Principal Components of Thermal Regimes in Central Idaho River Networks

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Introduction

Temperatures of flowing waters control many physicochemical processes and affect the ecology of aquatic organisms and communities. Knowledge of thermal regimes, characterized as the annual sequence of water temperatures specific to unique locations within river networks, is key to understanding natural conditions and diagnosing anthropogenic impairments but the limited availability of annual temperature records has slowed broad development and adoption of thermal regime concepts comparable to those that have long proven useful for flow regimes. Here, we use annual temperature records that spanned a five-year period and were compiled from several natural resource agencies in central Idaho river networks to characterize thermal regimes. Principal Components Analysis (PCA) was used to describe redundancy among metrics that were used to summarize regime properties, identify distinct aspects of thermal regimes based on orthogonal PCA axes, and assess water temperature responses to climatic variation associated with annual cycles in air temperature and stream discharge.

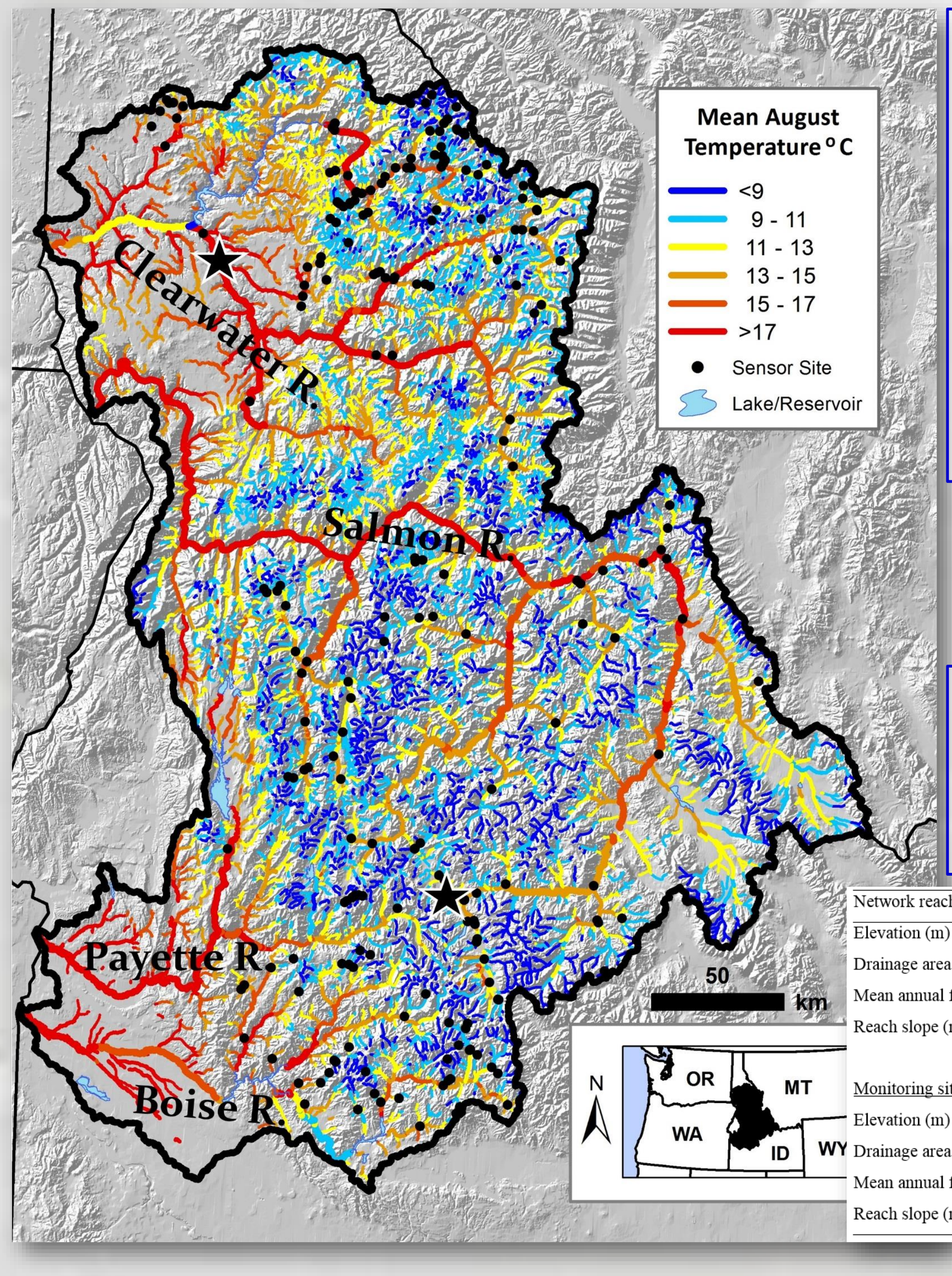


FIGURE 1. Locations of 226 monitoring sites with annual stream temperature records that spanned the period from December 1, 2010 to November 30, 2015 and were used in the analysis. Monitoring sites are overlaid on a NorWeST scenario of mean August stream temperatures for the 29,600 km network in the study area. Stars denote where air temperature and stream discharge records were obtained from a low-elevation site along the lower Clearwater River (294 m, northern station) and a high-elevation site along the upper Salmon River (1850 m, southern station) for comparison to stream temperatures.

Table 1. Descriptive statistics for spatial attributes of the study area network and the 226 sites with annual temperature records. Monitoring sites included a broad range of conditions from small headwater systems to downstream reaches of large rivers.

Network reaches	Mean	Median	SD	Minimum	Maximum
Elevation (m)	1,493	1,533	536	221	3,105
Drainage area (km²)	915	17.7	4,359	0.005	34,865
Mean annual flow (m³/s)	9.73	0.229	43.2	0.0253	379
Reach slope (m/m)	0.0584	0.0519	0.0429	0	0.150
Monitoring sites					
Elevation (m)	1,392	1,407	464	280	2,369
Drainage area (km²)	687	47.3	3,011	2.18	34,865
Mean annual flow (m³/s)	7.37	0.692	26.4	0.0253	281
Reach slope (m/m)	0.0389	0.0273	0.0403	0	0.150

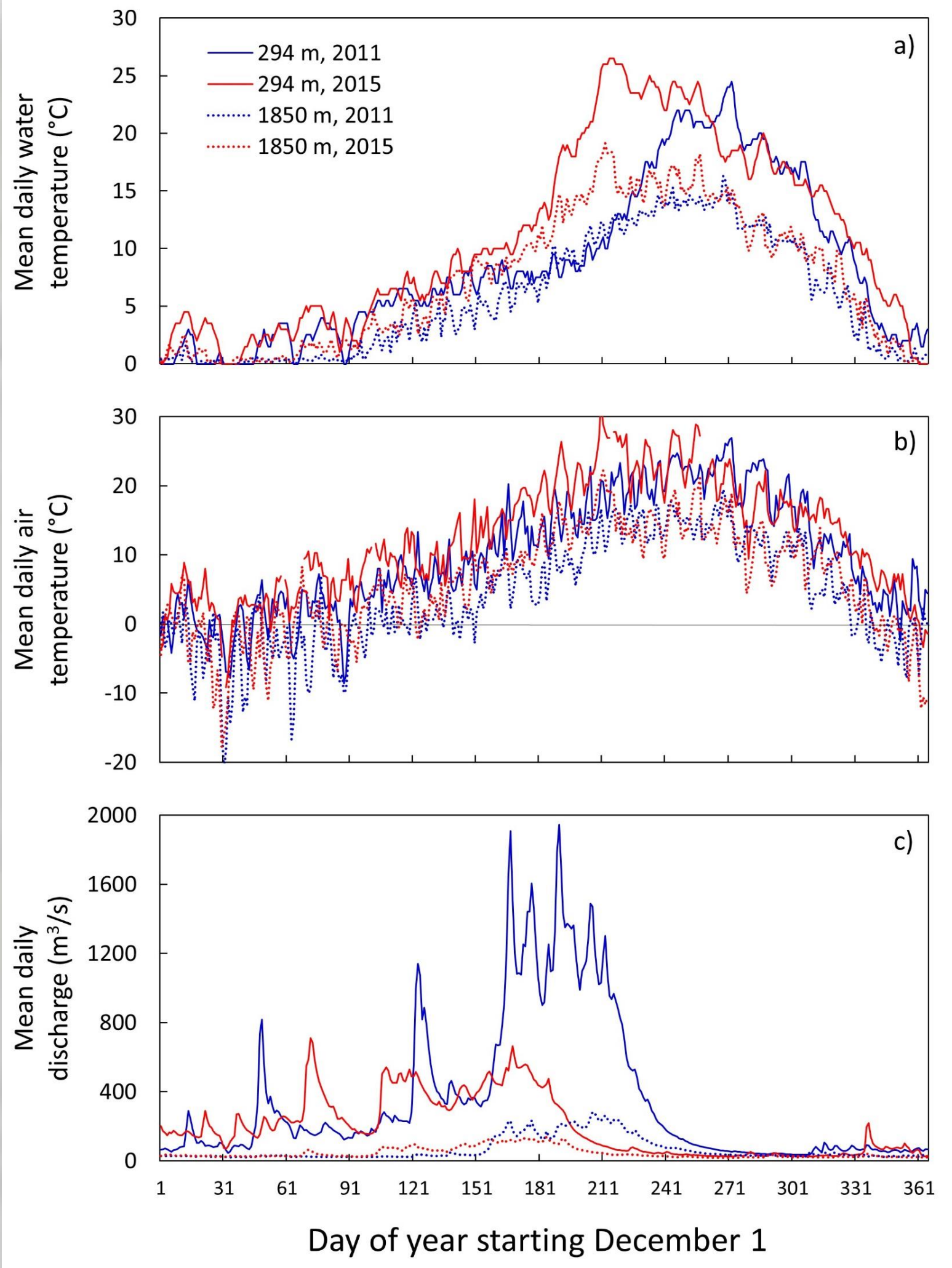


FIGURE 2. The five year study period included considerable inter- and intra-annual climatic variation. Panels show annual cycles of mean daily water temperatures (a), air temperatures (b), and discharge (c) during two contrasting climate years. 2011 was a relatively cool year with a large snowpack whereas 2015 was a warm year with a small snowpack and river runoff.

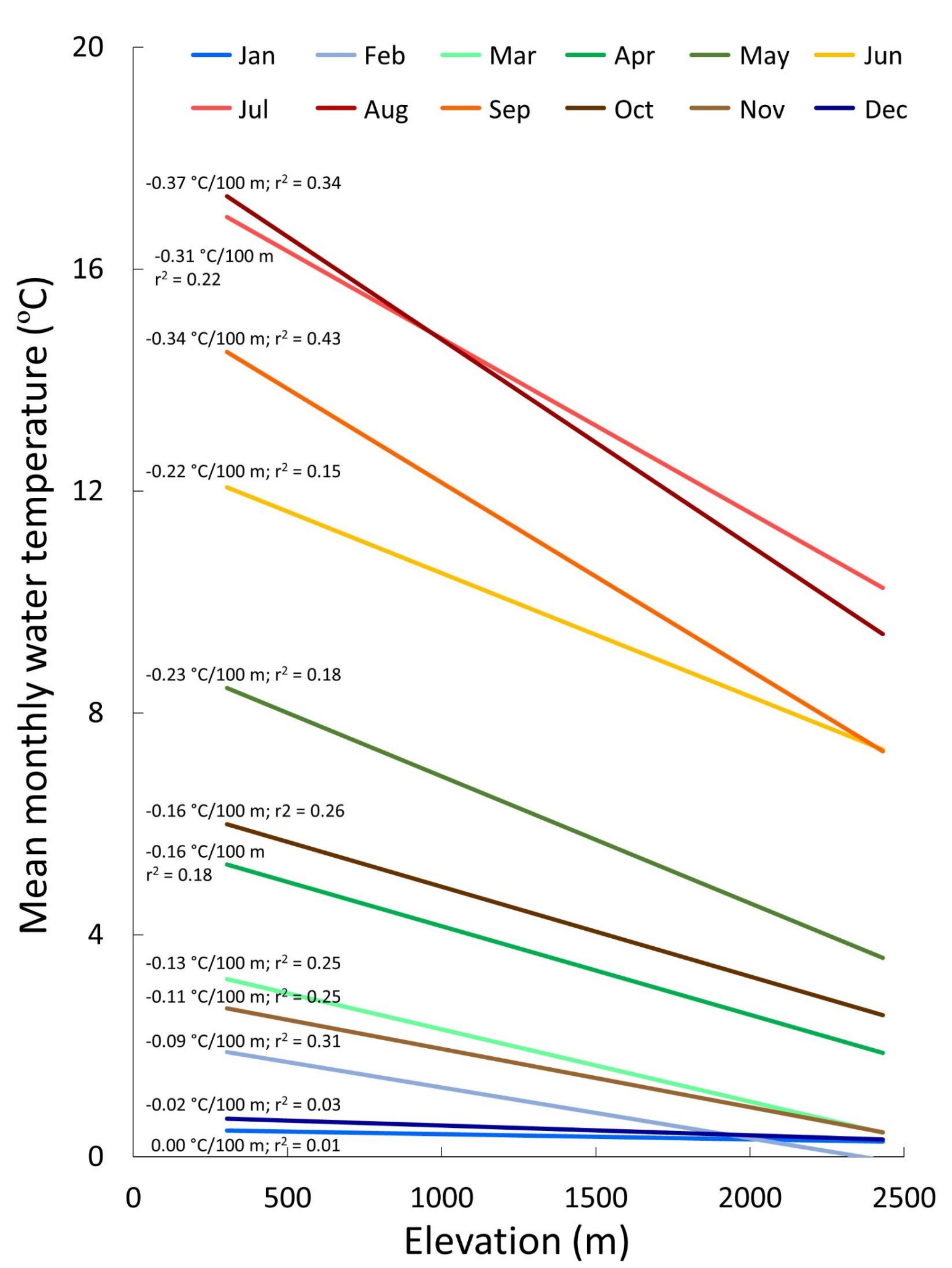
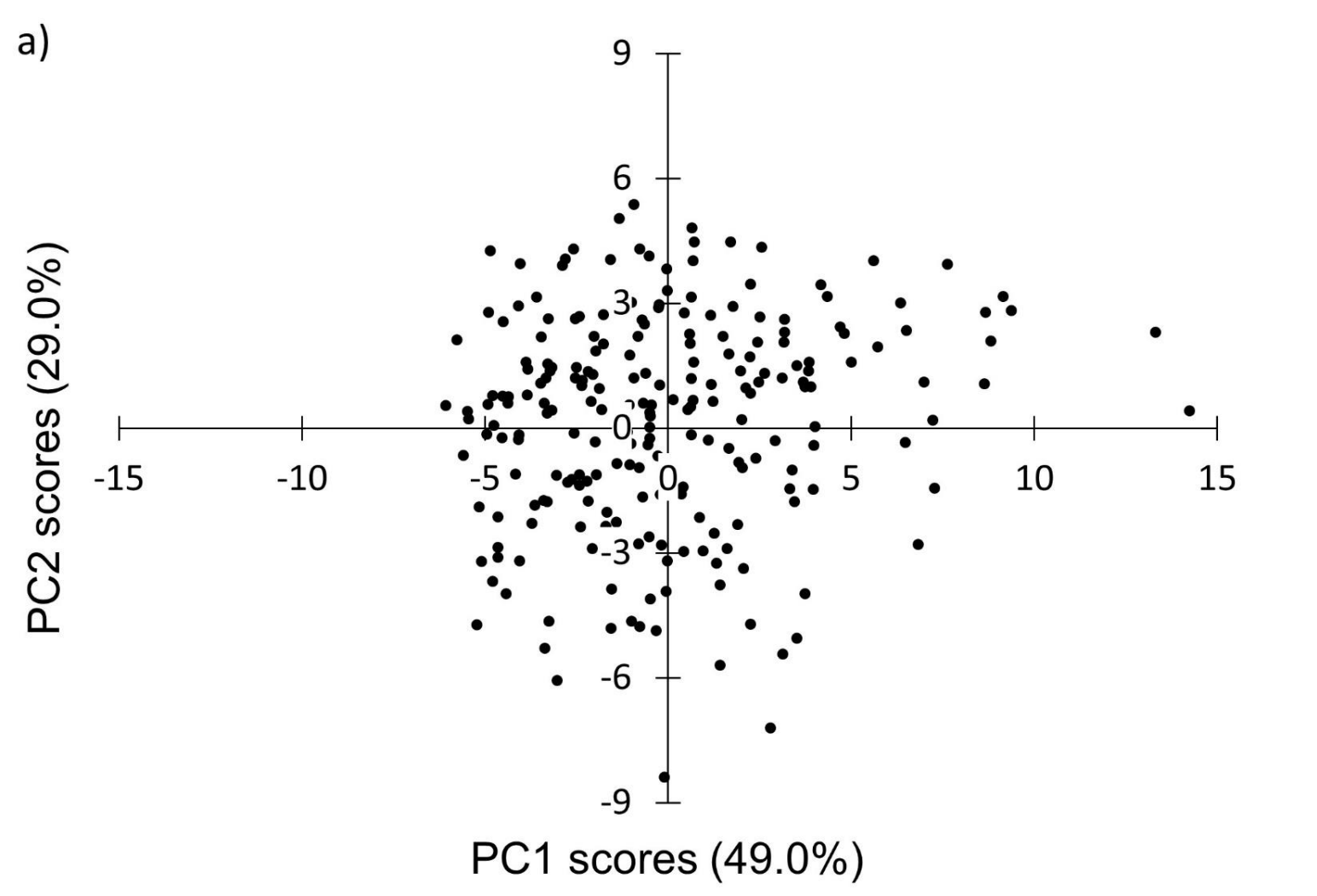


FIGURE 3. Graph summarizing relationship between elevation and mean monthly temperatures at the 226 stream sites shown in Figure 1 during 2013. Trend lines are linear regression slopes for each month (data values are not shown for clarity). During winter months no relationship with elevation was apparent because most sites have temperatures near 0 °C. An elevation trend emerged in the spring as temperatures increased and became most prounounced in July and August when temperatures reached their annual maximums.

Table 2. Twenty-eight temperature metrics were calculated from the records of mean daily temperatures at the 226 sites to describe thermal regimes characteristics. The metrics belonged to one of five general categories associated with magnitude, variability, frequency, timing, or duration as defined below.

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. Fall standard deviation	Standard deviation of mean daily temperature during fall months
	V6. Range in extreme daily temperatures	Difference between minimum and maximum mean daily temperatures during a year (M9 minus M7)
	V7. Range in extreme weekly temperatures	Difference between minimum and maximum weekly average temperatures during a year (M10 minus M8)
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% of degree days	Number of days from December 1st until 5% of degree days are accumulated
	T2. Date of 25% of degree days	Number of days from December 1st until 25% of degree days are accumulated
	T3. Date of 50% of degree days	Number of days from December 1st until 50% of degree days are accumulated
	T4. Date of 75% of degree days	Number of days from December 1st until 75% of degree days are accumulated
	T5. Date of 95% of 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

FIGURE 4a. Ordination plot showing the relationship between PC1 and PC2 scores that were derived from the PCA conducted on the thermal metric descriptors of temperature records from the 226 sites (a). Notice that for a given value of PC1, values of PC2 can be strongly positive or negative. That suggests streams with otherwise similar thermal magnitude and variance structures described by PC1 will sometimes differ substantially with regards to their winter periods and growing season lengths—a distinction that could have important implications for biological communities or stream physicochemical processes.



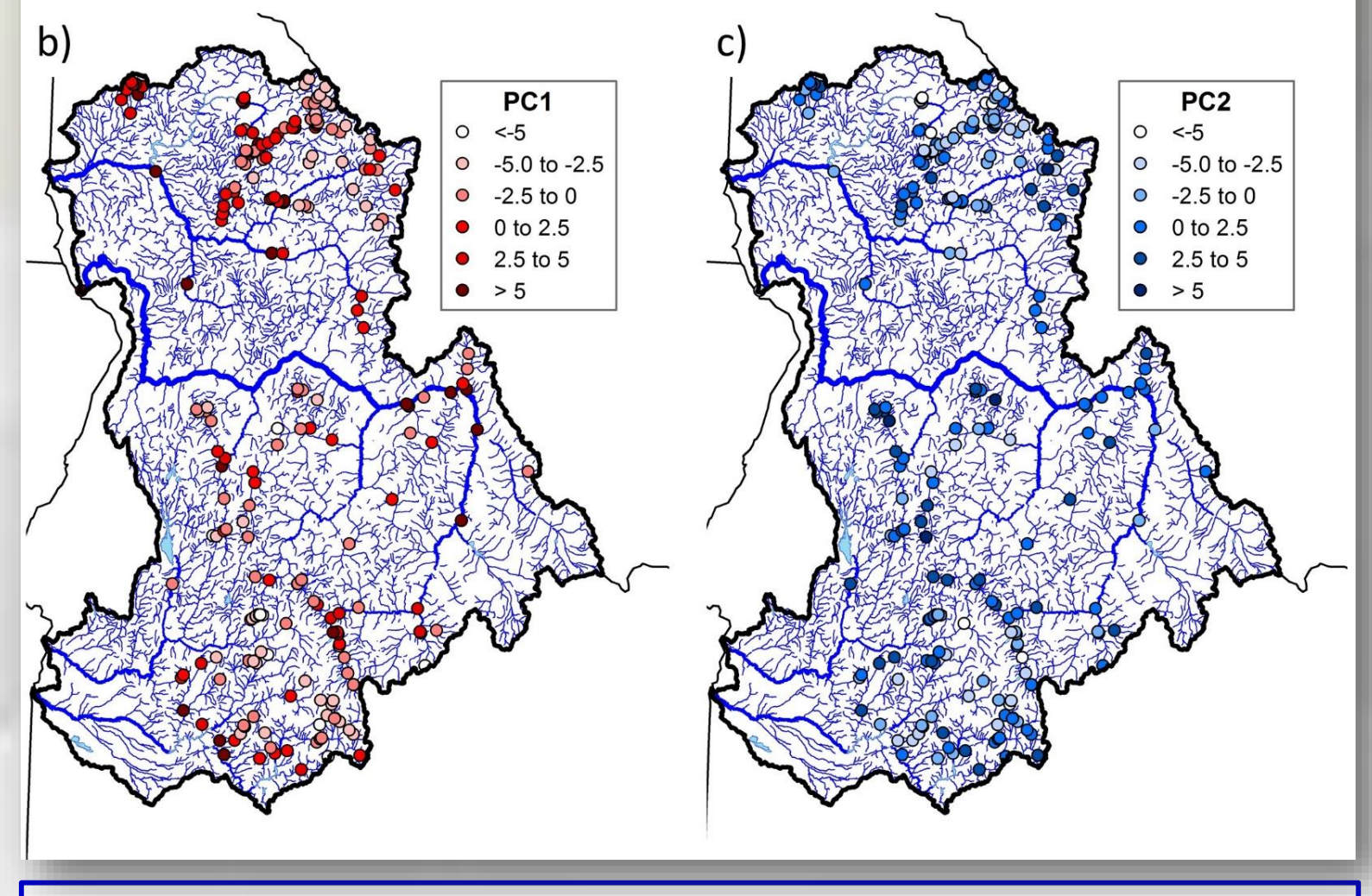


Figure 4b, c. Principal component scores from panel 4a are mapped to network locations in panels b and c. The spatial pattern shown among the PC1 scores in panel 4b (darker colors indicate warmer, more variable temperatures) reflects the network temperature scenario shown in Figure 1, which was expected based on the strong correlation of PC1 with the mean August temperature metric as described in Table 3 (r = 0.95). In panel 4c, darker colors indicate places with longer growing seasons and less intense winter periods with fewer days at or near 0 °C.

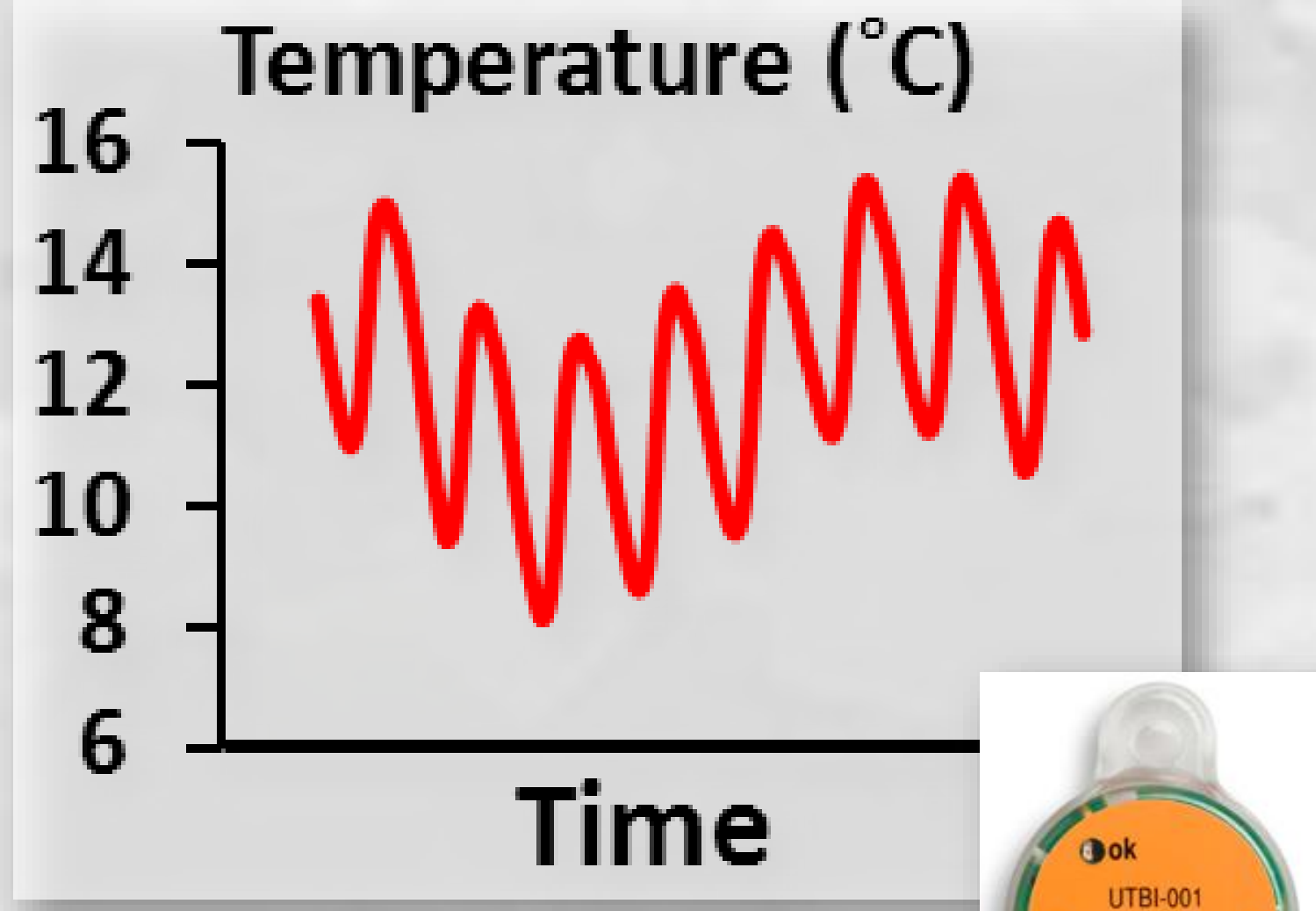
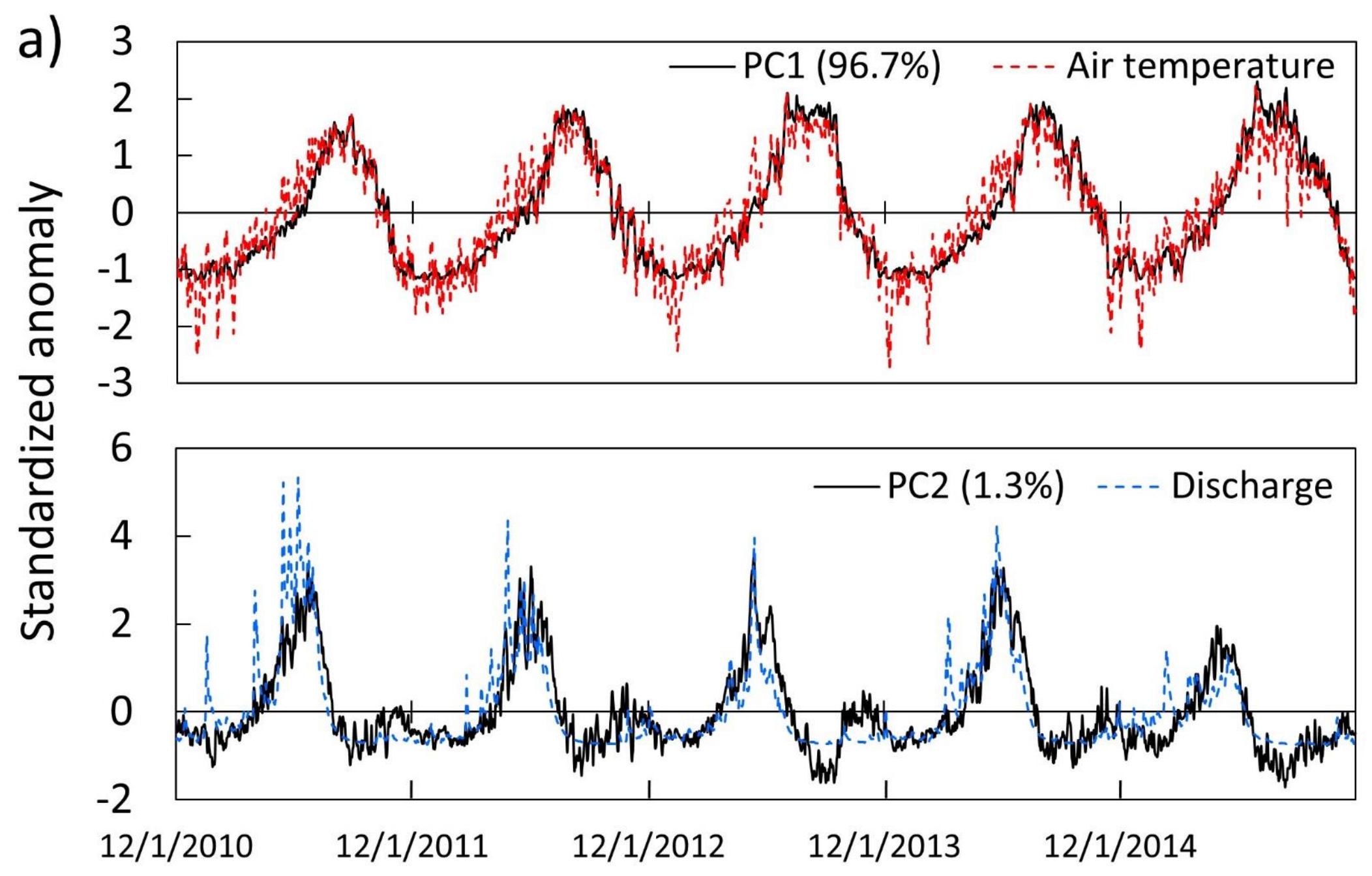


Table 3. PCA conducted on the 28 temperature metrics suggested that four principal components (PC) accounted for 93.4% of the variation among the metrics used to describe thermal regimes in the temperature dataset. PC1 accounted for 49% of total variance and was strongly associated with metrics that represented magnitude and variability, as indicated by the high correlation values (e.g., r > 0.8) of these metrics with PC1 in Table 3. PC2 accounted for 29% of variance and was associated with metrics that described the winter season as well as the timing and length of the growing season. PC3 and PC4 accounted for much smaller portions of the variance and had more ambiguous interpretations due to weaker correlations with most of the temperature metrics

Temperature metric	PC1	PC2	PC3	PC4
M1. Mean annual temperature	0.99	-0.07	-0.05	-0.03
M2. Mean winter temperature	0.26	-0.92	0.14	0.00
M3. Mean spring temperature	0.91	-0.19	-0.25	0.04
M4. Mean summer temperature	0.97	0.21	-0.06	-0.05
M5. Mean August temperature	0.95	0.22	0.16	-0.10
M6. Mean fall temperature	0.96	-0.18	0.14	-0.08
M7. Minimum daily temperature	-0.02	-0.86	0.08	-0.02
M8. Minimum weekly average temperature	-0.03	-0.90	0.08	0.00
M9. Maximum daily temperature	0.95	0.26	0.09	-0.08
M10. Maximum weekly average temperature	0.95	0.25	0.09	-0.07
M11. Annual degree days	0.99	-0.07	-0.05	-0.03
V1. Annual standard deviation	0.90	0.41	0.01	-0.07
V2. Winter standard deviation	0.69	-0.54	0.16	0.00
V3. Spring standard deviation	0.71	0.30	-0.55	0.04
V4. Summer standard deviation	0.42	0.32	0.78	-0.14
V5. Fall standard deviation	0.87	0.39	0.19	-0.12
V6. Range in extreme daily temperatures	0.93	0.33	0.08	-0.07
V7. Range in extreme weekly temperatures	0.93	0.33	0.08	-0.07
F1. Frequency of hot days	0.47	-0.01	0.30	0.82
F2. Frequency of cold days	-0.70	0.61	0.09	0.11
T1. Date of 5% of degree days	0.02	0.96	-0.10	0.01
T2. Date of 25% of degree days	-0.43	0.74	0.46	-0.08
T3. Date of 50% of degree days	-0.45	0.37	0.79	-0.16
T4. Date of 75% of degree days	-0.19	-0.51	0.72	-0.19
T5. Date of 95% of degree days	0.30	-0.88	0.12	-0.09
D1. Growing season length	0.03	-0.97	0.11	-0.03
D2. Duration of hot days	0.44	-0.03	0.32	0.84
D3. Duration of cold days	-0.64	0.66	0.07	0.11
Variance explained (%):	49.0%	29.0%	9.8%	5.6%
Cumulative variance (%):	49.0%	78.0%	87.8%	93.4%
Eigenvalue:	13.73	8.12	2.74	1.56

FIGURE 5a. To understand how water temperatures varied temporally within central Idaho over the five year study period, PCA was also conducted on the mean daily water temperature values at the 226 sites. This analysis suggested that two PCs accounted for 98% of the temperature variation among the stream and river sites, with PC1 accounting for the largest portion of this variation (96.7%) and PC2 accounting for a much smaller portion (1.3%). After that analysis was complete, mean daily air temperature and discharge values from the high- and low-elevation monitoring stations were aligned with the time-series of water temperature PC scores for comparison. PC1 scores were strongly correlated with air temperature variation (*r* = 0.92), whereas PC2 scores were strongly correlated with discharge variation (*r* = 0.84).



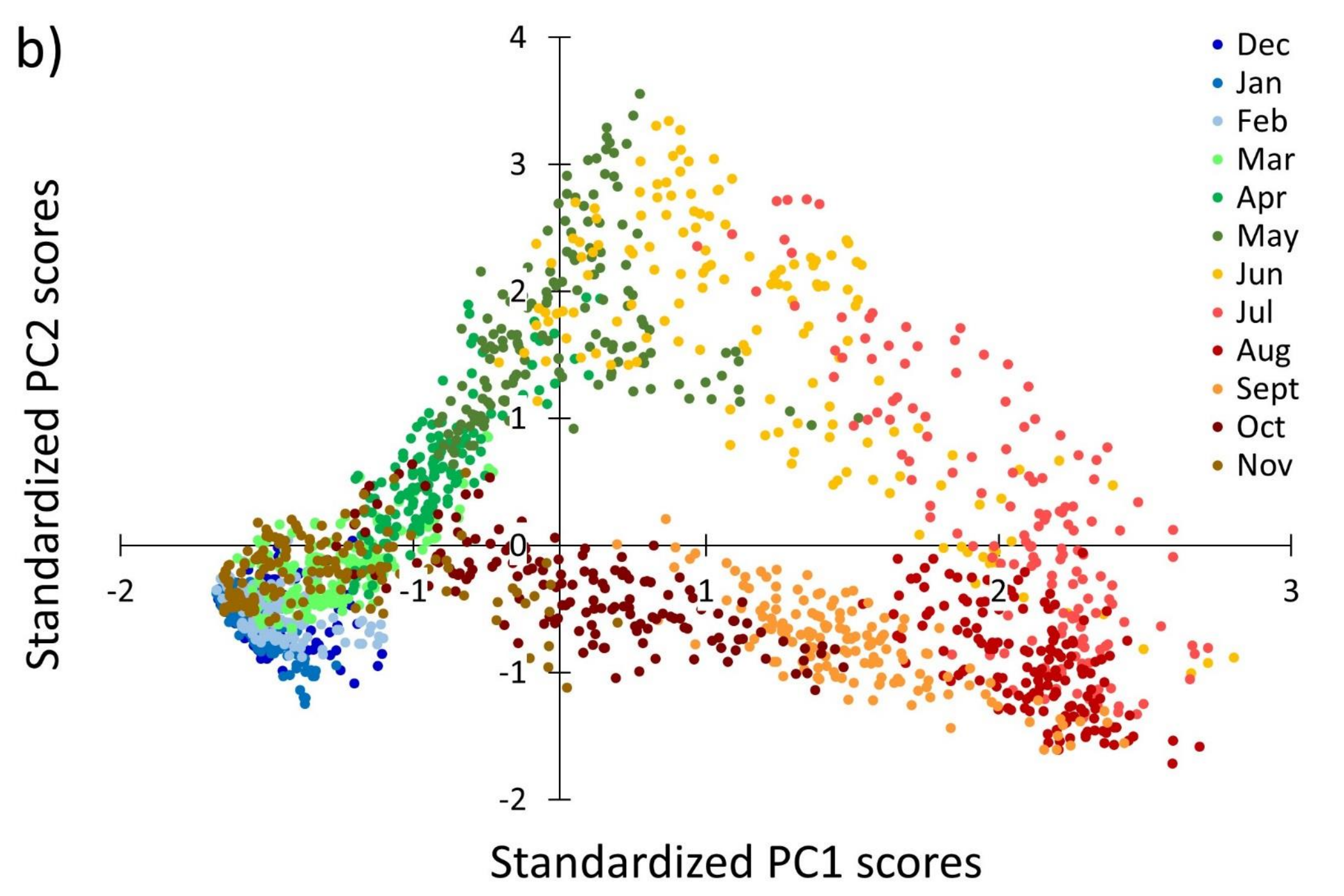


FIGURE 5b. A joint plot of the water temperature PC1 and PC2 scores from Figure 5a shows that variation along the two axes differs according to monthly and seasonal periods. Not surprisingly, little variation occurred during the cold winter months when temperatures of most rivers and streams were near 0 °C. During spring and early summer, however, variation was observed along both axes as air temperatures warmed and snowmelt runoff created a large discharge pulse. Once discharge returned to baseflow conditions in late summer, variability along PC1 was the primary signal until air temperatures cooled significantly in late fall and the winter cold period began again.

Discussion

Thermal regimes in central Idaho's river networks appear to be relatively simple and respond coherently to climatic variability. Strong seasonal patterns in water temperatures characteristic of temperate latitudes occurred in response to the annual air temperature cycle, and were modified by variation in discharge patterns that were of secondary importance. As might be expected due to the large elevational gradients in this landscape, the dominant regime aspect represented by PC1 in the metric-based PCA was associated with magnitude. Less expected was that many of the variability metrics also correlated strongly with PC1 because variability is often treated as a distinct element of thermal regimes. In contrast to the metrics associated with PC1, metrics that described the winter period and the extent of the growing season largely defined PC2. This "winter" PC is probably common to thermal regimes in mountainous landscapes like central Idaho where subzero air temperatures are frequent and result in prolonged periods with water temperatures near 0 °C.

Our results suggest that most of the information about thermal regimes in the study area may be adequately captured by a few principal components or allied metrics. A logical extension of this research involves application of PCA techniques to larger temperature datasets at regional scales to discern whether that is true elsewhere, to define distinct classes of thermal regimes if they exist, and delineate the geographic domains over which they are operable. Across sufficiently diverse landscapes, we might expect to observe classes of thermal regimes that, at a minimum, mimicked previously described classes of hydrologic regimes (e.g., rainfall, snowmelt, spring-groundwater, and regulated) but possible divergences from, or additions to, those categories would be useful to ascertain. Once described, detailed maps of thermal regime classes could be developed and used to aid in assessments of ecological conditions or anthropogenic effects on stream thermal regimes.

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For more information about this research, please see:

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