at elevations less than 1600m; some locations in the Rocky Mountain Region of Colorado and New Mexico are at elevations greater than 1800m.

Total winter season precipitation was computed for each COOP station for the months of November through March. Trends in spring temperatures were examined by computing the Julian day of a "warm spell" corresponding to snowmelt. A warm spell is defined here as a period of persistent daily maximum temperatures above some threshold. We calculated a seven-day moving average of daily maximum temperatures during spring and selected the first Julian day (midpoint of the seven day window) at which the seven-day temperature average exceeds a threshold value. We examined the effects of different temperature thresholds and averaging windows, and found good correspondence between the initiation of melt and a seven-day window with the threshold of 12^{o}C.

d. Regression Analysis

Trends are examined at each location using linear regression (Helsel and Hirsch 1995; Johnson 1995) for the following five variables: (i) timing of peak streamflow (as described above); (ii) monthly and seasonal flows; (iii) SWE; (iv) seasonal precipitation and; (v) temperature spell timing (described above). Standard statistical tests are used to assess the significance of individual trends (Helsel and Hirsch 1995; Johnson 1995).

3. Results

a. Peak flow Timing

Changes in the timing of peak spring flow at individual gaging stations are mapped across the western US in Figure 2. For a majority of stations, peak spring flows appear to be occurring earlier (negative trends in timing, indicated by red circles), however, the observed trends are statistically significant primarily only in the Pacific Northwest. Later occurrences of peak flows (positive trends in timing, indicated by blue circles) are present over a small number of stations in the interior west and also over the Sierra Nevada region. These stations correspond to high elevation locations, which are presumably less sensitive to temperature change. As shown in Figure 3, shifts in peak-flow timing (expressed in days) appear to vary with elevation; in basins less than 2500 m elevation, 10- to 20-day shifts in peak flow timing are common, whereas in basins greater than 2500 m little change is evident.

b. Trends in Accumulated Snowpack

Figure 4 maps trends in snow water equivalent (SWE) for the months of March, April and May. Significant declines in monthly SWE can be seen over roughly half of the sites, with the largest declines occurring in the Pacific Northwest region and in northern parts of Idaho, Utah, Wyoming and the Sierra Nevada region. A few locations in the northern Rockies and the southwestern US show increasing trends in May 1 SWE.

Trends in SWE can be influenced by both temperature and precipitation (Serreze et al. 1999). One approach to separate temperature and precipitation influences is to examine the SWE trends as a function of elevation (Mote 2003). Changes in SWE due to precipitation alone should be nearly uniform with altitude, whereas changes due to temperature should be much greater at lower elevation, since at lower elevation a moderate change in temperature can dramatically change the fraction of precipitation that falls as snow (Mote 2003). SWE trends as a function of elevation are plotted in Figure 5. This plot shows that low-elevation basins (2500m and less) exhibit a strong decreasing trend in SWE while there is little trend in high-elevation stations. Changes in SWE in the western US thus appear to be sensitive to the effects of temperature, but primarily in basins below about 2500m.

c. Trends in Temperature and Precipitation

Temperature plays an important role in shifting the timing of the flow peaks in snowmelt dominated basins. Figure 6 shows trends in the timing of the spring warm spell, estimated on the basis of the 12^{o}C threshold defined above, and trends in winter precipitation and winter temperature. The top panel indicates that there have been significant advances in spring warm spells over much of the western US. Departures in spring temperature are greatest in the Pacific Northwest and Rocky Mountains regions, whereas little change is evident in California, Arizona and New Mexico. On average there is at least a 10-15day advancement of spring temperature spells over the entire region. Some locations in Colorado, the Sierra Nevada Mountains and northern Utah (at elevations of ~2500m and above) indicate a later occurrence of temperature spell. The strong early shifts in temperature spell are consistent with early occurrence of spring flows (Figure 2).

The middle panel in Figure 6 indicates that winter precipitation is increasing across much of the western US, except in the coastal regions of Oregon and Washington, and a few areas in the northern Rockies. Winter temperatures (bottom panel in Figure 6) exhibit a broad pattern of warming in the interior west, but elsewhere little change. The increases in winter temperature in the interior region appear to be offset to a certain extent by the increases in winter precipitation, such that is little change overall in the timing of snowmelt. Decreases in winter precipitation, coupled with increases in spring warm-spell temperatures appear to have had a particularly strong effect on the timing of snowmelt in the Pacific Northwest.

Figure 7shows shifts in the spring temperature spell, winter precipitation, and winter temperatures as functions of elevation. There is a weak correspondence between temperature trends and elevation, but this mostly reflects the location of weather stations in low elevation areas. Similarly, trends in winter precipitation show no obvious relation to elevation (Fig. 7b). Winter temperatures above 1500 m elevation appear to be slightly lower, again reflecting the geographic distribution of stations.

d. Streamflow

To bring these results together, trends in annual runoff were computed and are shown in Figure 8. Basins in the Rocky Mountains in Colorado, the Sierra Nevada Mountains in California, as well as basins in Utah and New Mexico exhibit small increases in annual runoff, while basins in Idaho and Washington exhibit small decreases. On the whole there are very few basins that pass the significance test (i.e. hardly any filled circles). These results suggest that at most locations any changes in the timing or volume of snowmelt brought about by increases in temperature are offset by increases in precipitation (Figure 6).

Interesting differences are evident when trends in runoff are examined for individual months in spring and early summer (Figure 9). Many stations across the western US show significant increases in March monthly flows, with particularly large increases in the Pacific Northwest. Increasing trends in March flows in the Pacific Northwest would suggest that more precipitation is coming in the form of rain rather than snow, and also the early occurrence of spring melt. April exhibits a diffuse picture, while May and June show a strong decreasing trend over the Pacific Northwest and northern Idaho and Montana, and weak increasing trends elsewhere. A clearer picture emerges in the spatial patterns of trends in the fraction of monthly flow volumes (Figure 10). Here the trends are computed as the fraction of monthly flow volume relative to the total annual flow. It can be seen that in the Pacific Northwest and California there is a decrease in the fraction of monthly flows going from March to June. This result suggests that, in recent decades, more of the spring flows are coming in earlier months (March and April), which is consistent with earlier occurrence of flow peaks seen in Figure 2.

4. Summary and Discussion

The results of this analysis can be summarized in the following four points:

1. Advancement in the timing of spring temperature spells over the western US has resulted in the earlier occurrence of peak snowmelt flows in many mountain basins. Changes in the timing of snowmelt are most evident in basins in the Pacific Northwest, which fall below 2500 m elevation. Changes in the timing of snowmelt in high-elevation basins in the interior west are, for the most part, not statistically significant.

2. Increases in March and April streamflows, and decreases in May and June streamflows at a number of sites suggests a broad shift in spring peak flow timing.

3. Snowcourse measurements show a decreasing trend in snow-water equivalence (SWE) in April and May, which is also indicative of reduced snow and early melt.

4. Winter precipitation seems to be generally increasing, but there is no clear increasing trend in the spring streamflows. This suggests that in recent decades more of the precipitation is coming in the form rain rather than snow.

The changes in climate and hydrology observed in this study appear to strongly influenced by trends in the last 25 years Figure 11 shows the trends in the timing of peak streamflow during pre-1974 and post-1974 periods. It can be seen that the post-1974 period shows a stronger decreasing trend (i.e. early arrival of peak flow) relative to the earlier period. Owing to small sample size the trends are not significant, despite being higher in magnitude (size of the circles).

The general mid-latitude warming, perhaps with anthropogenic origins, in recent decades, is a plausible cause for the early shift in the spring peak flow timing. On the other hand, the trends in all the figures show an out of phase relationship (i.e. opposite sign) over the Northwestern U.S. and the Southwestern US. This is a classic ENSO teleconnection pattern (Roplewski and Halpert 1986; Redmond and Koch 1991; Cayan 1996; Cayan et al. 1999; Clark et al. 2001). There has been increased ENSO frequency in recent decade (Rajagopalan et al. 1997; Trenberth and Hoar 1996) and this could be a potential cause as well. Also there is the tantalizing possibility of interaction between the general warming and enhanced ENSO activity (Trenberth and Hoar 1996)

The concentration of negative trends in spring flow timing in the Pacific Northwest attests to the strong sensitivity of that region to climate change. In the high elevation regions in the interior West, winter temperatures are well below freezing, and the ratio of SWE to winter precipitation is high (>80%) and consistent from year-to-year. By contrast, in the lower-elevation Pacific Northwest, the ratio of SWE to winter precipitation is much lower and highly variable from year-to-year (Serreze et al. 1999). This occurs because the temperatures in the Pacific Northwest region are closer to the freezing-point, and even small inter-annual variations in temperature can have a dramatic effect on the fraction of precipitation that falls as rain, and thus on the timing of spring melt. If the trends in temperature, snowfall, and runoff demonstrated in this paper persist and even intensify, changes in water management practices will be necessary to adapt to the altered hydrologic regime.

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Figure Captions:

Figure 1. (a) Daily hydrograph for water year 1974 of the American River near Nile, WA (USGS gauge 13240000). Red line indicates the date of the annual maximum flow; this peak is likely the result of rainfall. Blue line indicates the day corresponding to 50% of the annual flow; this date precedes the main snowmelt peak by about 10 days, but coincides relatively closely to the centroid of the snowmelt hydrograph. (b) Trends in the timing (day of the water year) of peak flows on the American River near Nile, WA for the period 1950-99.Red circles indicate dates corresponding to the annual maximum flow; a number of these flows were produced by rainfall rather than snowmelt. The blue circles indicate dates corresponding to 50% of the annual flow; nearly all of these dates fall within the period of snowmelt runoff. The trend formed from annual peaks (red line) is not statistically significant, whereas the trend formed by selecting peaks in snowmelt (blue line) is significant at the 0.10 level.

Figure 2. Locations of gauging stations used to evaluate changes in the timing of snowmelt runoff for the period 1950-1999. Red circles depict stations with earlier flow timing, and blue circles indicate stations with later flow timing. Filled (open) symbols represent stations passing (failing) significance tests, based on a two-tailed t-test (Helsel and Hirsch, 1995; Johnson, 1995).

Figure 3. (a) Scatter plot comparing the trends in the timing of 50% of annual runoff against the mean basin elevations, and (b) a map illustrating spatial distribution of basins

where the mean basin elevation (meter) is above 2500m. Note that mean basin elevations are considerably higher in the Interior West.

Figure 4. Locations of snowcourse measurement sites used in the analysis of snow-water equivalence (SWE). Separate panels show trends in accumulated snowpack for (a) April 1, (b) May 1, and (c) June 1. Red circles indicate decreasing SWE values, and blue circles indicate increasing SWE values; filled (open) symbols represent stations passing (failing) two-tailed t tests of significance.

Figure 5. Scatter plots comparing the trends in SWE against snowcourse elevation, in meters, for measurements taken (a) March 1, (b) April 1, and (c) May 1, and maps illustrating the spatial distribution of stations where the elevation is above/below 2500 m (right panel).

Figure 6. Locations of weather stations used in the analysis of climate variations Separate panels show (a) changes in the timing of the spring warm spell, in days; (b) changes in winter precipitation, in centimeters; and (c) changes in winter temperature, in degrees celsius. Color coding is the same as in Figure 4.

Figure 7. Scatter plots showing realtions between weather station elevation and trends in (a) warm day spells, (b) winter temperature and (c) winter precipitation, and a map (d) illustrating the spatial distribution of COOP stations below 800 m (green circles),

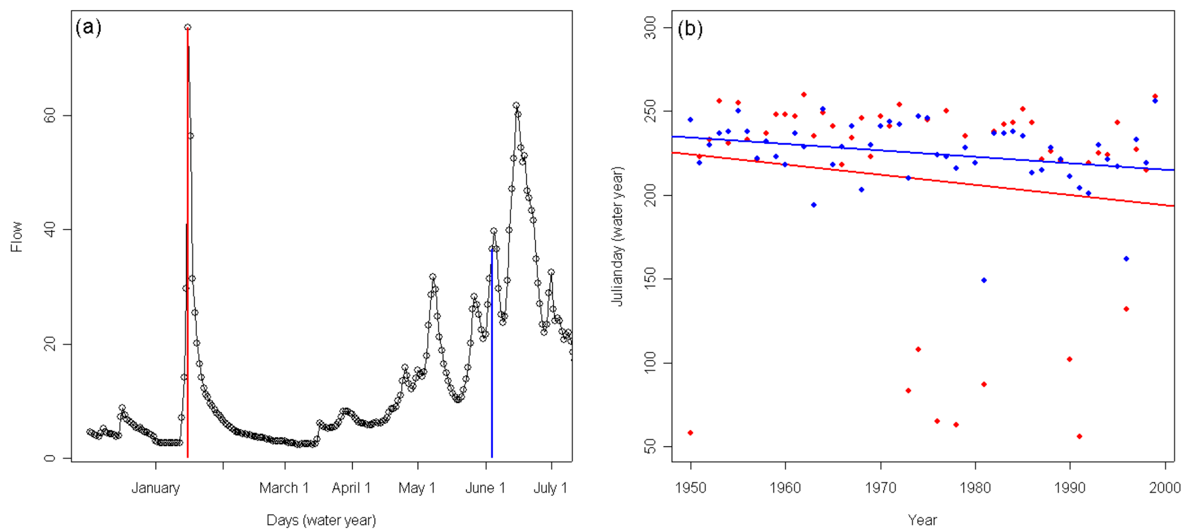
between 800 m and 2500 m (blue circles), and COOP stations above 2500 m (red circles). Note that there are very few COOP stations at high elevations.

Figure 8. Trends in annual runoff at USGS gauging stations. Color coding is the same as in previous figures.

Figure 9. Trends in monthly runoff for (a) March, (b) April, (c) May, and (d) June. Color coding is the same as in previous figures.

Figure 10. Trends in the fraction of annual runoff that occurs in (a) March, (b) April, (c) May, and (d) June. Color coding is the same as in previous figures.

Figure 11. Trends in the timing of 50% of the annual runoff, in days, for separate time periods: (a) 1950-1974 and (b) 1975-99. Color coding is the same as in previous figures.



(a)
Flow
0
20
40
60
January
March 1
April 1
May 1
June 1
July 1
Days (water year)
(b)
Julianday (water year)
50
100
150
200
250
300
1950
1960
1970
1980
1990
2000
Year

Figure 1

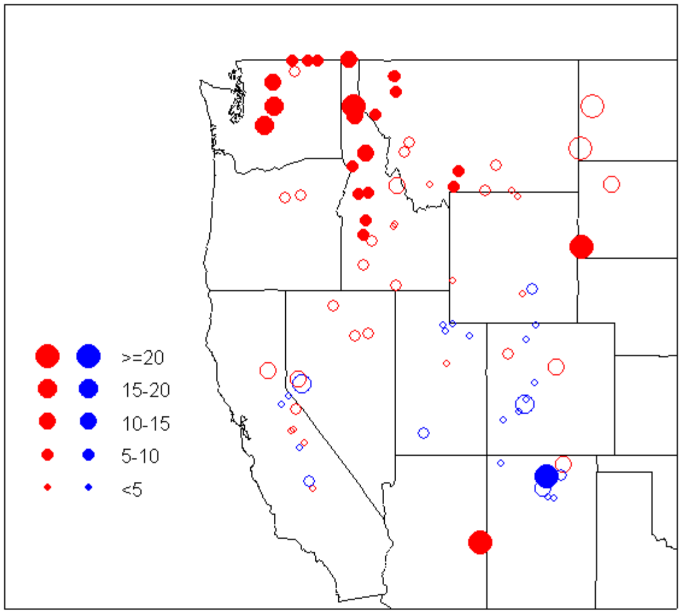
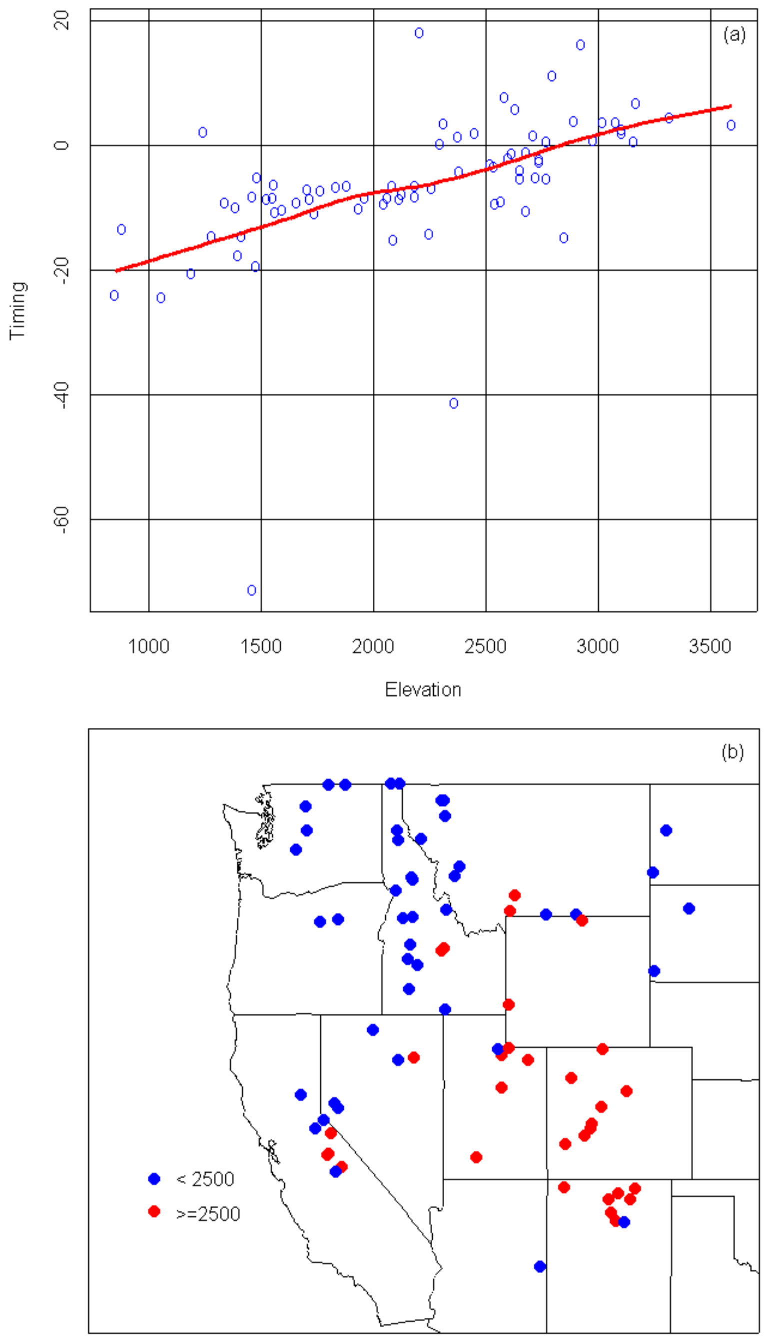


Figure 2



(a)
Timing
20
0
-20
-40
-60
1000
1500
2000
2500
3000
3500
Elevation
(b)
< 2500
>=2500

Figure 3

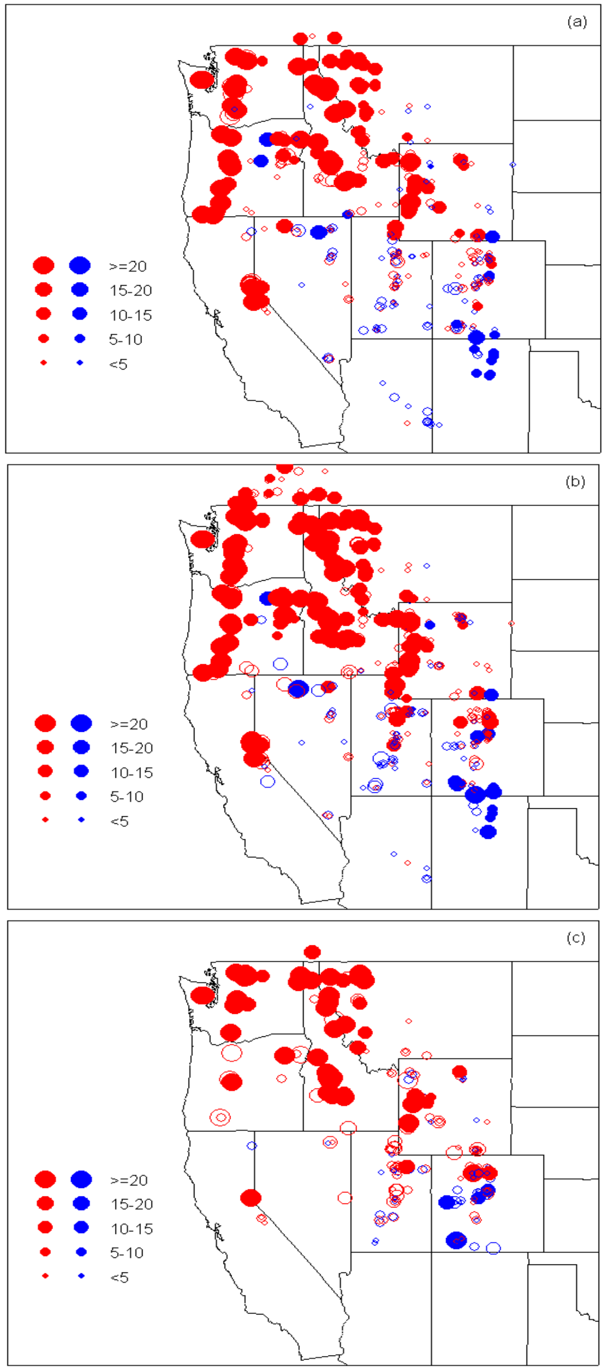


Figure 4

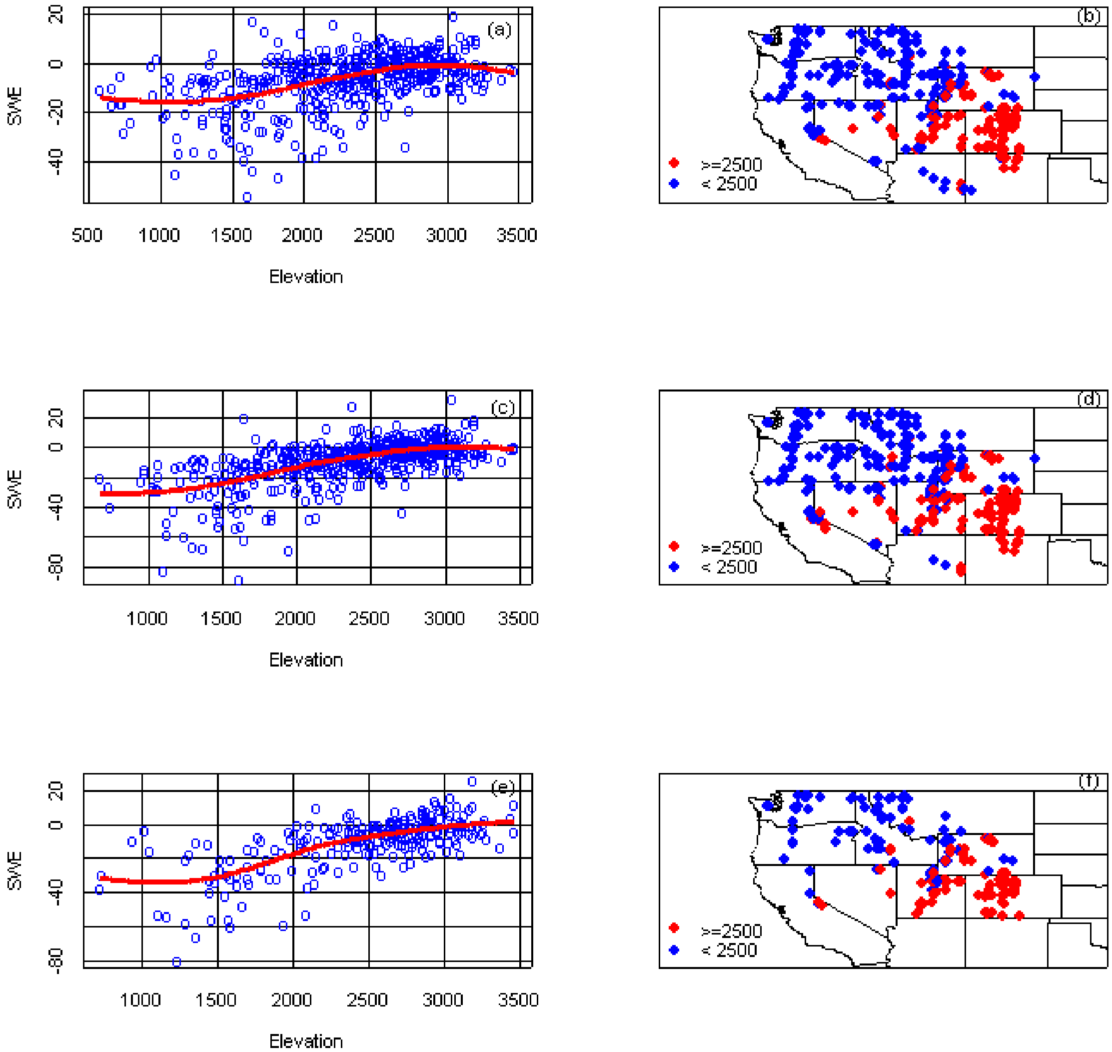

(a)
SWE
20
0
-20
-40
500
1000
1500
2000
2500
3000
3500
Elevation
(b)
>=2500
< 2500
(c)
SWE
20
0
-40
-80
1000
1500
2000
2500
3000
3500
Elevation
(d)
>=2500
< 2500
(e)
SWE
20
0
-40
-80
1000
1500
2000
2500
3000
3500
Elevation
(f)
>=2500
< 2500

Figure 5

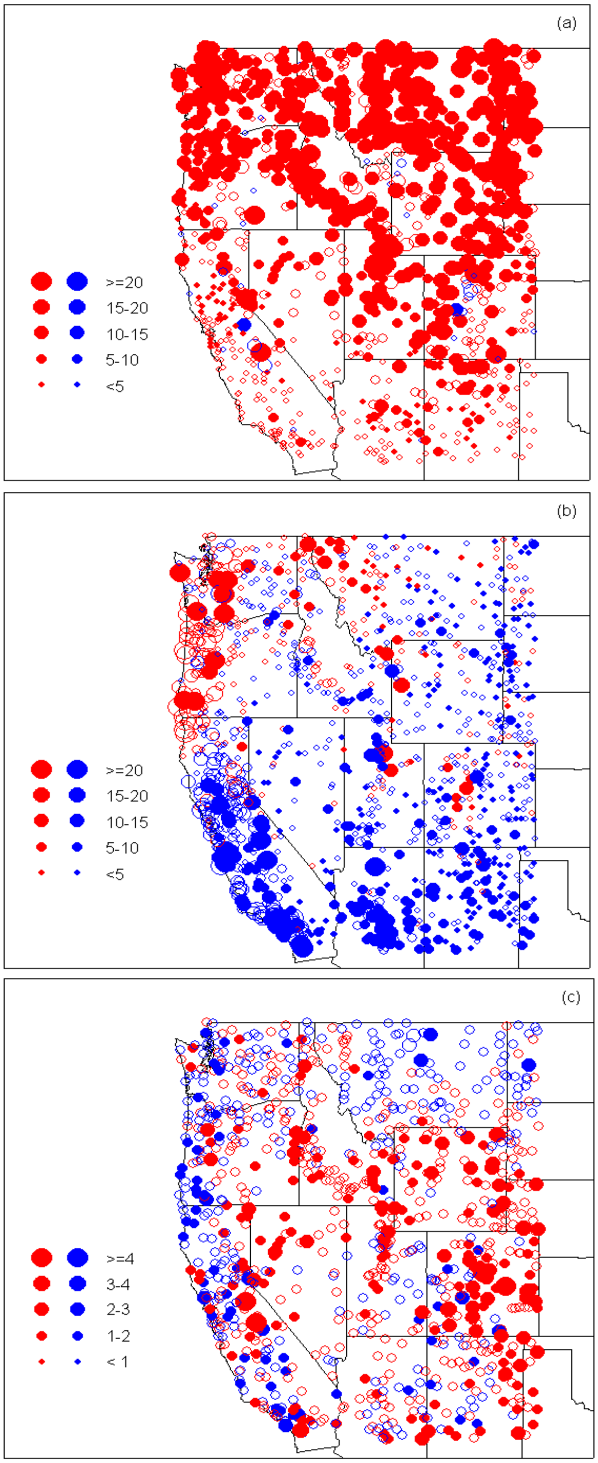


Figure 6

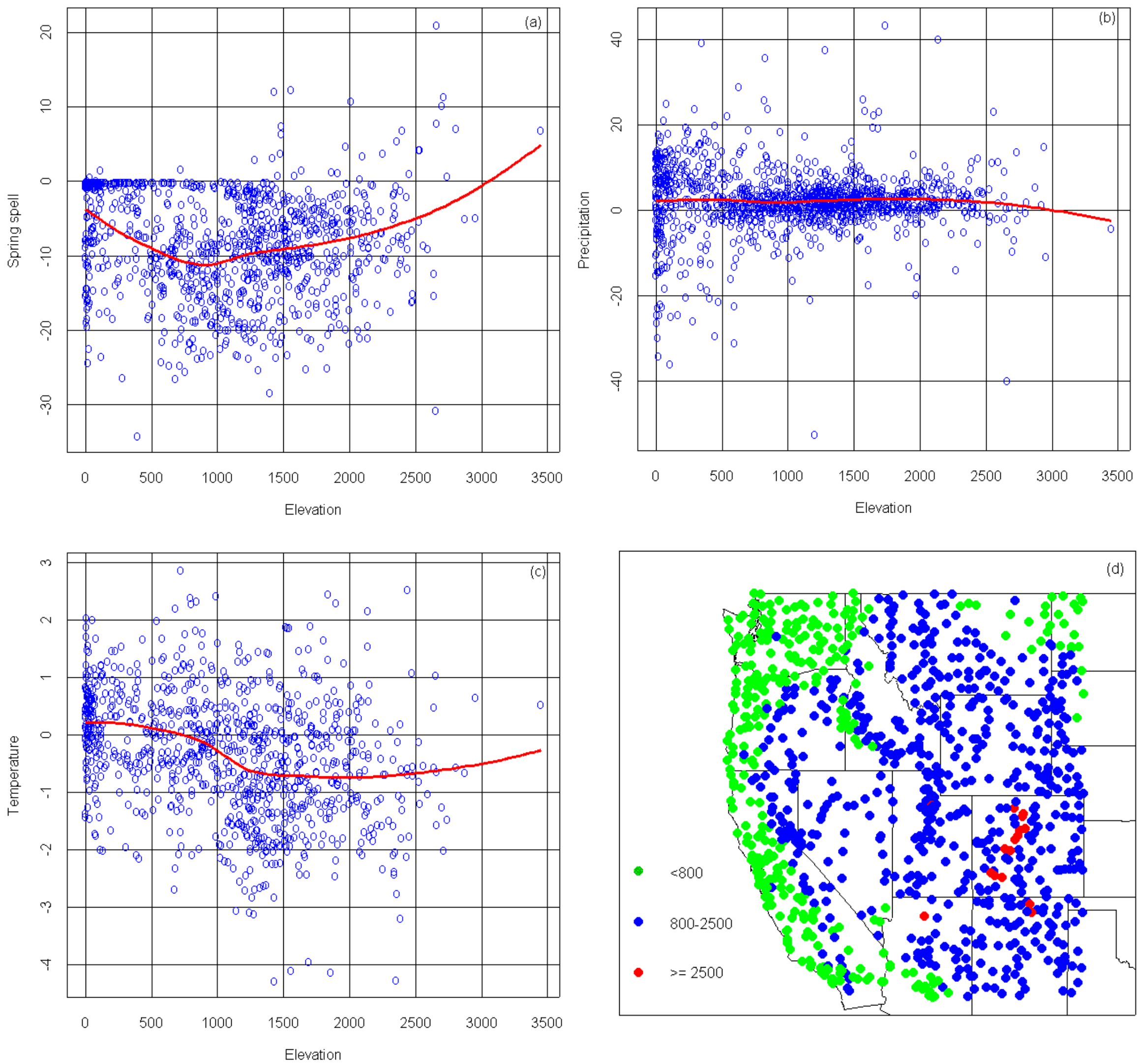

(a)
Spring spell
Elevation
(b)
Precipitation
Elevation
(c)
Temperature
Elevation
(d)
<800
800-2500
>= 2500

Figure 7

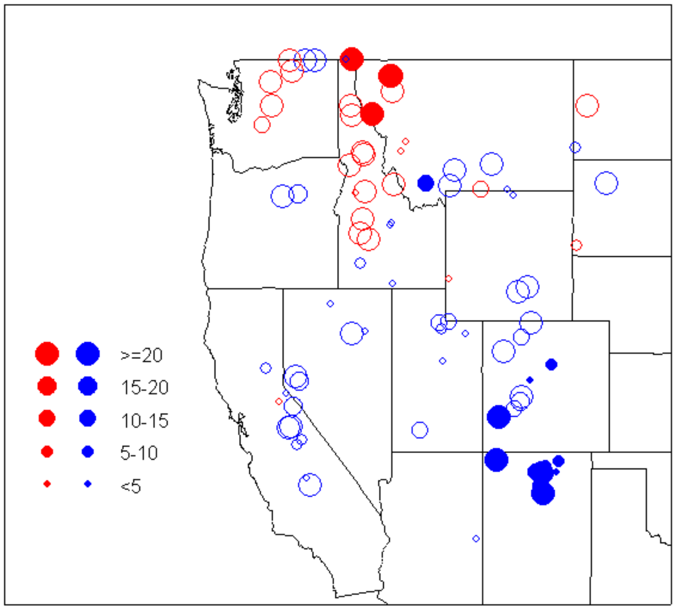


Figure 8

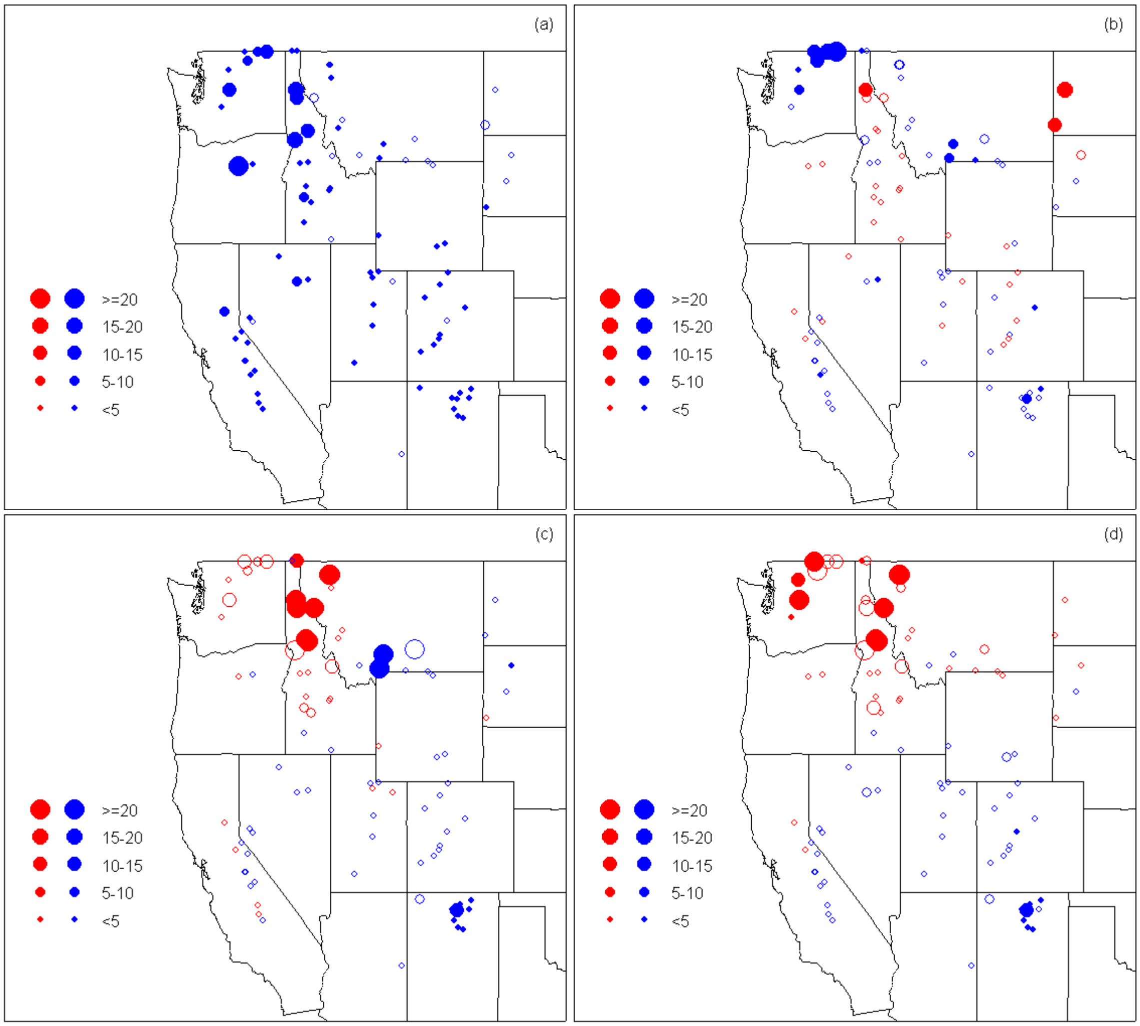


Figure 9

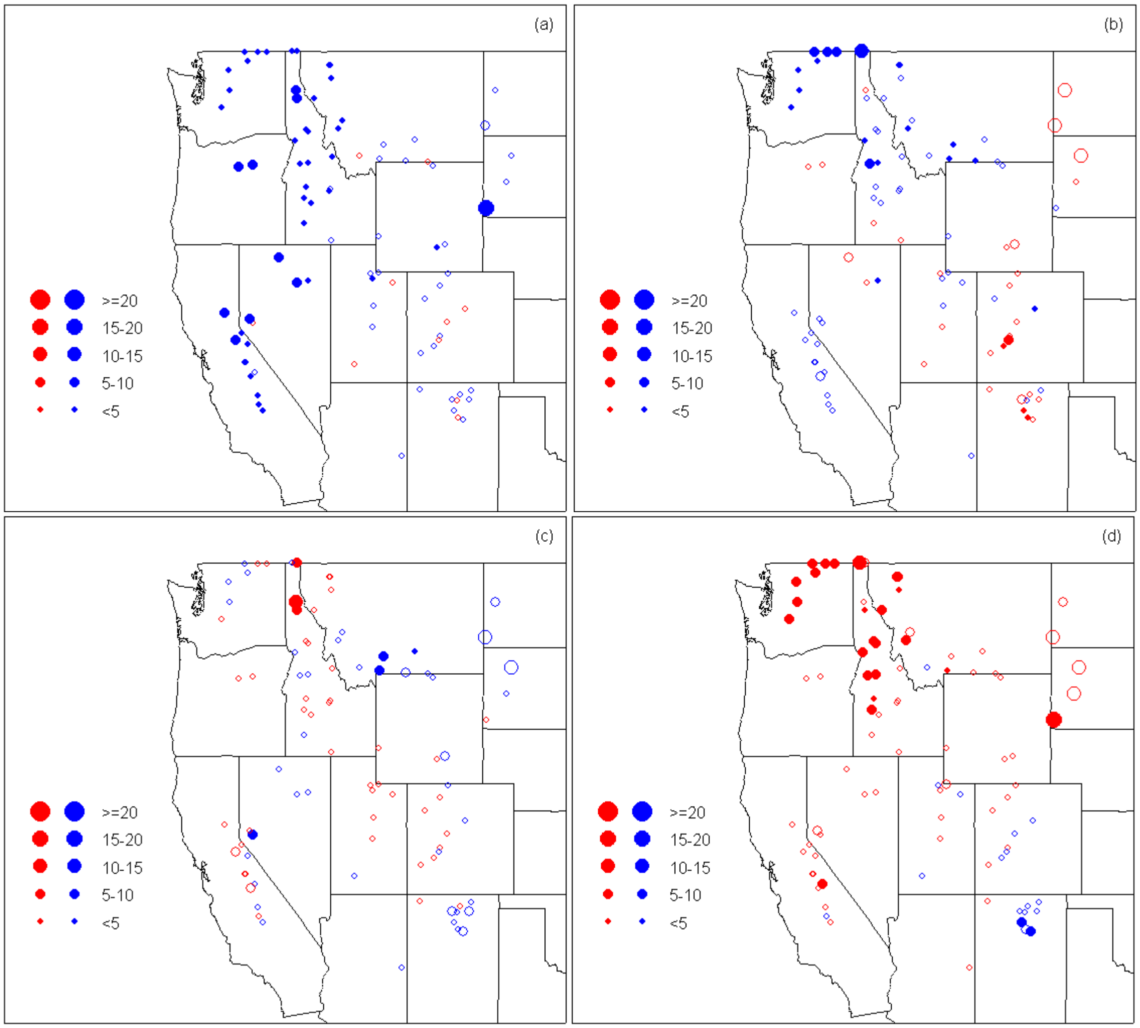

(a)
>=20
15-20
10-15
5-10
<5
(b)
>=20
15-20
10-15
5-10
<5
(c)
>=20
15-20
10-15
5-10
<5
(d)
>=20
15-20
10-15
5-10
<5

Figure 10

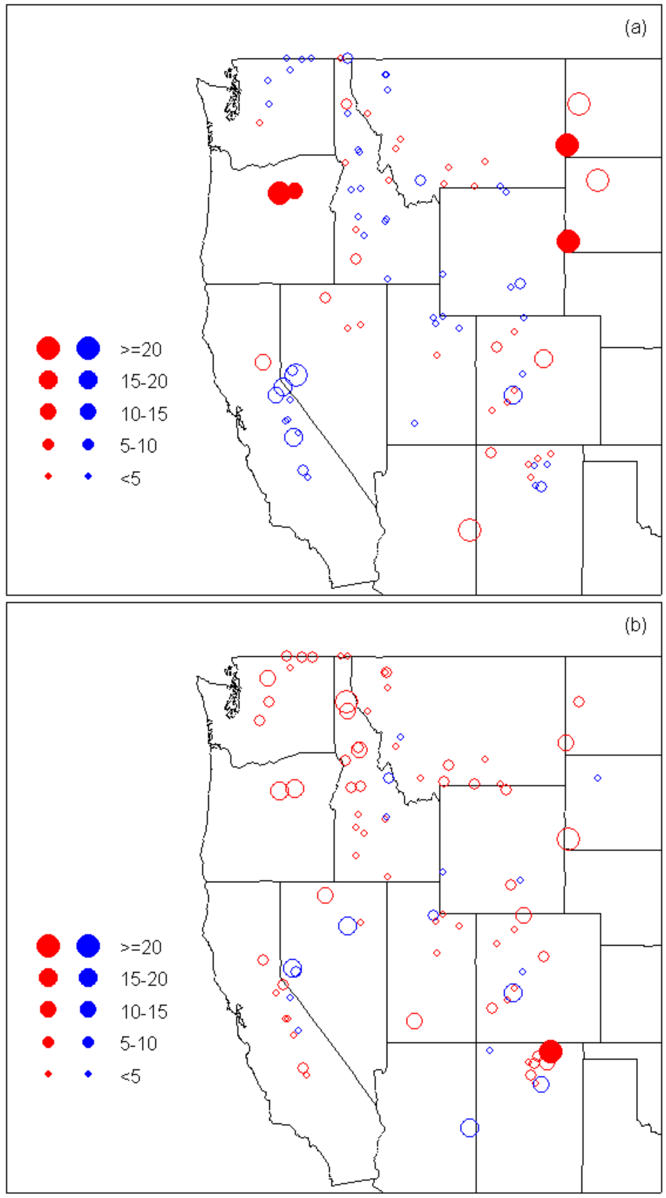


Figure 11