Thermal Regimes of Flowing Waters in the Western U.S.

Dan Isaak, Charlie Luce, Dona Horan, Gwynne Chandler, Sherry Wollrab, William Dubois, and Dave Nagel

Introduction

Thermal regimes profoundly affect aquatic ecosystems through controls on stream metabolism, species distributions, phenology, and community structure but have been poorly described, classified, and mapped due to the limited availability of annual datasets from spatially extensive and representative monitoring networks. Here, we mine the NorWeST temperature database (Chandler et al. 2016; Isaak et al. 2017) to extract a representative set of annual records for a five-year period (December 1, 2010 to November 30, 2015) at 578 sites that spanned a diverse set of free-flowing and regulated rivers and streams in the western U.S. The records were summarized using a set of 34 metrics in five categories related to magnitude, variability, frequency, timing, and duration (Table 1). Multivariate cluster analysis and principal components analysis (PCA) were used to describe metric commonalities and discern those that conveyed the most information about thermal regimes, before predictive multiple regression models were used to map key regime elements throughout the western perennial network based on relationships with climatic, geomorphic, landscape, and hydrologic covariates.

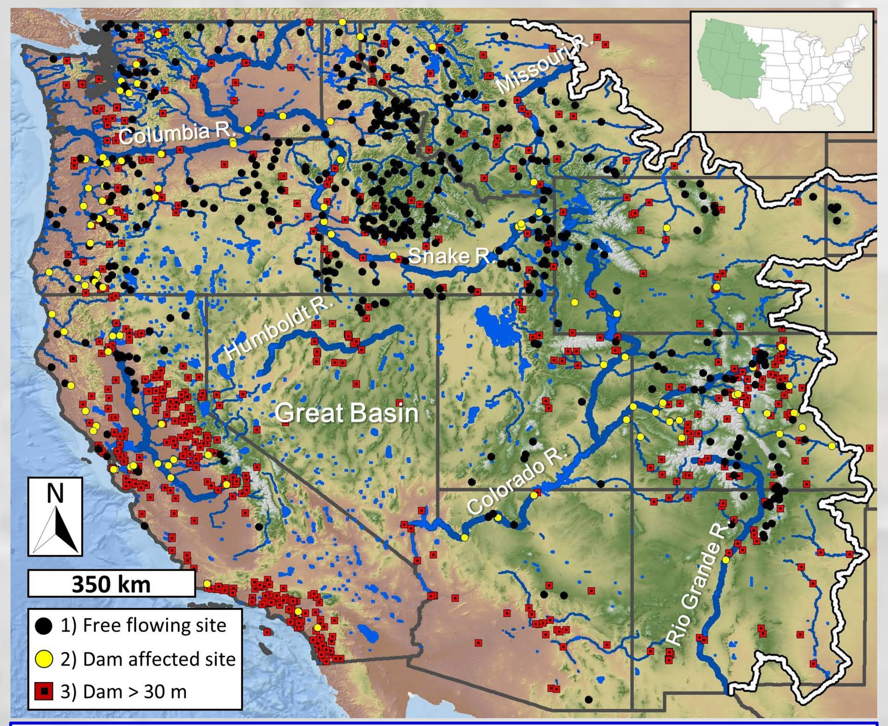


FIGURE 1. Study area map showing the 578 temperature monitoring sites and the locations of dams that exceeded 30 m in height. Temperature sites are color coded based on their occurrence relative to dams and flow regulated reaches.

Table 1. Temperature metrics used to describe thermal regimes of rivers and streams in the western U.S.

Category	Thermal metric	Definition
Magnitude	M1. Mean annual temperature	Average of mean daily temperatures during a year
	M2. Mean winter temperature	Average of mean daily temperatures during December, January, and February
	M3. Mean spring temperature	Average of mean daily temperatures during March, April, and May
	M4. Mean summer temperature	Average of mean daily temperatures during June, July, and August
	M5. Mean August temperature	Average of mean daily temperatures during August
	M6. Mean fall temperature	Average of mean daily temperatures during September, October, and November
	M7. Minimum daily temperature	Lowest mean daily temperature during a year
	M8. Minimum weekly average temperature	Lowest seven-day running average of mean daily temperature during a year
	M9. Maximum daily temperature	Highest mean daily temperature during a year
	M10. Maximum weekly average temperature	Highest seven-day running average of mean daily temperature during a year
	M11. Annual degree days	Cumulative total of degree days during a year (1°C for 24 hours = 1 degree day)
Variability	V1. Annual standard deviation	Standard deviation of mean daily temperature during a year
	V2. Winter standard deviation	Standard deviation of mean daily temperature during winter months
	V3. Spring standard deviation	Standard deviation of mean daily temperature during spring months
	V4. Summer standard deviation	Standard deviation of mean daily temperature during summer months
	V5. August standard deviation	Standard deviation of mean daily temperature during the month of August
	V6. Fall standard deviation	Standard deviation of mean daily temperature during fall months
	V7. Range in extreme daily temperatures	Difference between minimum and maximum mean daily temperatures during a year (M9 minus M7)
	V8. Range in extreme weekly temperatures	Difference between minimum and maximum weekly average temperatures during a year (M10 minus M8)
	V9. Inter-annual standard deviation of mean annual	Inter-annual standard deviation in mean annual temperature
	V10. Inter-annual standard deviation of minimum weekly	Inter-annual standard deviation in minimum weekly average temperature
	V11. Inter-annual standard deviation of maximum weekly	Inter-annual standard deviation in maximum weekly average temperature
	V12. Inter-annual standard deviation of 5% degree days	Inter-annual standard deviation in date of 5% of degree days
	V13. Inter-annual standard deviation of 50% degree days	Inter-annual standard deviation in date of 50% of degree days
Frequency	F1. Frequency of hot days	Number of days with mean daily temperatures >20 °C
	F2. Frequency of cold days	Number of days with mean daily temperatures <2 °C
Timing	T1. Date of 5% degree days	Number of days from December 1st until 5% of degree days are accumulated
	T2. Date of 25% degree days	Number of days from December 1st until 25% of degree days are accumulated
	T3. Date of 50% degree days	Number of days from December 1st until 50% of degree days are accumulated
	T4. Date of 75% degree days	Number of days from December 1st until 75% of degree days are accumulated
	T5. Date of 95% degree days	Number of days from December 1st until 95% of degree days are accumulated
Duration	D1. Growing season length	Number of days between the 95% and 5% of degree days (T5 minus T1)
	D2. Duration of hot days	Longest number of consecutive days with mean daily temperatures >20 °C
	D3. Duration of cold days	Longest number of consecutive days with mean daily temperatures <2 °C

The metric summaries of the 578 temperature records were used in an agglomerative hierarchical cluster analysis, which suggested that the record sites could be grouped into seven discrete classes. Mapping those categories revealed geographic distinctions between coastal and inland areas, as well as northern and southern areas, although there was a mix of classes in some areas, probably due to strong local gradients in elevation or other factors that affected thermal dynamics over short distances in complex terrain (Figures 2 and 3). Streams of the coastal thermal regime class were at low elevations along the Pacific Ocean and characterized by warm winters, early spring onsets, and moderate summer temperatures (Figures 2 and 3). Often in close proximity were streams with mid-elevation mountain regimes, which occurred in the Cascade Mountain range of Oregon and Washington and were scattered in parts of the Rocky Mountains. These streams had cold temperatures during both the winter and summer and a limited annual range. High mountain thermal regimes were common throughout the Rocky Mountain region and characterized by streams with winter temperatures near 0 °C for prolonged periods, cold summers, and spring onset that was 1–3 months later than other classes. Streams with continental thermal regimes were also common in the Rocky Mountain region but occurred at lower elevations and had warmer summer temperatures and larger annual temperature ranges. Spring thermal regimes were rare in our sample and distinct from the other regime types by their nearly constant temperatures. Another uncommon regime type was the river-reservoir class, which had cold winters, warm summers, late peak temperatures, and little short-term variability. Sites in this class occurred in run-of-the-river reservoirs along the Columbia and Snake Rivers, which are the two largest rivers by discharge in the West. Hot variable streams comprised the last thermal class and were mostly confined to the southwest and inland portions of southern California.

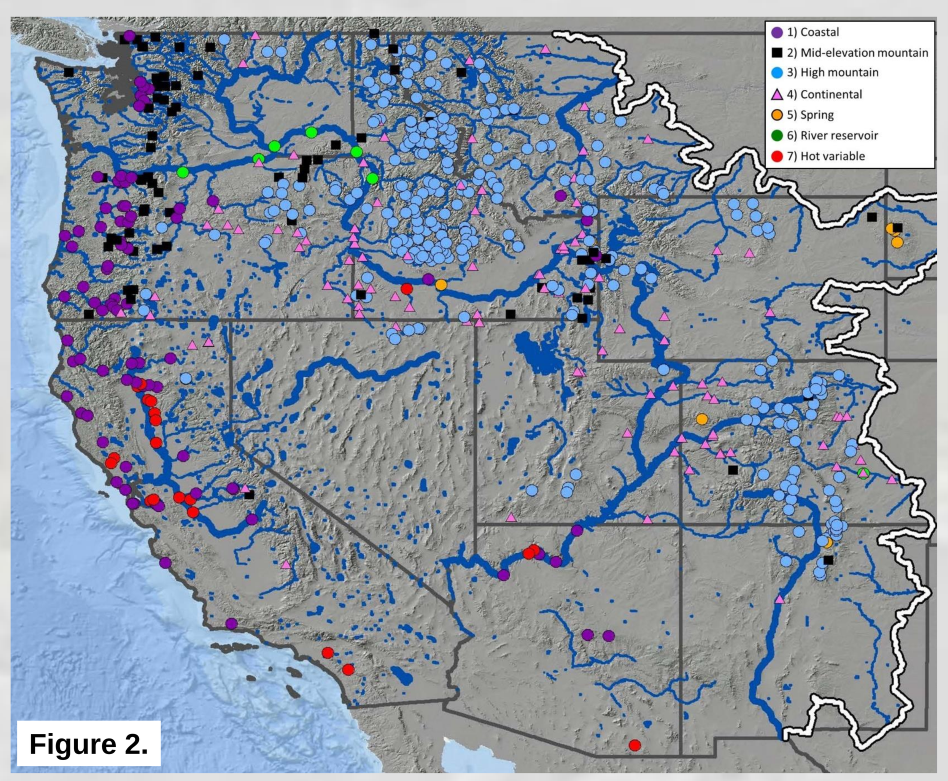
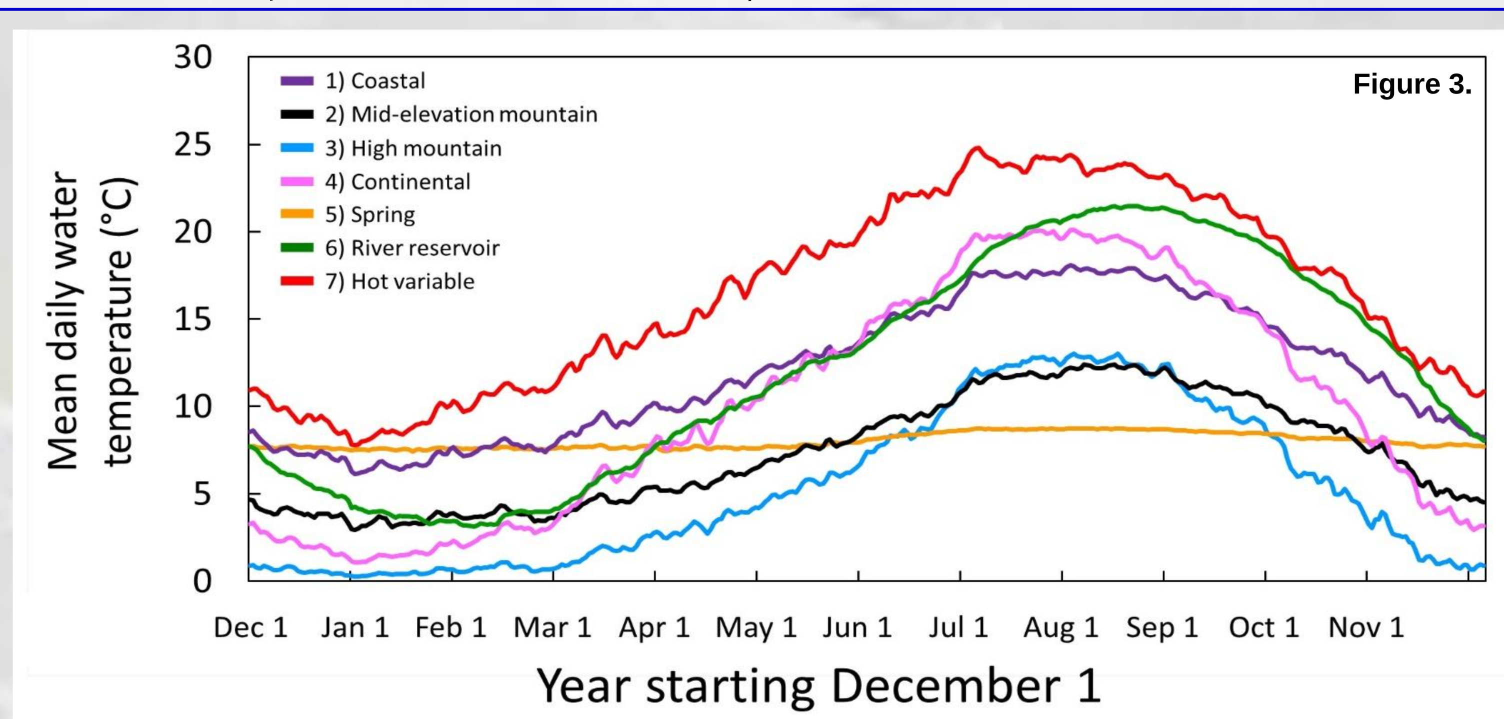
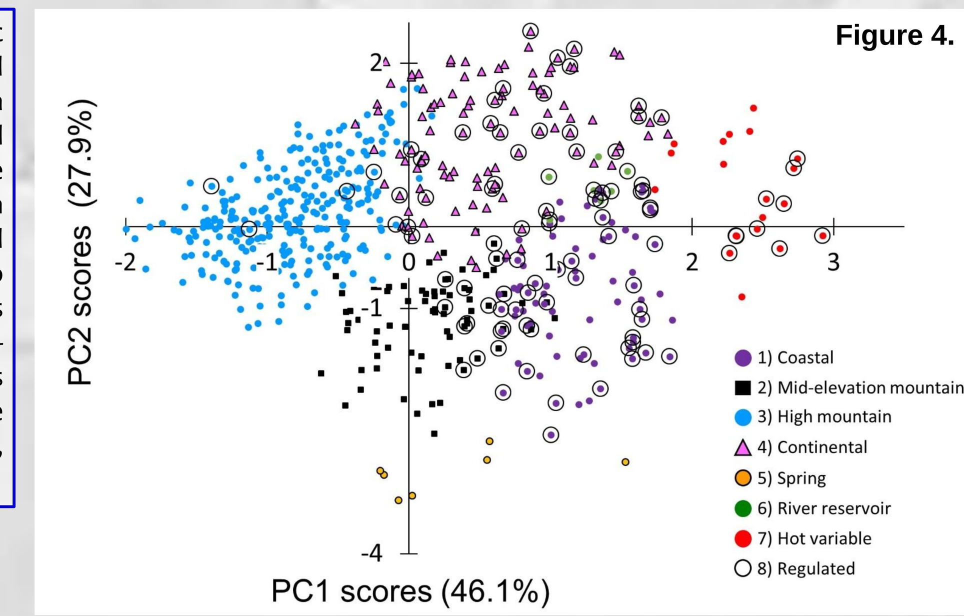


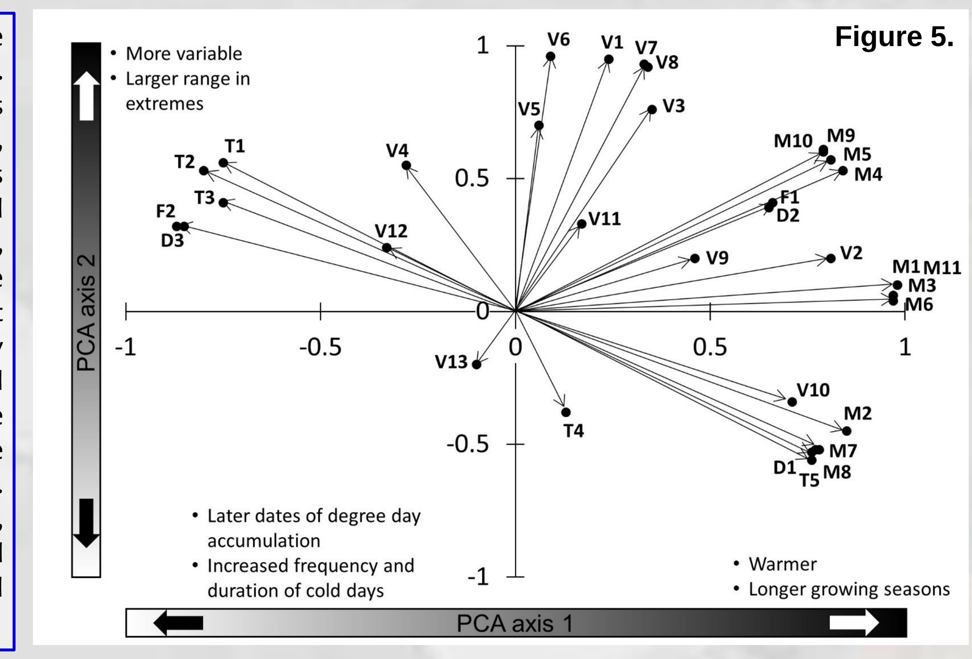
Figure 2.



As a compliment to the cluster analysis, the 34 metric summaries were also used in a PCA to describe and summarize relationships among the metrics along a reduced set of orthogonal axes. Those results indicated that five PCs cumulatively accounted for 89.1% of the variation in the metrics dataset but most of this variation was attributable to the first PC (46.1% of variation) and the second PC (27.9% of variation). The ordination plot to the right of PC1 versus PC2 scores revealed a continuous data cloud in which the 578 stream sites plotted as semi-discrete areas by their thermal class (Figure 4). Sites affected by dam regulation are also highlighted in the ordination plot, and usually fell within the hot variable, river reservoir, continental, or coastal regime types.



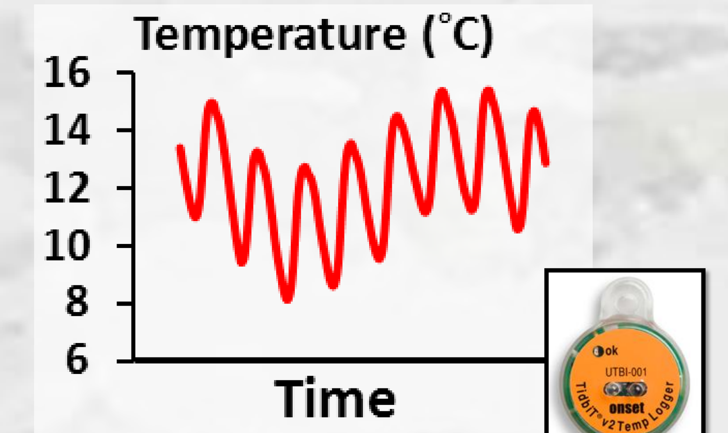
The Figure 5 biplot to the right shows which temperature metrics best defined the PC axes in the ordination plot. PC1 correlated strongly (r > 0.7) with most of the metrics that represented magnitude (Mx), frequency (Fx), duration (Dx), and timing (Tx). The second PC and was correlated with variability (Vx) metrics during seasonal and annual time periods. Not surprisingly, therefore, stream sites in the hot variable class plotted at the extreme right on the PC1 axis in the ordination plot (Figure 4) because these systems tended to be especially warm, had earlier springs, longer growing seasons, and few cold days. High mountain streams, where the opposite of those attributes was common, plotted at the other end of the PC1 spectrum with negative values. Large values on the PC2 axis indicated greater variability, which is where streams with continental regimes plotted opposite spring streams that showed little temporal variability.



The scores summarizing thermal variation along the PC1 and PC2 axes were used as response variables in two multiple linear regressions (Table 2). Covariate predictors in the regressions were derived from nationally available GIS datasets and represented climatic, geomorphic, landscape, and hydrologic factors hypothesized to affect stream and river temperatures. The first multiple regression explained 87% of the variation in PC1 and included seven covariates (in decreasing order of effect size): elevation, latitude, riparian canopy, reach slope, annual precipitation, upstream lake proportion, and dam height. A quadratic effect for dam height was included because small dams with shallow reservoirs tend to warm downstream rivers whereas taller dams with deep reservoirs had a cooling effect. The second multiple regression explained 63% of the variation in PC2 and many of the same covariates that appeared in the PC1 model again had significant effects. Exceptions were the addition of significant covariates for mean August temperature, precipitation, and the Baseflow index. Dam height had a small linear negative effect on PC2, suggesting that taller dams dampened the variability of downstream thermal regimes.

Model	Covariate	b (SE)	t	p-value	r^2
PC1	Intercept	7.36 (0.23)	31.4	< 0.01	0.87
	Elevation	-0.00104 (0.0000239)	-43.6	< 0.01	
	Latitude	-0.129 (0.00528)	-24.5	< 0.01	
	Riparian canopy	-0.00593 (0.000683)	-8.68	< 0.01	
	Reach slope	-3.32 (0.584)	-5.69	< 0.01	
	Annual precipitation	-0.000200 (0.0000385)	-5.20	< 0.01	
	Lake	0.0671 (0.0153)	4.38	< 0.01	
	Dam height	0.00213 (0.00114)	1.88	< 0.01	
	Dam height^2	-0.0000203 (0.00000702)	-2.89	0.06	
PC2	Intercept	-11.9 (0.56)	-21.4	< 0.01	0.63
	August temperature	0.275 (0.011)	24.5	< 0.01	
	Elevation	0.00104 (0.000053)	19.5	< 0.01	
	Latitude	0.159 (0.011)	14.4	< 0.01	
	Riparian canopy	0.00368 (0.0012)	3.13	< 0.01	
	Lake	-0.070 (0.025)	-2.84	< 0.01	
	Precipitation	-0.00014 (0.000070)	-1.98	0.05	
	Drainage area	-0.0000015 (0.00000059)	-2.48	0.01	
	Baseflow index	-0.00499 (0.00287)	-1.74	0.08	
	Reach slope	1.78 (1.0)	1.77	0.08	
	Dam height	-0.0027 (0.0045)	-1.47	0.10	

The expansive and geoclimatically diverse western U.S. hosts a variety of lotic systems that include high-elevation mountain streams and rivers (a), spring streams associated with karst or other geologic types with high water yields (b), impounded rivers (c), low elevation coastal streams that drain into the Pacific Ocean (d), mid-elevation streams flowing through rangelands and steppe (e), and desert streams (f). The likelihood that differences in the landscapes through which western streams flow would be reflected in distinct thermal regimes was an important motivation for this research.



The multiple regression models were used to create west-wide maps of thermal regime components by multiplying the parameter estimates from Table 2 by covariate values associated with each reach in the 343,000 km network of perennial streams and rivers. The resulting map of PC1 showed significant heterogeneity throughout the region, with high scores indicating warmer streams with earlier springs, longer growing seasons, and fewer cold days common at lower elevations in California, coastal Oregon, and the southwest (Figure 6a). Not surprisingly, streams with low PC1 scores and opposing regime characteristics were prevalent in the mountainous areas and adjacent foothills throughout the interior Rocky Mountain region, the Sierra Nevadas of eastern California, and the Cascade Range of western Oregon and Washington.

The PC2 map representing thermal variability (Figure 6b) showed broadly similar spatial patterns as the PC1 map in that stream thermal regimes throughout coastal areas were generally distinct from streams in the Rocky Mountain region. Streams with particularly low PC2 scores and variability were most common in coastal and mountainous areas of Oregon, Washington, and northern California, whereas low variability streams also occurred at the highest elevations in the mountains or at lower elevations in portions of northern Idaho and northwest Montana that have maritime climates. The highest PC2 scores occurred in the interior and foothill areas that bordered mountains, high elevation steppe rangelands, and large, low elevation rivers.

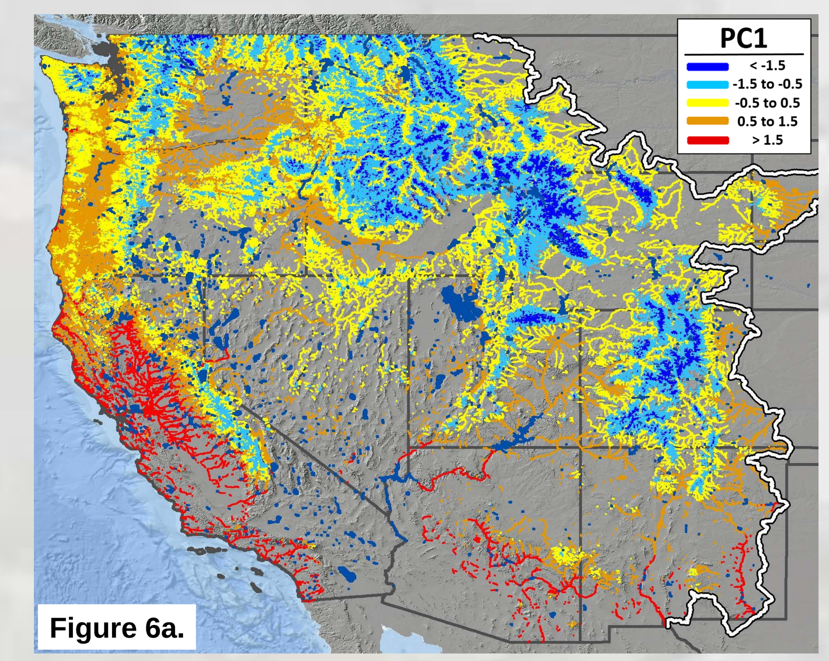


Figure 6a.

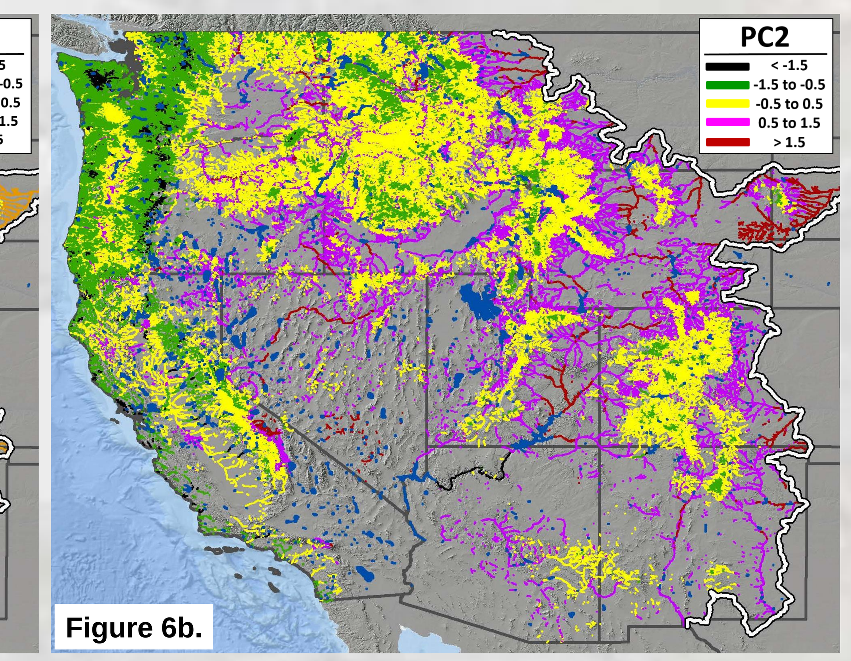


Figure 6b.

Discussion

Our results highlight the diversity and key attributes of thermal regimes in flowing waters across the West, as well as many of the environmental factors that shape these regimes. Despite that diversity, much of the information in temperature records could be summarized by a small number of PCs—indicating that distinct regime components were limited and that careful selection of a few metrics could represent much of the salient thermal information in subsequent ecological applications. Highlighting that fact, a mean August temperature metric that is closely allied with PC1, has already been used in numerous studies to understand where throughout western river networks species invasions, range contractions from climate warming, and hybridization zones may occur, to develop accurate species distribution models, and to precisely predict where climate refuge streams will occur for species of conservation concern (Isaak et al. 2017). Those studies, like most previous considerations of temperature in stream ecology have focused on a summer magnitude metric, but consideration and testing of additional thermal metrics, especially those correlated with PC2, could aid development of a more nuanced understanding of the ecologically relevant aspects of thermal regimes.

This research also highlights the fact that a centralized temperature database can be easily repurposed when a useful research question is used to guide a database query and extract a relevant subset of data. It is important that researchers have access to extensive temperature records because many important questions pertaining to thermal ecology and regimes have yet to be adequately addressed, and many new types of temperature models and inference are yet needed at a variety of scales to address these questions. In the western U.S., the NorWeST database provides a valuable resource for those endeavors because the 578 temperature time-series used here were only a small subset of records from the >23,000 unique sites in the database, all of which are available at the project website (https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). As thermal regime research proliferates and matures, it should complement the corpus of knowledge developed in previous decades for flow regimes and will broaden and diversify our understanding of hydroclimates in flowing waters to benefit many aspects of stream ecology.

Acknowledgements

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For more information about this research, please see:

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