Freshwater Biology

Freshwater Biology (2013) **58**, 880–894 doi:10.1111/fwb.12094

Descriptors of natural thermal regimes in streams and their responsiveness to change in the Pacific Northwest of North America

IVAN ARISMENDI*, SHERRI L. JOHNSON†, JASON B. DUNHAM‡ AND ROY HAGGERTY*

*College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, U.S.A.

†US Forest Service Pacific Northwest Research Station, Corvallis, OR, U.S.A.

‡US Geological Survey, Forest and Rangeland Ecosystem Science Center, Corvallis, OR, U.S.A.

SUMMARY

1. Temperature is a major driver of ecological processes in stream ecosystems, yet the dynamics of thermal regimes remain poorly described. Most work has focused on relatively simple descriptors that fail to capture the full range of conditions that characterise thermal regimes of streams across seasons or throughout the year.
2. To more completely describe thermal regimes, we developed several descriptors of magnitude, variability, frequency, duration and timing of thermal events throughout a year. We evaluated how these descriptors change over time using long-term (1979–2009), continuous temperature data from five relatively undisturbed cold-water streams in western Oregon, U.S.A. In addition to trends for each descriptor, we evaluated similarities among them, as well as patterns of spatial coherence, and temporal synchrony.
3. Using different groups of descriptors, we were able to more fully capture distinct aspects of the full range of variability in thermal regimes across space and time. A subset of descriptors showed both higher coherence and synchrony and, thus, an appropriate level of responsiveness to examine evidence of regional climatic influences on thermal regimes. Most notably, daily minimum values during winter–spring were the most responsive descriptors to potential climatic influences.
4. Overall, thermal regimes in streams we studied showed high frequency and low variability of cold temperatures during the cold-water period in winter and spring, and high frequency and high variability of warm temperatures during the warm-water period in summer and autumn. The cold and warm periods differed in the distribution of events with a higher frequency and longer duration of warm events in summer than cold events in winter. The cold period exhibited lower variability in the duration of events, but showed more variability in timing.
5. In conclusion, our results highlight the importance of a year-round perspective in identifying the most responsive characteristics or descriptors of thermal regimes in streams. The descriptors we provide herein can be applied across hydro-ecological regions to evaluate spatial and temporal patterns in thermal regimes. Evaluation of coherence and synchrony of different components of thermal regimes can facilitate identification of impacts of regional climate variability or local human or natural influences.

Keywords: coherence, global warming, North American streams, stream temperature, synchrony, trends

Introduction

Although the fundamental role of temperature in shaping aquatic ecosystems has been long recognised (Shelford, 1931; Fry, 1947; Magnuson, Crowder & Medvick, 1979; Vannote & Sweeney, 1980), a comprehensive quantification of the thermal characteristics of streams is needed (Caissie, 2006; Webb *et al*., 2008). The seemingly simple

Correspondence: Ivan Arismendi, Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331, U.S.A. E-mail: ivan.arismendi@oregonstate.edu

question of which temperature(s) should be used to characterise thermal conditions in a particular stream does not have a straightforward answer. Most characterisations of stream temperature have focused on relatively simple descriptors, as reflected in minimum, maximum and mean temperatures, and typically measured during the summer season when elevated temperatures could have greatest impacts on cold-water biota (Poole *et al.*, 2004; Caissie, 2006; Webb *et al.*, 2008). These common descriptors of temperature magnitude do not capture frequency, duration or timing; thermal maxima and minima can be short- or long-lived (Dunham *et al.*, 2005), and frequent or rare. Furthermore, two streams with similar mean or maximum daily temperatures may be ecologically quite different due to a difference in the range of daily temperatures (Meeuwig, Bayer & Seelye, 2005). Accumulations of temperature over time, such as cumulative degree-days, have been used to characterise temperatures that can affect the phenology of organisms (Noormets, 2009) over longer temporal scales, but they do not incorporate information about short-term events (e.g., daily to seasonal extremes) that can be stressful to instream biota. Even though these descriptors of magnitude of the stream temperature are commonly reported in the literature and are easily calculated, they are not representative of the full range of natural variability of a thermal regime and they do not capture the thermal experience of organisms (Poole *et al.*, 2004; Caissie, 2006).

Like all continuous phenomena, temperature can be characterised in terms of the magnitude, variability, frequency, duration and timing of events. Thus, the challenge of characterising temperature needs to begin with an evaluation of multiple descriptors of patterns of variability within thermal regimes. Hydrologists have characterised flow regimes (Poff *et al.*, 1997) using these descriptors (Poff, 1996; Olden & Poff, 2003; Mathews & Richter, 2007) based on critical components of the hydrologic cycle. However, similar descriptors have not been fully evaluated for thermal regimes (see Poole *et al.*, 2004; Olden & Naiman, 2010) and the potential long-term changes of these multifaceted descriptors have not being examined previously.

Although a need for more regime-based perspectives on stream temperature has been made repeatedly in the literature (Poole *et al.*, 2004; Caissie, 2006; Olden & Naiman, 2010), there has yet to be a comprehensive analysis of how to describe and evaluate them. In this study, we (i) develop and evaluate descriptors of thermal regimes that summarise the magnitude, variability, frequency, duration and timing of stream temperature events across a year and (ii) apply these descriptors to long-term (31 year) records of water temperatures in streams to evaluate how different descriptors vary through space and time, and how they may be useful in identifying regionally synchronous and coherent trends (e.g. as may be realised through climate impacts) or more localised factors (e.g. local human and natural influences on temperature). Here, we examine synchrony (temporal scale) and coherence (spatial scale) of descriptors of thermal regimes of streams as an approach to identify those most responsive to change (Magnuson, Benson & Kratz, 1990; Benson *et al.*, 2000; Webster *et al.*, 2000). By evaluating the temporal synchrony across descriptors of stream temperature from minimally human-influenced sites, we identify whether similar dynamics are influencing the descriptors over time. We also examine spatial coherence by identifying the consistency in the directionality of historical trends among streams to detect which descriptors exhibit a common, positive or negative trend over time. We hypothesise that if regional and common climatic forcing mechanisms are affecting the thermal regime of streams, we should see an increase in both inter-annual synchrony and spatial coherence for the most responsive descriptors. Alternatively, lack of synchrony and coherence would highlight the importance of local, rather than regional, influences on thermal regimes. Collectively, this work represents the first comprehensive analysis of descriptors of thermal regimes and their utility for detecting spatial (coherence) or temporal patterns (synchrony) in stream temperature.

Methods

Study system

We selected five long-term gage stations (US Geological Survey and US Forest Service) that measured year-round daily stream temperature in western Oregon, United States (Table 1). The sites were selected based on (i) available records for at least 31 years (1 January 1979–31 December 2009), (ii) complete information for time series of daily minimum (min), mean (mean) and maximum (max) stream temperature for at least 90% of the period of record and (iii) location in minimally human-influenced forested catchments (i.e. absence of water regulation upstream).

Data management and primer on descriptors of thermal regimes

All time series were carefully inspected to ensure there were no artefacts or processing errors (e.g. non-numerical

Table 1 Characteristics of gauging sites on streams in minimally human-influenced catchments (n = 5) and time series (from January 1979 to December 2009) examined in this study

Site characteristics	Site ID	14138870	14139800	TSMCRA	TSLOOK	14338000
	Stream name	Fir Creek	SF Bull Run River	McRae Creek	Lookout Creek	Elk Creek
	State	OR	OR	OR	OR	OR
	Lat N	45.48	45.445	44.256	44.225	42.679
	Long W	122.024	122.108	122.168	122.122	122.741
	Elevation (m)	439	302	840	998	455
	Drainage area (km^2)	14.1	39.9	5.9	4.9	334.1
	Nearest national forest	Mt Hood	Mount Hood	Willamette	Willamette	Rogue-Siskyou
	Disturbance score*	8	7	NA	NA	17
	Diversions above	Not	Not	Not	Not	Irrigation
	BFI*,†	48.1	49.5	NA	NA	62.4
	Runoff (mm year^{-1})*,‡	1,879	1,879	NA	NA	703
Time series	No. records	11 380	11 158	11 784	11 735	12 335
	% of missing records	2.8	2.0	3.5	2.6	5.2

NA, not available.
*Falcone *et al.* (2010).
†Base Flow Index (BFI) = Ratio of base flow to total stream flow, expressed as a percentage and ranging from 0 to 100.
‡Runoff = Estimated catchment annual runoff, mm year^{-1}, mean for the period 1971–2000.

values and those out of the range between less than −10 °C and over 40 °C). After inspection, each time series was completed by interpolating missing data (see Appendix S1). Overall, interpolation was required for a low proportion of daily missing records (<6%; Table 1).

To characterise the thermal regime of the streams, we derived several descriptors that were summarised for events occurring at daily and weekly intervals, and within (seasons) and among years (Fig. 1; Table 2). The temperature magnitude represented the observed temperature for a specific period of time. The temperature variability described the temporal fluctuations of stream temperature conditions across daily, weekly or seasonal intervals. The temperature frequency was the sum total of events that occurred when a particular magnitude or exceedance was attained (see detailed explanation below), and the temperature duration represented the time over which a given thermal condition was continuously expressed (e.g.

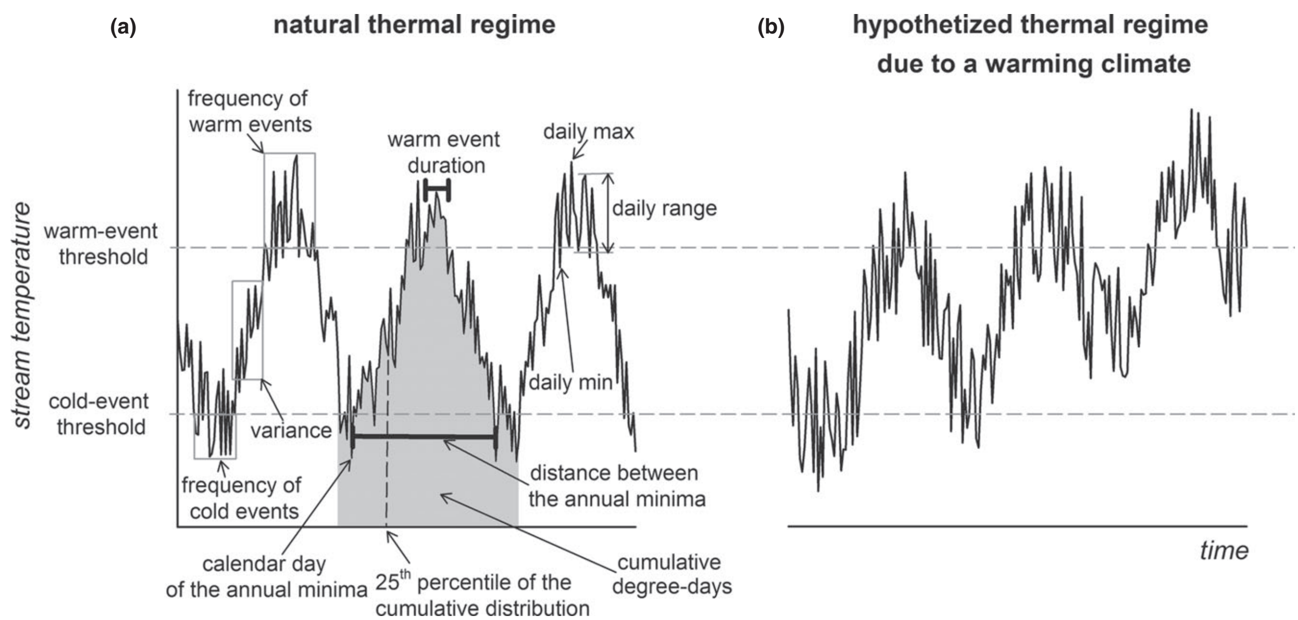

Fig. 1 Conceptual model and hypotheses. (a) Diagram of a typical thermograph showing examples of descriptors used here and (b) hypothesised changes in the thermograph due to the recent warming climate.

Table 2 List of the stream temperature descriptors and the time scales analysed for this study

Category	Abbreviation	Units	Description	Daily time series	Monthly	Annual
Magnitude	MIN, MEAN, MAX	°C	Daily temperature	Min, mean, max	X	X
	Degree-days	°C	Cumulative degree-days	Mean	X	X
Variability	Range	°C	Daily range	Min, max	X	X
	VAR	C^2	Variance	Min, mean, max	X	X
	CV	None	Coefficient of variation	Min, mean, max	X	X
Frequency	FREQ_cold	*n*	No. of cold events (days ≤ −1 ST)	Min		X
	FREQ_7dcold	*n*	No. of cold events (≥ 7 days)	Min		X
	FREQ_warm	*n*	No. of warm events (days ≥ 1 ST)	Max		X
	FREQ_7dwarm	*n*	No. of warm events (≥ 7 days)	Max		X
Duration	DUR_longestcold	Days	Longest duration of cold events (≤ −1.5 ST)	Min		X
	DUR_cold	Days	Mean duration of cold events	Min		X
	DUR_dist-coldest	Days	Distance between two coldest days	Min		X
	DUR_7dMAdist-coldest	Days	Distance between two coldest 7-days moving window	Min		X
	DUR_longestwarm	Days	Longest duration of warm events (≥ 1.5 ST)	Max		X
	DUR_warm	Days	Mean duration of warm events	Max		X
	DUR_dist-warmest	Days	Distance between two warmest days	Max		X
	DUR_7dMAdist-warmest	Days	Distance between two warmest 7-days moving window	Max		X
Timing	TIM_5th	Date	Date of the 5th percentile of CTD	Mean		X
	TIM_25th	Date	Date of the 25th percentile of CTD	Mean		X
	TIM_50th	Date	Date of the 50th percentile of CTD	Mean		X
	TIM_75th	Date	Date of the 75th percentile of CTD	Mean		X
	TIM_minima	Date	Date of the coldest event (1-day)	Min		X
	TIM_7dMA minima	Date	Date of the coldest event (7-days moving window)	Min		X
	TIM_maxima	Date	Date of the warmest event (1-day)	Max		X
	TIM_7dMA maxima	Date	Date of the warmest event (7-days moving window)	Max		X

ST, standardised temperature; CTD, cumulative temperature distribution; min, daily minimum time series; max, daily maximum time series.

duration of warm or cold events). The temperature timing referred to the date of a thermal event (e.g. the calendar day of the annual maxima or/minima).

Because we were primarily interested in changes in temperature patterns rather than absolute values, we standardised daily temperature values before analysing events (i.e. descriptors of frequency, timing, and duration) as follows:

$$\mathrm{ST}_i = \frac{T_i - \mu}{\sigma}$$

where ST_i is the standardised (min, mean or max) temperature at day i, T_i is the actual temperature value at day i (°C), μ is the mean and σ is the standard deviation of the respective time series considering a baseline of a 31-year period. Standardising temperature allowed us to avoid the difficulties created by sites having different local characteristics (e.g. thermal regimes associated with geology, microclimate), assuming that while absolute values may be strongly affected by these local characteristics, standardised values should be insensitive (Strangeways, 2010). We defined a 'cold event' (Fig. 1; Table 2) when a standardised stream temperature value was equal to or below −1 (using time series of daily minimum) and a 'warm event' when a standardised stream temperature value was equal to or exceeding 1 (using time series of daily maximum). Events were classified as 1- and 7-day events (Table 2).

Ordination and similarity among temperature descriptors

We used an ordination approach to compare the similarity/dissimilarity of the 29 descriptors displayed in a multivariate space according to non-metric multidimensional scaling (N-MDS) on Euclidean distance. Based on an iterative optimisation procedure (999 random starts), descriptors were rearranged to minimise a measure of disagreement or stress between their distances across sites and over time (year to year) in a two-dimensional plot (Kruskal, 1964). Proximity of points in the 2D plot indicated a higher degree of similarity, whereas dissimilar points were positioned further apart. We tested the null hypothesis of no difference among groups of descriptors using an analysis of similarity (ANOSIM). The ANOSIM is a nonparametric procedure analogous to analysis of variance (ANOVA) that tests differences in distance in the ordination space of previously defined groups against random groups (a detailed procedure is provided by Clarke, 1993). We conducted 99 999 random permutations to estimate the significance of the *R* test statistic associated with ANOSIM and the posteriori pairwise tests. The *R* statistic ranged between −1 and 1; −1 indicates more similarity between groups than within groups, 0 indicates no effect of groups and 1 indicates more dissimilarity between groups than within groups. We used both N-MDS and ANOSIM procedures and compared among categories of descriptors (i.e. magnitude, variability, frequency, duration and timing). We also compared groups of descriptors, depending on the temporal scale used including annual, cold season (1- and 7-day events) and warm season (1- and 7-day events).

Trends in temperature descriptors

We evaluated the significance of trends of temperature descriptors over time using a nonparametric seasonal Mann–Kendall tau test for monotonic series (Mann, 1945; Hirsch, Slack & Smith, 1982). This rank-based test is robust to non-normal data, series with outliers and nonlinear trends (Hirsch *et al.*, 1982; Helsel & Hirsch, 1992). We determined the magnitude of the trend using the nonparametric Sen slope estimator, which represents the median slope of all possible pairs in the data set (Sen, 1968; Helsel & Hirsch, 1992; Hipel & McLeod, 1994). The seasonal Mann–Kendall tau test and its slope estimator have been described as particularly useful for the detection of trends because it considers both seasonality in the water quality time series and missing values (Hipel & McLeod, 1994; Esterby, 1996). We also used the Mann–Kendall tau test to detect trends for descriptors of events in a particular month (i.e. magnitude and variability).

Synchrony and coherence

We analysed synchrony and coherence as two complementary indices to identify which descriptors showed most consistent responsiveness to change among sites. To evaluate synchrony, we compared 31 annual values originating from each descriptor at each site. The degree of synchrony was determined by the proportion of significant Spearman rank cross-correlations from the potential paired-stream combinations of our five streams (n = 10). We measured the degree of spatial coherence using the percentage of sites with the same directionality in their trends and assumed that coherence represented the case of climate having a common influence on water temperatures across broad extents. All the statistical analyses were performed using the software R ver. 2.11.1 (R Development Core Team, 2005). To improve the detection of an early climate change signal, we set alpha levels at = 0.1 for assessing statistical significance (e.g. Enfield, Mestas-Nuñez & Trimble, 2001; Spagnoli *et al.*, 2002).

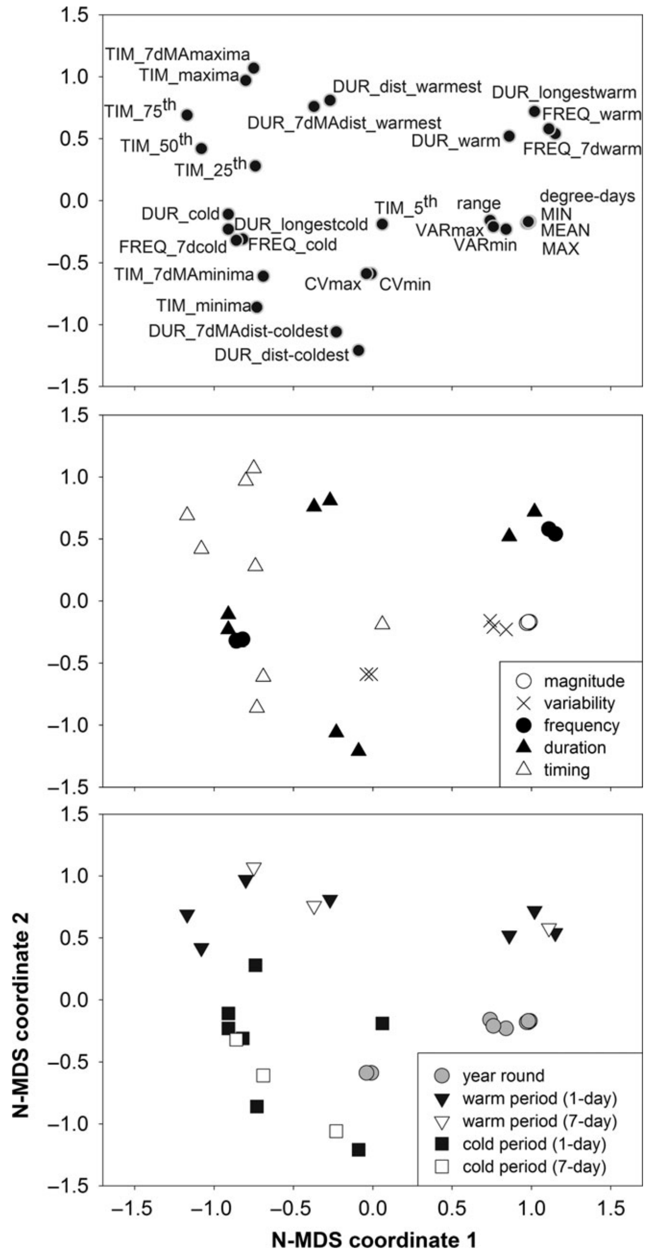

Fig. 2 Non-metric MDS ordination plot (2D) showing the degree of similarity among descriptors of stream temperature derived from five sites (Table 1) and 31 years of data using Euclidian distance (Stress = 0.14). The upper panel shows the location of each individual descriptor in the ordination plot. The descriptors in the middle panel are grouped by category and in the lower panel by time scale used. Proximity of symbols indicates a higher degree of similarity.

Table 3 Similarity of the thermal descriptors (pairwise ANOSIM) grouped by category and time scale

Groups	Pairwise tests	*R* statistic	*P*-value	Significance
Category	Magnitude, variability	0.519	0.024	**
	Magnitude, frequency	0.333	0.057	*
	Magnitude, timing	0.820	0.002	***
	Variability, frequency	0.350	0.056	*
	Variability, timing	0.593	0.004	***
	Frequency, timing	0.279	0.079	*
	Magnitude, duration	0.180	0.111	
	Frequency, duration	−0.024	0.455	
	Duration, timing	−0.012	0.487	
	Variability, duration	0.071	0.257	
Time scale	Year round, warm period (1 day)	0.733	<0.001	***
	Year round, warm period (7-day)	0.875	0.005	***
	Year round, cold period (1 day)	0.742	<0.001	***
	Year round, cold period (7-day)	0.930	0.005	***
	Warm period (1 day), cold period (1 day)	0.405	0.003	***
	Warm period (1 day), cold period (7-day)	0.282	0.058	*
	Warm period (7-day), cold period (1 day)	0.603	0.017	**
	Warm period (7-day), cold period (7-day)	0.481	0.001	*
	Cold period (1 day), cold period (7-day)	−0.083	0.617	
	Warm period (1 day), warm period (7-day)	−0.091	0.708	

Significance at *P < 0.1, **P < 0.05, and ***P < 0.01.

Results

Ordination and similarity among temperature descriptors

Overall, the ordination plot from the N-MDS analysis of Euclidian distances among all individual descriptors (n = 29) showed a relatively low disagreement (stress = 0.14; upper panel in Fig. 2), highlighting an adequate level of how the plot summarises the observed distances among temperature descriptors. Further, there was a high degree of dissimilarity of descriptors grouped by category showing significant differences among them (middle panel in Fig. 2; R statistic = 0.255, P = 0.003). In particular, pairwise ANOSIM results (Table 3) indicated that all descriptors of magnitude, variability, frequency and timing were dissimilar. Only descriptors of duration overlapped with the rest of the categories showing a higher degree of similarity. Similarly, there was a high dissimilarity among descriptors grouped by the temporal scale (lower panel in Fig. 2; R statistic = 0.581; P < 0.001). Pairwise ANOSIM results (Table 3) indicated that almost all groups were dissimilar. In only two cases, for descriptors of short time event duration, was there overlap indicating a high similarity, specifically, for the case of the cold period (1- versus 7-day events) and warm period (1- versus 7-day events).

Trends in temperature descriptors

Stream temperature magnitude showed significant warming trends at all sites, with increases between 0.10 and 0.29 °C per decade (Fig. 3; Table S1). In particular, MIN had significant warming trends at all sites, and in three of the five sites, we found significant warming trends for all of the magnitude descriptors (MIN, MEAN, MAX and degree-days). The analysis by month showed that only winter (January–February) and summer (July–August–September) had significant warming trends (Table S2). Specifically, in January, there were significant warming trends for all descriptors at four of the five sites. Moreover, there were four, three and two sites with significant warming trends in July, August and September, respectively, for at least one descriptor of magnitude. At one of these sites (Lookout Creek), warming trends were observed for all of the descriptors during the three consecutive summer months.

Stream temperature variability displayed significant decreasing trends at all sites with maximum rates of 0.38 °C^2 per decade for variance (VAR), 0.02 per decade for the coefficient of variation (CV) and 0.19 °C per decade for the range (Table 4). Specifically, we found significant decreasing trends for all of the variability descriptors at Elk Creek and, in two additional sites, at least one descriptor had significant decreasing trends. Among sites, the CV descriptor for time series of daily min, mean and max showed a greater incidence of significant and decreasing trends compared with the variance. Range exhibited significant decreasing trends at three sites but at one site was positive. Although the analysis of temperature variability by month showed mixed responses of both

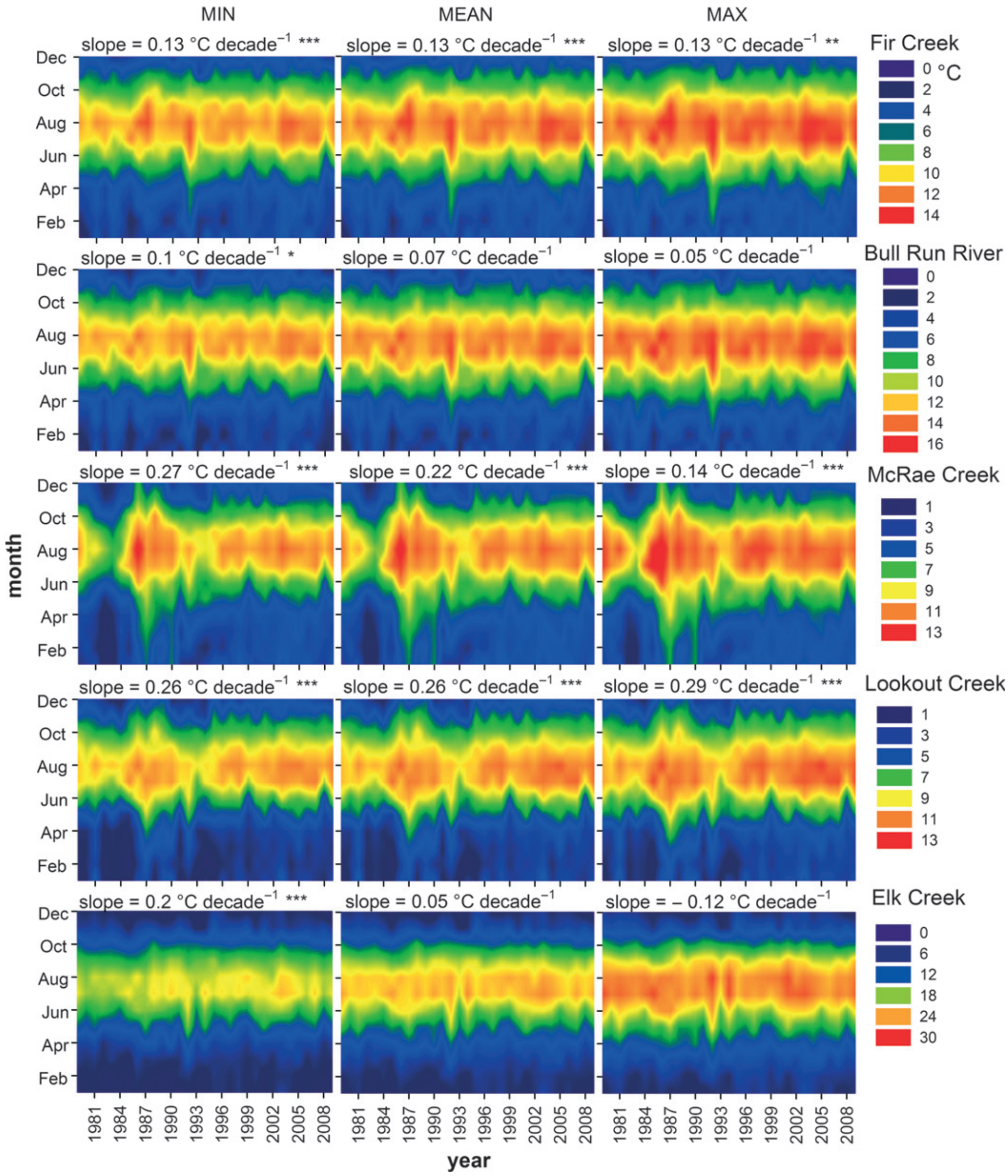

Fig. 3 Contour plots of monthly mean values of magnitude descriptors of stream temperature using time series of daily min (MIN), mean (MEAN) and max (MAX). MIN (left panel), MEAN (centre panel) and MAX (right panel) at each site includes observed trends. The magnitude of the trend is represented by the Sen slope (°C per decade). Significance at $^{*}P < 0.1$, $^{**}P < 0.05$ and $^{***}P < 0.01$. Colours indicate the temperature magnitude value (°C). Detailed results are provided in Tables S1 & S2.

increasing and decreasing trends (Table S3), most of the trends were negative and occurred typically during winter, spring and summer. The highest CV occurred in winter; most of the significant trends for both CV and variance were in winter and spring even though the highest variance was in summer. For range, the majority of significant trends occurred in summer and winter.

There was a decreasing cumulative frequency of cold events (1- and 7-day) over time, while warm events exhibited little change (Fig. 4). In particular, at two sites, there were significant decreasing trends in both the frequency of 1-day cold events at rates of 18–20 days per decade and the frequency of 7-day cold events at rates of 14–18 events per decade (Figures S1 & S2). Cold events of 1 day ranged from 4 to 160 with a mean of 56, whereas cold events of 7 days ranged from 0 to 29 with a mean of 4. In addition, there was one site with a significant increasing trend in the number of warm events (7 day) with an increase of 13 events per decade. One-day warm events ranged from 19 to 138 with a mean of 78 and warm events of 7 day ranged from 0 to 17 with a mean of 8.2.

The duration of warm and cold events showed significant decreasing trends for the duration of cold events in two sites at rates of 1.5–2.0 days per decade,

Table 4 Trends in descriptors of stream temperature variability (CV, VAR and range) over the period 1979–2009 with the seasonal Mann–Kendall test and Sen slope estimator (°C per decade)

Stream	Variability metric (monthly)	τ	Sen slope (unit per decade)	*P*-value	Significance
Fir Creek	VAR min	−0.012		0.739	
	VAR mean	−0.017		0.638	
	VAR max	−0.031		0.393	
	CV min	−0.049		0.179	
	CV mean	−0.055		0.133	
	CV mean	−0.063	−0.01	0.086	*
	Range	−0.029		0.424	
Bull Run River	VAR min	0.008		0.829	
	VAR mean	−0.017		0.638	
	VAR max	−0.033		0.367	
	CV min	−0.026		0.480	
	CV mean	−0.029		0.421	
	CV mean	−0.041		0.267	
	Range	−0.194	−0.04	<0.001	***
McRae Creek	VAR min	−0.017		0.645	
	VAR mean	−0.076	−0.04	0.037	**
	VAR max	−0.142	−0.08	<0.001	***
	CV min	−0.120	−0.01	0.001	***
	CV mean	−0.152	−0.01	<0.001	***
	CV mean	−0.201	−0.02	<0.001	***
	Range	−0.201	−0.06	<0.001	***
Lookout Creek	VAR min	0.017		0.634	
	VAR mean	−0.035		0.341	
	VAR max	−0.055		0.136	
	CV min	−0.075	−0.01	0.040	**
	CV mean	−0.111	−0.01	0.002	***
	CV mean	−0.137	−0.01	<0.001	***
	Range	0.202	0.04	<0.001	***
Elk Creek	VAR min	−0.088	−0.21	0.016	**
	VAR mean	−0.095	−0.23	0.009	***
	VAR max	−0.133	−0.38	<0.001	***
	CV min	−0.118	−0.01	0.001	***
	CV mean	−0.099	−0.01	0.007	***
	CV mean	−0.111	−0.01	0.002	***
	Range	−0.237	−0.19	<0.001	***

CV, coefficient of variation; VAR, variance.
Significance at $*P < 0.1$, $**P < 0.05$ and $***P < 0.01$.

whereas warm events had a significant increase of 3.5 days per decade in Lookout Creek (Fig. 5). The standard deviation for the duration of cold events per year was almost always lower than for warm events. Further, the duration of the warmest event of the year (mean of 19.4 days and up to 90 days) was almost always longer than the duration of the coldest event in a year (mean of 5.2 days and up to 44 days) and, at Lookout Creek, the duration of the warmest event of the year showed a significant increasing trend with a rate of 8 days per decade (Figure S3). In addition, the number of days between the coldest and warmest event (1- and 7-day moving window) in two consecutive years showed no significant changes over time, but their inter-annual variability was higher for the coldest (240–511 days) than for warmest events (270–447 days; Figures S4 & S5).

Timing descriptors showed significant decreasing trends in the 5th percentile of the total degree-days per year at three sites with rates between 2.2 and 3.2 days per decade (Fig. 6). The 5th percentile normally occurred during winter and between the third week of January and the first week of March. We observed no trends in the 25th, 50th and 75th percentiles of the total degree-days per year (Figure S6). Similarly, timing of the annual maxima (single-day and 7-day moving window) did not change over time occurring between the first week of May and the first week of September with a mean around the first week

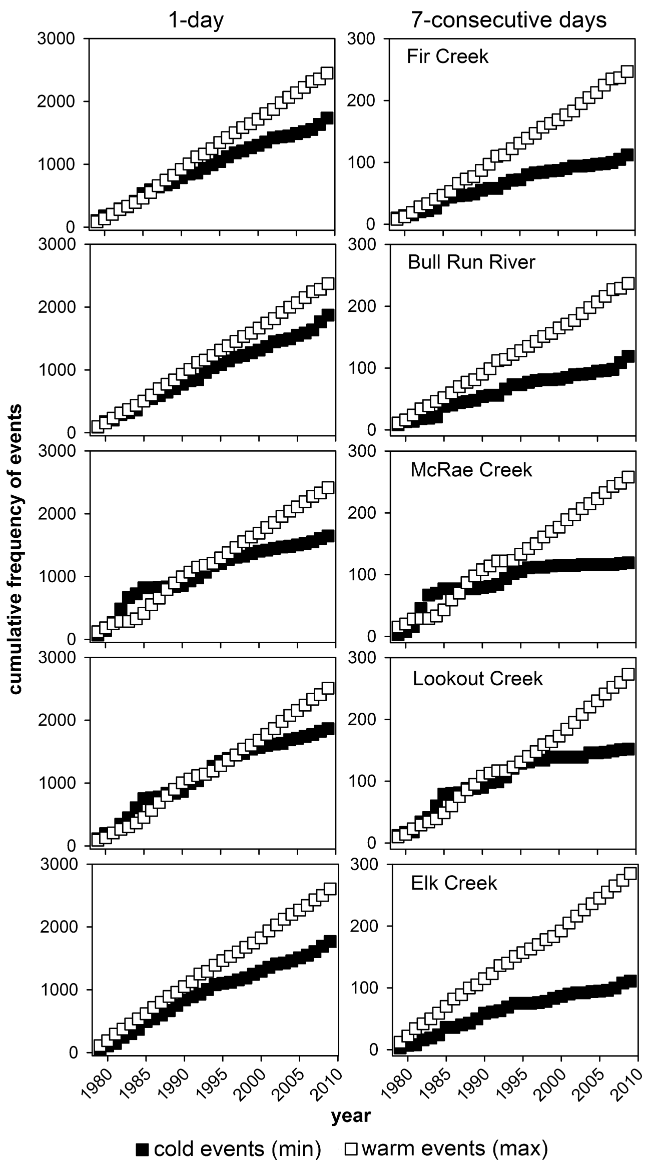

Fig. 4 Cumulative frequency distribution of cold (using time series of daily min) and warm (using time series of daily max) events per year for the period 1979–2009 for 1-day (left panel) and 7-day (right panel) events.

of August (Figure S7). Annual minima (single-day and 7-day moving window) also did not change over time, but there was greater variability in their timing, which occurred between the last week of October and the third week of March with a mean around the second week of January (Figure S8).

Synchrony and coherence

Our analysis of inter-annual synchrony of descriptors showed only eight of the 29 descriptors (27.6%) in total synchrony for the period 1979–2009 (Fig. 7; Tables S4–S10). Specifically, most of the descriptors of magnitude (MIN, MEAN and degree-days) were in total synchrony except for daily maximum. Four descriptors of warm events were in total synchrony and three of them were timing descriptors. Only one descriptor of cold events (timing of 25th percentile) was in total synchrony across years and it was also a descriptor of timing. Descriptors of variability and duration had the lowest synchrony.

At all sites, the directionality of historical trends of magnitude was in total coherence only for daily minimum (Fig. 7). Other descriptors of magnitude (MEAN, MAX and degree-days) and variability (CV) only exhibited an intermediate degree of coherence. Even though descriptors of frequency, duration and timing of events had an overall low coherence, descriptors of cold events had higher coherence than those for warm events. Moreover, some descriptors of duration (number of days between warmest or coldest events) and all of the timing descriptors for cold or warm events had low coherence, except for timing of 5th percentile that showed an intermediate degree of coherence.

Discussion

Thermal regimes of cold-water mountain streams

Thermal regimes in our study sites can be characterised by two distinct periods: a ‘cold-water period’ during winter and spring dominated by high frequency and low variability of colder temperatures and a ‘warm-water period’ during summer and autumn dominated by high frequency and high variability of warmer temperatures. These periods also differ in the distribution of events (cold and warm) with a higher frequency and longer duration of warm events relative to cold events. The cold-water period also exhibits lower variability in the duration of events, but events are more variable in their timing.

The utility of using several descriptors to characterise thermal regime of streams

The use of multiple descriptors allows us to capture the natural variability of thermal regimes in streams and to identify characteristics of thermal regimes that are most responsive to change. Indeed, the low similarity (redundancy) among descriptors highlights the importance of using multiple, rather than individual descriptors, to characterise a portion or the entire thermal regime of streams. If one wishes to efficiently provide an overall description of a regime, we should use a combination of

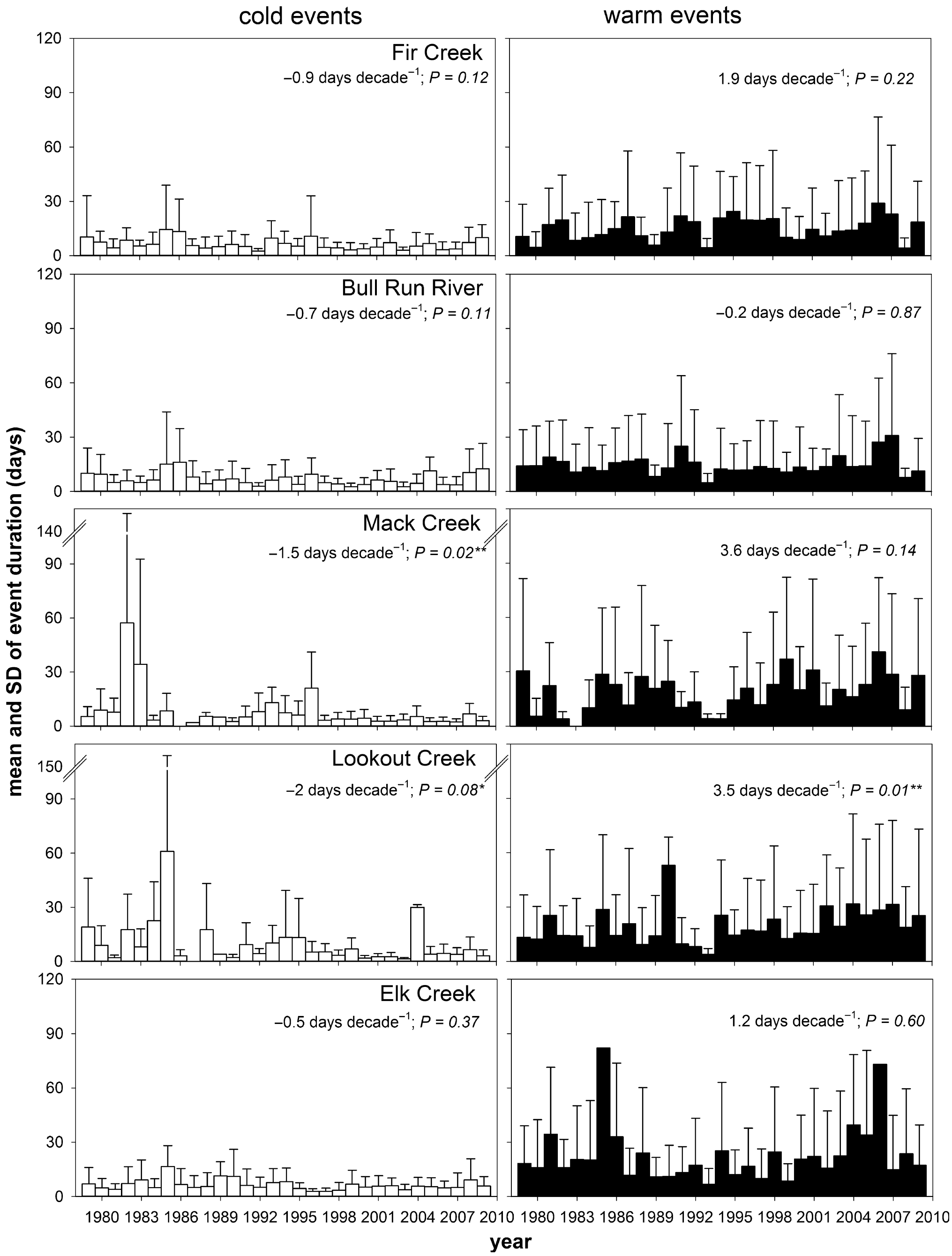

Fig. 5 Duration (mean ± SD) of cold (left panel using time series of daily min) and warm (right panel using time series of daily max) events per year for the period 1979–2009. Values denote magnitude of the trend represented by the Sen slope (days per decade). Significance at $^{*}P < 0.1$, $^{**}P < 0.05$ and $^{***}P < 0.01$.

descriptors from different categories (e.g. magnitude, variability, frequency, timing and duration) and temporal scale (e.g. annual or seasonal). This provides unique insights into different facets of variability in temperature across space and time. Patterns of change in stream temperature could be more strongly associated with particular portions of thermal regimes (e.g. cold or warm temperatures) and time frame (e.g. annual or seasonal). Overall, a year-round perspective using different seasons appears to be more informative than the resolution of observations (e.g. daily or weekly summaries of events) that could be redundant (a high similarity of descriptors using 1 versus 7 days). Moreover, each particular subset of descriptors may help to link questions related to

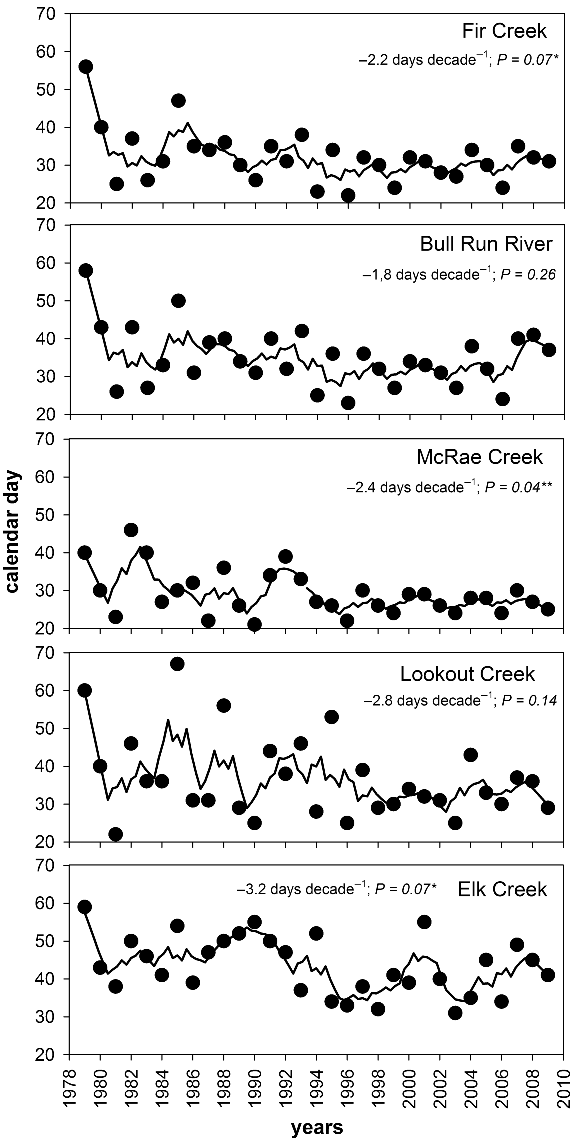

Fig. 6 Timing (calendar day) of the 5th percentile of the cumulative degree-days (using time series of daily mean) per year (period 1979–2009). Values denote magnitude of the trend represented by the Sen slope (days per decade). Significance at *$P < 0.1$, **$P < 0.05$ and ***$P < 0.01$. To improve visualisation a smoothed line (LOWESS) is included.

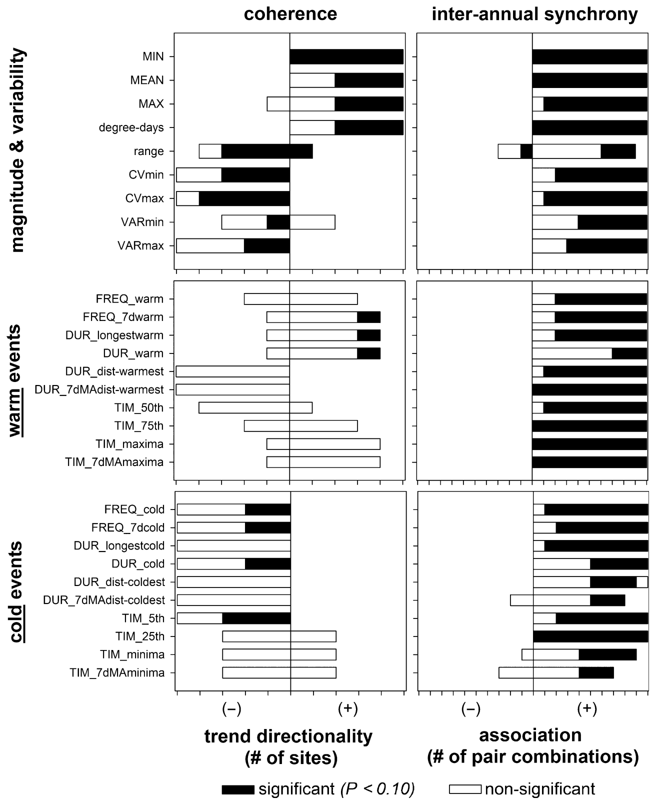

Fig. 7 Coherence and temporal synchrony of the most relevant descriptors ($n = 29$) of magnitude, variability, frequency, duration and timing used in this study (includes cold and warm events).

biology, phenology or regulatory criteria to particular aspects of the thermal regime of streams. In addition, the timing and length of the entire time series are also very important to consider when examining climate change influences of stream temperature (Arismendi *et al.*, 2012a).

Descriptors that characterise stream temperatures throughout the year may have a strong link to potentially unique biological responses in stream ecosystems. Typical descriptors of temperature magnitude provide information about acute thermal exposure in summer, but the timing of reproduction, development and growth of many cold-water species is based on temperatures during the winter–spring seasons; salmonids in the Pacific Northwest of North America are an example (e.g. Beacham & Murray, 1990; Brannon *et al.*, 2004). Changes towards earlier timing and warmer winter temperatures, as we observed, can lead to shifts in the life history of these cold-water fishes. For example, phenological decoupling (Noormets, 2009) such as shifts in timing of spawning (Wedekind & Kung, 2010; Shoji *et al.*, 2011) may affect other life stages, including earlier ocean migrations of salmon (Crozier, Scheuerell & Zabel, 2011; Mundy & Evenson, 2011). Moreover, changes in timing of stream temperature could also be linked to changes in the predator–prey relationship between salmonids and aquatic insects due to early/late changes in emergence (Vannote & Sweeney, 1980; Rosenberger *et al.*, 2011).

Descriptors of variability, frequency and duration of temperature may also provide relevant information about how thermal regimes may affect aquatic organisms and stream ecosystems. For example, increases in daily minima and associated decreases in range are relevant to fish in both summer and winter. Increases in summer daily minima may not provide as much relief after elevated daily maxima (Johnstone & Rahel, 2003; Schrank, Rahel & Johnstone, 2003), while increases in minima in winter might increase metabolic demands and feeding rates (Cunjak, 1996). Documenting changes in temperature variability could also help researchers to understand both shifts in the competitive ability of populations living in suboptimum colder habitats (e.g. Vannote & Sweeney, 1980) and behavioural thermoregulation such as balancing metabolic costs to conserve energy when food is limited (Brett, 1971; Jones *et al.*, 2002). Descriptors of frequency and duration of particular events (e.g. warmest or coldest) could be useful for hypotheses concerning temporal changes in extreme conditions and their ecological impacts (Gaines & Denny, 1993). It is valuable that researchers and managers have a range of clearly defined descriptors available for characterising thermal regimes and using in context specific evaluations. Future consideration of biological responses in relation to descriptors proposed herein should provide a means of better understanding their relevance to species and ecosystems.

Recent trends in temperature descriptors

A subset of the descriptors of thermal regimes is highly responsive to change over time in the time series we considered. Whereas we detected warming trends for all the descriptors of magnitude, warming was more frequently observed for MIN stream temperatures than for MAX and consistent with our observed decline in the daily range and variability of stream temperature at these sites over time. This finding parallels recent analyses of air temperatures (Easterling *et al.*, 1997; Alexander *et al.*, 2006; Strangeways, 2010; Morak, Hegerl & Kenyon, 2011). The latter study also reported faster rates of warming of daily minimum air temperatures than daily maximum, with concurrent narrowing of the range of daily air temperatures. Over time, the frequency and duration of cold events in our study streams declined, whereas there was a slight increase in the frequency and duration of warm events. In western North America, surface air temperatures show similar decreases in the annual frequency of cold nights (daily minimum of air temperature) and increases in the annual occurrence of warm nights (Alexander *et al.*, 2006; Morak *et al.*, 2011).

Warming of sites occurs in both winter and summer, but our results of trends by month suggest that temperatures warmed most strongly in winter than other seasons. This is supported by evidence from several descriptors including magnitude (i.e. MIN), variability (i.e. CV) and timing (5th percentile). Similarly, in terrestrial ecosystems, it has been reported that at higher latitudes most of the warming since 1975 has occurred in winter and spring, and in western North America, the warming has been strongest during winter (Strangeways, 2010; Kerkhoven & Gan, 2011).

Relative to other descriptors, timing seems to show less change over time except for timing of 5th percentile of accumulated degree-days. For example, the timings of thermal minima and maxima, as well as timings of the 25th–75th, percentiles of accumulated degree-days do not change over the period evaluated (1979–2009). The timing of thermal events or thresholds is thought to be key for many species (Parmesan & Yohe, 2003), and metrics to characterise these shifts are valuable to consider. Timing for most of the temperature events we considered remain consistent (but see Arismendi *et al.*, 2012b).

Synchrony and coherence

Overall, only a few descriptors showed a high degree of synchrony across years and coherence among streams. The high degree of both coherence and synchrony of daily minimum could suggest it is a representative indicator of regional factors and changes, including the influences of climatic patterns. Notably, among the sites we studied, daily minimum appears to be more responsive than daily maximum values during summer, which have been commonly used as indicators of past change (e.g. Johnson, 2004; Dunham *et al.*, 2007; Groom *et al.*, 2011) or to project effects of global warming (e.g. Mohseni, Stefan & Eaton, 2003; Mantua, Tohver & Hamlet, 2010). Several other descriptors, including cumulative degree-days, CVmax and TIM_5th, exhibited an intermediate degree of coherence and synchrony and could be useful as additional descriptors to test climate change–related responses of thermal regimes of cold-water mountain streams.

Although descriptors of frequency, duration and timing seem to have less coherence than descriptors of magnitude and variability, they are more coherent for colder than for warmer events. Specifically, TIM 5th, duration and frequency of cold events exhibit consistent declines, whereas for warm events, we see much more of a mix of responses, suggesting that cold events could be showing a greater long-term responsiveness to potential influences of the recent warming climate. Here, we considered only a small number of streams with long-term available information, and therefore, we cannot generalise beyond them to infer broader patterns of change in temperature (see also Arismendi *et al.*, 2012a). Differences between synchrony and coherence of the frequency, timing and duration of events were not a function of changes in riparian cover or human alterations, but could be attributed to other influence, such as long-term trends in groundwater recharge or flow (Tague *et al.*, 2008; Webb *et al.*, 2008; Arismendi *et al.*, 2012b). Primarily, we were focused on describing changes in the behaviour of temperature over daily, seasonal and annual time scales rather than addressing the local physical processes influencing temperature in streams (see reviews by Caissie, 2006 and Webb *et al.*, 2008).

Here, we propose a comprehensive range of descriptors of thermal regimes to better characterise stream temperatures throughout the year. The spatial coherence and temporal synchrony of thermal regimes can be evaluated using these descriptors, which will better characterise responsiveness of stream temperature to changes over time, including potential impacts of climate change. Although we focused these analyses on characteristics of a small number of cold-water mountain streams in the Pacific Northwest, this approach is transferable and will be useful for comparative studies among and within different hydroclimatic regions (e.g. Wolock, Winter & McMahon, 2004). Our finding of trends in daily minimum temperature (winter/spring) has important implications for considering the timing of monitoring temperatures in streams, typically conducted during the summer (June–August) and highlights the importance of using a year-round perspective to identify the most responsive characteristics of stream temperature under current and future environmental changes. We suggest that multiple descriptors can improve our understanding of thermal regimes and provide better quantification of year-round thermal characteristics, in addition to being valuable for identifying trends and disturbances over time.

Acknowledgments

Brooke Penaluna and two anonymous reviewers provided comments on the manuscript. Part of the data was provided by the HJ Andrews Experimental Forest research program, funded by the National Science Foundation's Long-Term Ecological Research Program (DEB 08-23380), US Forest Service Pacific Northwest Research Station and Oregon State University. Financial support was provided by US Geological Survey, the US Forest Service Pacific Northwest Research Station and Oregon State University through joint venture agreement 10-JV-11261991-055. The contribution of RH is based upon work supported by the National Science Foundation under Grant No. EAR-1039192. Use of firm or trade names is for reader information only and does not imply endorsement of any product or service by the U.S. Government.

References

Alexander L., Zhang X., Peterson T., Caesar J., Gleason B., Tank A.K. *et al.* (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, **111**, D05109.

Arismendi I., Johnson S.L., Dunham J.B., Haggerty R. & Hockman-Wert D. (2012a) The paradox of cooling streams in a warming world: regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophysical Research Letters*, **39**, L10401.

Arismendi I., Safeeq M., Johnson S.L., Dunham J.B. & Haggerty R. (2012b) Increasing synchrony of high temperature and low flow in western North American streams: double trouble for coldwater biota? *Hydrobiologia*, doi: 10.1007/s10750-012-1327-2.

Beacham T.D. & Murray C.B. (1990) Temperature, egg size, and development of embryos and alevins of five species of Pacific salmon: a comparative analysis. *Transactions of the American Fisheries Society*, **119**, 927–945.

Benson B.J., Lenters J.D., Magnuson J.J., Stubbs M., Kratz T.K., Dillon P.J. *et al.* (2000) Regional coherence of climatic and lake thermal variables of four lake districts in the Upper Great Lakes Region of North America. *Freshwater Biology*, **43**, 517–527.

Brannon E.L., Powell M.S., Quinn T.P. & Talbot A. (2004) Population structure of Columbia River Basin Chinook salmon and steelhead trout. *Reviews in Fisheries Science*, **12**, 99–232.

Brett J.R. (1971) Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). *American Zoologist*, **11**, 99–113.

Caissie D. (2006) The thermal regime of rivers: a review. *Freshwater Biology*, **51**, 1389–1406.

Clarke K.R. (1993) Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology*, **18**, 117–143.

Crozier L.G., Scheuerell M.D. & Zabel R.W. (2011) Using time series analysis to characterize evolutionary and plastic responses to environmental change: a case study of a shift toward earlier migration date in sockeye salmon. *The American Naturalist*, **178**, 755–773.

Cunjak R.A. (1996) Winter habitat of selected stream fishes and potential impacts from land-use activity. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**(Suppl. 1), 267–282.

Dunham J.B., Chandler G.L., Rieman B.E. & Martin D. (2005) Measuring stream temperature with digital data loggers- a user's guide. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Center General Technical Report RMRS-GTR-150WWW, pp. 15.

Dunham J.B., Rosenberger A.E., Luce C.H. & Rieman B.E. (2007) Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. *Ecosystems*, **10**, 335–346.

Easterling D.R., Horton B., Jones P.D., Peterson T.C., Karl T.R., Parker D.E. *et al*. (1997) Maximum and minimum temperature trends for the globe. *Science*, **277**, 364–367.

Enfield D.B., Mestas-Nuñez A.M. & Trimble P.J. (2001) The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters*, **28**, 2077–2080.

Esterby S.R. (1996) Review of methods for the detection and estimation of trends with emphasis on water quality applications. *Hydrological Processes*, **10**, 127–149.

Falcone J.A., Carlisle D.M., Wolock D.M. & Meador M.R. (2010) GAGES: a stream gage database for evaluating natural and altered flow conditions in the conterminous United States. *Ecology*, **91**, 621.

Fry F.E.J. (1947) Effects of the environment on animal activity. University of Toronto Studies, Biological Series 55. *Publication of the Ontario Fisheries Research Laboratory*, **68**, 1–62.

Gaines S.D. & Denny M.W. (1993) The largest, smallest, highest, lowest, longest, and shortest: extremes in ecology. *Ecology*, **74**, 1677–1692.

Groom J.D., Dent L., Madsen L.J. & Fleuret J. (2011) Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management*, **262**, 1618–1629.

Helsel D.R. & Hirsch R.M. (1992) *Statistical Methods in Water Resources*. Elsevier Press, Amsterdam, the Netherlands.

Hipel K.W. & McLeod A.I. (1994) *Developments in Water Science: Time Series Modelling of Water Resources and Environmental Systems*. Elsevier Press, Amsterdam, the Netherlands.

Hirsch R.M., Slack J.R. & Smith R.A. (1982) Techniques of trend analysis for monthly water quality data. *Water Resources Research*, **18**, 107–121.

Johnson S.L. (2004) Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences*, **61**, 913–923.

Johnstone H.C. & Rahel F.J. (2003) Assessing temperature tolerance of Bonneville cutthroat trout based on constant and cycling thermal regimes. *Transactions of the American Fisheries Society*, **132**, 92–99.

Jones W., Gurney W.C.S., Speirs D.C., Baconand P.J. & Youngson A.F. (2002) Seasonal patterns of growth, expenditure and assimilation in juvenile Atlantic salmon. *Journal of Animal Ecology*, **71**, 916–924.

Kerkhoven E. & Gan T. (2011) Differences and sensitivities in potential hydrologic impact of climate change to regional-scale Athabasca and Fraser River basins of the leeward and windward sides of the Canadian Rocky Mountains respectively. *Climatic Change*, **106**, 583–607.

Kruskal J.B. (1964) Nonmetric multidimensional scaling: a numerical method. *Psychometrika*, **29**, 115–129.

Magnuson J.J., Benson B.J. & Kratz T.K. (1990) Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. *Freshwater Biology*, **23**, 145–159.

Magnuson J.J., Crowder L.B. & Medvick P.A. (1979) Temperature as an ecological resource. *American Zoologist*, **19**, 331–343.

Mann H.B. (1945) Nonparametric tests against trend. *Econometrica*, **13**, 245–259.

Mantua N., Tohver I. & Hamlet A. (2010) Climate change impacts on stream flow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change*, **102**, 187–223.

Mathews R. & Richter B.D. (2007) Application of the indicators of hydrologic alteration software in environmental flow setting. *Journal of the American Water Resources Association*, **43**, 1400–1413.

Meeuwig M.H., Bayer J.M. & Seelye J.G. (2005) Effects of temperature on survival and development of early life stage Pacific and Western brook lampreys. *Transactions of the American Fisheries Society*, **134**, 19–27.

Mohseni O., Stefan H.G. & Eaton J.G. (2003) Global warming and potential changes in fish habitat in U.S. streams. *Climate Change*, **59**, 389–409.

Morak S., Hegerl G.C. & Kenyon J. (2011) Detectable regional changes in the number of warm nights. *Geophysical Research Letters*, **38**, L17703.

Mundy P.R. & Evenson D.F. (2011) Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. *ICES Journal of Marine Science*, **68**, 1155–1164.

Noormets A. (2009) *Phenology of Ecosystem Processes Applications in Global Change Research*. Springer, New York.

Olden J. & Naiman R.J. (2010) Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology*, **55**, 86–107.

Olden J.D. & Poff N.L. (2003) Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, **19**, 101–121.

Parmesan C. & Yohe G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37–42.

Poff N.L. (1996) A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology*, **36**, 71–91.

Poff N.L., Allan J.D., Bain M.B., Karr J.R., Prestegaard K.L., Richter B. *et al.* (1997) The natural flow regime: a new paradigm for riverine conservation and restoration. *BioScience*, **47**, 769–784.

Poole G.C., Dunham J.B., Keenan D.M., McCullough D.A., Mebane C., Sauter S. *et al*. (2004) The case for regime-based water quality standards. *BioScience*, **54**, 155–161.

R Development Core Team (2005) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, Available at: http://www.R-project.org.

Rosenberger A.E., Dunham J.B., Buffington J.M. & Wipfli M.S. (2011) Persistent effects of wildfire and debris flows on the invertebrate prey base of rainbow trout in Idaho streams. *Northwest Science*, **85**, 55–63.

Schrank A.J., Rahel F.J. & Johnstone H.C. (2003) Evaluating laboratory derived thermal criteria in the field: an example involving Bonneville cutthroat trout. *Transactions of the American Fisheries Society*, **132**, 100–109.

Sen P.K. (1968) Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, **63**, 1379–1389.

Shelford V.E. (1931) Some concepts of bioecology. *Ecology*, **123**, 455–467.

Shoji J., Toshito S., Mizuno K., Kamimura Y., Hori M. & Hirakawa K. (2011) Possible effects of global warming on fish recruitment: shifts in spawning season and latitudinal distribution can alter growth of fish early life stages through changes in daylength. *ICES Journal of Marine Science*, **68**, 1165–1169.

Spagnoli B., Planton S., Déqué M., Mestre O. & Moisselin J.M. (2002) Detecting climate change at a regional scale: the case of France. *Geophysical Research Letters*, **29**, 1450.

Strangeways I. (2010) *Measuring Global Temperatures: Their Analysis and Interpretation*. Cambridge University Press, New York.

Tague C., Grant G., Farrell M., Choate J. & Jefferson A. (2008) Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change*, **86**, 189–210.

Vannote R.L. & Sweeney B.W. (1980) Geographic analysis of thermal Refugia equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *The American Naturalist*, **115**, 667–695.

Webb B.W., Hannah D.M., Moore R.D., Brown L.E. & Nobilis F. (2008) Recent advances in stream and river temperature research. *Hydrological Processes*, **22**, 902–918.

Webster K.E., Soranno P.A., Baines S.B., Kratz T.K., Bowser C.J., Dillon P.J. *et al*. (2000) Structuring features of lake districts: landscape controls on lake chemical responses to drought. *Freshwater Biology*, **43**, 499–515.

Wedekind C. & Kung C. (2010) Shift of spawning season and effects of climate warming on developmental stages of a grayling (Salmonidae). *Conservation Biology*, **24**, 1418–1423.

Wolock D.M., Winter T.C. & McMahon G. (2004) Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management*, **34**, 71–88.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 contains a description of the interpolation method and supplementary results (Tables S1–S10; Figures S1–S8).

Appendix S1. Interpolation method.

Figure S1. Trends in the frequency of 1-day events (cold and warm) at each site.

Figure S2. Trends in the frequency of 7-day events (cold and warm) at each site.

Figure S3. Trends in the duration of both the coldest and warmest event per year at each site.

Figure S4. Trends in the distance between 1-day events (coldest and warmest) at each site.

Figure S5. Trends in the distance between 7-day MA events (coldest and warmest) at each site.

Figure S6. Trends in the timing of the 25th, 50th, and 75th percentile of cumulative degree-days.

Figure S7. Trends in the timing of the warmest events (1- and 7-day MA) at each site.

Figure S8. Trends in the timing of the coldest events (1- and 7-day MA) at each site.

Table S1. Trends in stream temperature magnitude.

Table S2. Trends in stream temperature magnitude by month.

Table S3. Trends in stream temperature variability by month.

Table S4. Synchrony analysis of temperature magnitude.

Table S5. Synchrony analysis of temperature variability.

Table S6. Synchrony analysis of temperature frequency of events.

Table S7. Synchrony analysis of temperature duration of cold events.

Table S8. Synchrony analysis of temperature duration of warm events.

Table S9. Synchrony analysis of temperature timing of events (part 1/2).

Table S10. Synchrony analysis of temperature timing of events (part 2/2).

(Manuscript accepted 7 December 2012)